First Lab on Muon Lifetime, Data Acquisition

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Introduction

In this lab you will measure the lifetime of the mu mesons which are produced by cosmic Rays. The experiment will introduce you to three important physics topics: 1) the muon, 2) the radiation from outer space, and 3) the interaction mean free path for strongly interacting particles and the use of this concept to identify weakly interacting particles.

The muon (μ) was the first real break in the "standard model" of the early 1900s which viewed electrons, protons and neutrons as the fundamental building blocks of matter. The muon didn't fit into that picture and is now known to be the lepton or "electron" of the second quark generation of the standard model which is proving to be so successful at the end of the 1900s and the beginning of the 2000s. The muon was also the principal actor in one of the most famous dramas of physics history: The verification of relativistic time dilation was first done by comparing the muon flux at Denver with the flux on nearby Mt. Evans, about two miles higher. If the lifetime for muons in flight were as short as you will measure for muons at rest, the fraction of muons, even traveling at the speed of light, which traversed the approximately two mile vertical drop between Mt. Evans and Denver would have been extremely small. Stated in terms of the experiment you will do, your measurement of lifetime and flux at (approximately) sea level in Nashville would require a lethal flux at airplane altitudes if the effective lifetime for relativistic muons were not considerably greater than the value you will obtain for stopped muons.

The work which led to the discovery of cosmic radiation began about 1900 as an attempt to understand the electrical conductivity of gases. It was first speculated that the conductivity was due to ionization produced by charged particles knocking electrons out of the gas molecules as they passed through the gas and that the charged particles were the emissions from radioactive elements. Measurements at the top of the Eiffel Tower (Wulf, a Jesuit priest in 1910), over the water, and at mountain altitudes showed that most, but not all, of the ionization was produced by such radioactivity. The notion of extraterrestrial radiation was vigorously opposed by many physicists until data from balloon borne experiments in 1910 (Hess) and 1919 (Kolhörster, data up to 30,000 feet above sea-level) showed that the ionization first decreased as the instruments got away from the radioactive elements in the earth and then increased to much higher levels with increasing altitude. (The preceding is from pp. 1-3 of *Cosmic Rays*, L. Janossy, 1950, Oxford Clarendon Press, The International Series of Monographs on Physics. A briefer, more up-to-date discussion is in *American Scientist*, September 2000, article by Alex Dzerba, *et al.*, p 406.) The study of the cosmic radiation was pursued with new vigor in the period from 1940 to 1960, the period before particle accelerators had been developed, when these energetic particles from outer space were used to explore the newly discovered force which binds the neutrons and protons into nuclei.

The primary Cosmic Radiation is protons with a few percent of helium and heavier elements (and perhaps some neutrinos) with a spectrum of energies per particle up to at least 10^{22} eV. That is about 100 Joules. A single proton in the cosmic radiation can have an energy comparable to that of a very fast baseball moving at about 40 m/s. While sources and detailed mechanisms for accelerating particles to these extreme energies are still not understood, it is becoming clear that pulsars, black holes, and rotating neutron stars are likely candidates. In fact the energy spectrum of primary cosmic rays is now one of the experimental tools for studying these objects. Unfortunately, the magnetic fields in outer space deflect the charged particles so their trajectories measured on Earth no longer point back to the source. Measurement of the uncharged (neutrino) component is only now becoming possible by experiments such as the AMANDA project at the South Pole, and the hope is that measurements of the directions of very high energy neutrinos will help identify the sources of cosmic rays.

(Note: High energy jargon is used here. Masses of particles are given as rest energy measured in energy units. Also the column mass is the mass of unit area of the slab of material under discussion and the column density is the mass of a block of unit thickness and unit area. The atmosphere is the slab of interest in this note and it has a column density which decreases exponentially (for an isothermal atmosphere which is a reasonable approximation) and integrates to a column mass of 10,000 kg per sq m or 1000 g per sq cm.)

The high energy piece of the charged spectrum of incident radiation has the characteristic hadronic interaction mean free path (100 g/sq cm column density) which is about a tenth of the of the atmosphere. That is, the typical high energy proton incident vertically at the top of the atmosphere (about 20 miles above sea level) penetrates about a tenth of the atmosphere and then collides with the nucleus of an air atom. Some of the energy is usually turned into matter in the collision and typically ten to fifty new hadrons are produced, each having some fraction of the original particle energy. Most of the particles which are produced are pions. The charged pions have a similar interaction mean free path, so an extremely crude picture of the fate of a high energy proton which hits the top of the atmosphere is that it generates a cascade of particles which increases in number and decreases in average energy per particle. The particles with energies below a few tens of GeV drop out of this model because they do not have enough energy to produce new particles and hence no longer participate in the cascade process. They lose energy only by atomic processes until they stop in a few meters of air or a few cm of solid or liquid material. The number of particles in the cascade increases exponentially with depth and the energy of the initial particle is distributed among the particles. When the average energy per particle is reduced to a few tens of GeV, the multiplication stops and the cascade ends within a few meters. The neutral pions have such a short lifetime that they usually decay into two gamma rays before they have time to interact, and the hadron cascade thus generates a number of electromagnetic cascades of photons and electron pairs which is similar in general structure to the charged particle cascade. Note that this crude model predicts that the number of steps, and thus the length, of a cascade is proportional to the logarithm of the incident energy. The overall result of this cascade process is that the background from cosmic rays reaches a maximum at an altitude of about 60,000 feet and only a few of the protons or pions reach sea level. However, the charged pion has a life time of 2.6×10^{-8} seconds and some small fraction of pions will decay before they have time to interact. The pion decays into a muon and a neutrino. The muon is not sensitive to the strong force, so it does not participate in the cascade process and simply looses energy by bumping into atomic electrons. It is these muons which make up most (about 98%) of the charged flux at sea level.

The fact that the muon passes through a lot of air before it stops and subsequently decays is the original proof that the muon does not interact strongly - that it cannot be the "field particle" predicted by the early field theorists to explain the strong nuclear force. We now recognize it as the "electron" of the second generation in the standard model of the constituents of matter. It has a mass which is 106 MeV (roughly 210 times heavier than the electron) and decays into an electron and two neutrinos. The average of quality measurements of the lifetime is 2.19703 ± 0.00004 microseconds [Particle Data Group: Review of Particle Physics, *The European Physical Journal*, **15**, 2000].

At sea level, the muons have an angular distribution which is approximately proportional to the square of the cosine of the angle to the vertical. The energy spectrum is inversely proportional to the cube (2.7 power is somewhat more accurate) of the energy for energies above a few hundred MeV. (See the Cosmic Ray section in the PDG review, *loc. cit.*, pp 150-155, for more detail.) The energy loss of these muons is almost entirely to excitation and ionization of the material which the muon passes through and this is about 2 MeV per g/sq cm (column density) until the muon is within a few centimeters of the end of its range. Near the end, the rate of energy loss increases dramatically (as $1/v^2$). Consequently a few muons stop in a slab of material but most simply pass through with only a very minor decrease in energy and higher energy muons continue to penetrate several kilometers into the earth. (The rate of energy loss is 2 MeV per g/sq cm which is roughly 2 TeV/km of water, but, for energies above about a TeV, bremsstrahlung from muons becomes important and the rate of energy loss increases.)

Turning now to a more specific description of this experiment, we are concerned with the light produced by muons incident on a block of scintillator as shown in Fig. 1. Most of the muons incident on the block simply pass through the block leaving a cone of Ĉerenkov light and a trail of excited and ionized atoms behind them. The excited and ionized atoms return to the ground state by radiating photons, primarily in the ultraviolet. For most materials, even transparent substances like plastic, the ultraviolet would be absorbed with an attenuation length of a few millimeters and eventually turned into heat energy. Scintillator is simply plastic which has been doped with a small quantity of wave shifter, material which absorbs ultraviolet and reemits in the visible. The wave shifter absorbs the ultraviolet even more strongly but it reemits the energy in the visible where the attenuation length is a few meters and the light can be detected by a photomultiplier held against the block a reasonable distance away. The time scale for this process depends upon the type of scintillator, but is usually a couple of nanoseconds for useful scintillators. The light from scintillation is isotropic and the intensity which reaches the cathode of the photomultiplier is typically an order of magnitude greater than from the Ĉerenkov radiation.

A few (about 1/170) of the muons incident on the block will have an energy low enough so that they stop in the block. Most of these will decay with an average lifetime of 2.2 microseconds into an electron and two neutrinos. Since this is a three body decay, the electron can have a kinetic energy from zero up to about half the muon rest energy, but measurements show that the electron usually gets more than a third of the muon rest energy (*Introduction to High Energy Physics*, Donald E. Perkins, Addison Wesley Publishing Co., 1982, p 242) and the electron produces a later pulse of light of roughly the same intensity as the light produced by the parent muon in a block of the size used here. The distribution of times between the muon and electron light pulses is the data which is needed to compute the muon lifetime. Figure 2 shows such a plot from 300 hours of running. An overview of the experimental procedure is thus:

1. Record the time between light pulses which occur within about 20 microseconds of one another. Several tens of thousands of these measurements will be needed.
2. Histogram these differences in bins no more than 250 nanosecond wide and make the vertical axis logarithmic. (100 nanosec is used in the example.)
3. A portion of the histogram at a few microseconds is expected to be a straight line and the (negative of the) slope of this line is the decay probability, the reciprocal of the lifetime.
4. Worry about
   (a) a constant background due to the passage of another muon through the block (accidentals or random coincidences).
   (b) how to put an error on the measurement,
   (c) whether there are ways to make more efficient use of the data to calculate a better estimate of the lifetime and error, and
   (d) photomultiplier after pulsing at short times,
   (e) physics effects which might make this type of measurement give a result which is not simply the free muon lifetime.

Specific Implementation with Equipment Provided

Equipment provided:

1. A block of scintillator one foot square and 8 inches thick
2. a 5 inch, 10 stage photomultiplier in a light tight and RF shielded box
3. a high voltage power supply to bias the photomultiplier
4. a discriminator to select signals above noise and make digital pulses
5. a gate generator to set the maximum length between 2 pulses
6. a coincidence unit (to see if there is a second pulse in coincidence with the gate set by the gate generator)
7. a computer running the HPVEE data acquisition and analysis software

8. a TDS210 Digital Oscilloscope

Caution note: The photomultiplier requires an anode voltage of about 1500 V. That is high enough to be dangerous. High voltage is run only on red cables with special connectors that do not mate easily with other BNC connectors. You should never connect or disconnect red cables without turning the power supplies off and waiting a few seconds for capacitors to discharge. In this laboratory you should have no reason to connect or disconnect red cables and you should not do so without explicit and very clear permission from the instructor. The connectors are constructed so that it would require a deliberate (and very foolish) attempt on your part to expose yourself to the high voltage, but connecting or disconnecting a high voltage cable with the power on can send large transients into sensitive electronics and destroy them.

The first part of the experiment is establishing the operating point for the PM, the high voltage and the discriminator bias. The PM puts out a negative pulse with rise time determined by the decay time of the light from the scintillator, the variation in time of various photon paths from particle track to photocathode, and variation in time for the electron cascades in the PM. This usually amounts to a few nanoseconds. The decay time of this pulse depends upon the RC of the capacitance and resistance (high frequency resistance) to ground at the anode. The resistance is usually determined by the 50 Ohm impedance of the cable and the RC is a few nanoseconds. Consequently the output pulse is about 10 nanoseconds wide with both area and height proportional to the number of photons which strike the photocathode. The pulse height must be significantly above the level of RF noise for the smallest pulses to be detected. The gain of the PM is a sensitive function of the high voltage but most of the noise does not depend upon the voltage. The procedure is to increase the high voltage so that the desired pulses are clearly above the noise. Since most of the muons go through the full 8 (20 cm) inch thickness, most pulses from muons correspond to an energy deposition of 40 MeV in the scintillator, you should first find the high voltage needed to see that pulse height above the noise background. Set the high voltage to some nominal voltage, 800 V, which is too low to give signal pulses and adjust the scope threshold so it does not quite trigger the sweep on noise. Try a sweep speed of 20 nanosec/cm, 50 Ohm DC coupled input, vertical sensitivity of about 20 mV/cm, and trigger on the slope of a negative pulse. Your threshold should be negative and 10 to 35 mV, depending upon the room in the building and other circuitry in the room. Now slowly increase the voltage on the PM until you see signal pulses. The signal pulses should occur at the rate of about 20 per sec and should be very well defined at 1200 V. Do not take the voltage above 1600 V. Most of the pulses you see will be from muons which go through the entire 8 inches of scintillator. You will be interested in muons which stop and thus go through part, perhaps a quarter of the way through the block, so you want the muons which go all the way through to give a pulse which is more than 4 times the pulse you can reliably see above background. Increase the PM high voltage until the band of pulses from the muons which pass through is approximately four times greater than the threshold pulse determined by the noise. These numbers characterize the detector and you should now turn your attention to the read–out electronics.

The first element in the read–out electronics is a discriminator. The threshold circuitry of the scope is an example of a discriminator which you have already used: it gives a standard square wave or digital pulse whenever the input exceeds (is more negative than) a set voltage. The role of the discriminator is to select PM pulses and provide several copies of a standard pulse which can be fed to the digital logic and the scope. The discriminator also provides a pin at which ten times the threshold can be read on a DC voltmeter. Experience shows that many discriminators are not reliable below 35 mV and that it is not generally safe to assume that the noise in the building will remain below 35 mV for an extended period of time. (If you were optimistic and thought that noise level was significantly less than 35 mV, you should redo the high voltage adjustment.) Put a tee on the cable from the PM, put the tee on the scope input and run a cable from the tee to the discriminator. Turn the scope input to high impedance (why? ask instructor if you need to) and connect a second scope input to the other discriminator output. (Some manufacturers save money by using the same driving circuit for pairs or for all outputs, and these behave properly only if all outputs are terminated in 50 Ohms.) The display of the pulses on the scope should be similar to the previous display. Use a simple multimeter set on DC and a jeweler's screw driver to set the threshold. Switch the scope display and trigger to the channel with the discriminator and set the width for the discriminator. The width is not critical unless further coincidence measurements are to be performed and 25 to 50 nanoseconds is suitable. Leave the trigger on the discriminator output and switch the display to the PM signal to verify that discriminator pulses occur only for PM pulses greater than the value you have selected.

The gate produced by the discriminator is sent to three points:

1. a delayed gate generator. The delayed and stretched (20 microseconds) gate in coincidence with the digitized phototube signal is used as a trigger by the scope.)
2. a coincidence unit to produce a digital signal if the delayed and stretched gate and a second pulse from the discriminator occur in coincidence.
3. the scope. This is the signal that the scope will use to calculate a time difference. The scope measurement of the period between these 2 pulses is triggered by the coincidence unit. The period is maintained in the scope memory until the value is read out by the computer (if you had it set up to run with the computer) To understand this, consider the two typical cases:
   (a) A muon goes through without stopping. A delayed gate is generated, but no second pulse occurs. The coincidence unit does not output a pulse, and the scope is not triggered.
   (b) A muon stops and decays a few microseconds after stopping. Again the muon pulse starts both units. The electron pulse a few microseconds later sends a pulse to the coincidence unit and a coincidence pulse is generated. This pulse triggers the scope and a time difference is measured. You can see this on the scope without the computer connected. If the computer were connected, this time difference would be recorded and plotted. The time the muon lived is the

time reported. The plot shown in figure 1 shows a collection of these times acquired in a typical short run. Most "events" have only one and a few have more than two hits. These other types are not explicitly used in the calculation of the number of triggers, but you may have acquired a few of these in the course of running.

The program in the computer is set to record a set number of events, though you can stop the acquisition at the next event read maually. At the end of the run, the number of events taken should be the same as those you requested.

The plot from a few tenths to about 5 microseconds is straight on log plot. At times greater than about 15 microsec it is a flat line and is due to accidentals. Plots from 55 hours of running run are included with this writeup. You will probably want to take 4 times more than this or so (about 50,000 events) The height of the flat line can be estimated from the data at long times (i.e. where the data looks really flat).

Methods of analysis:

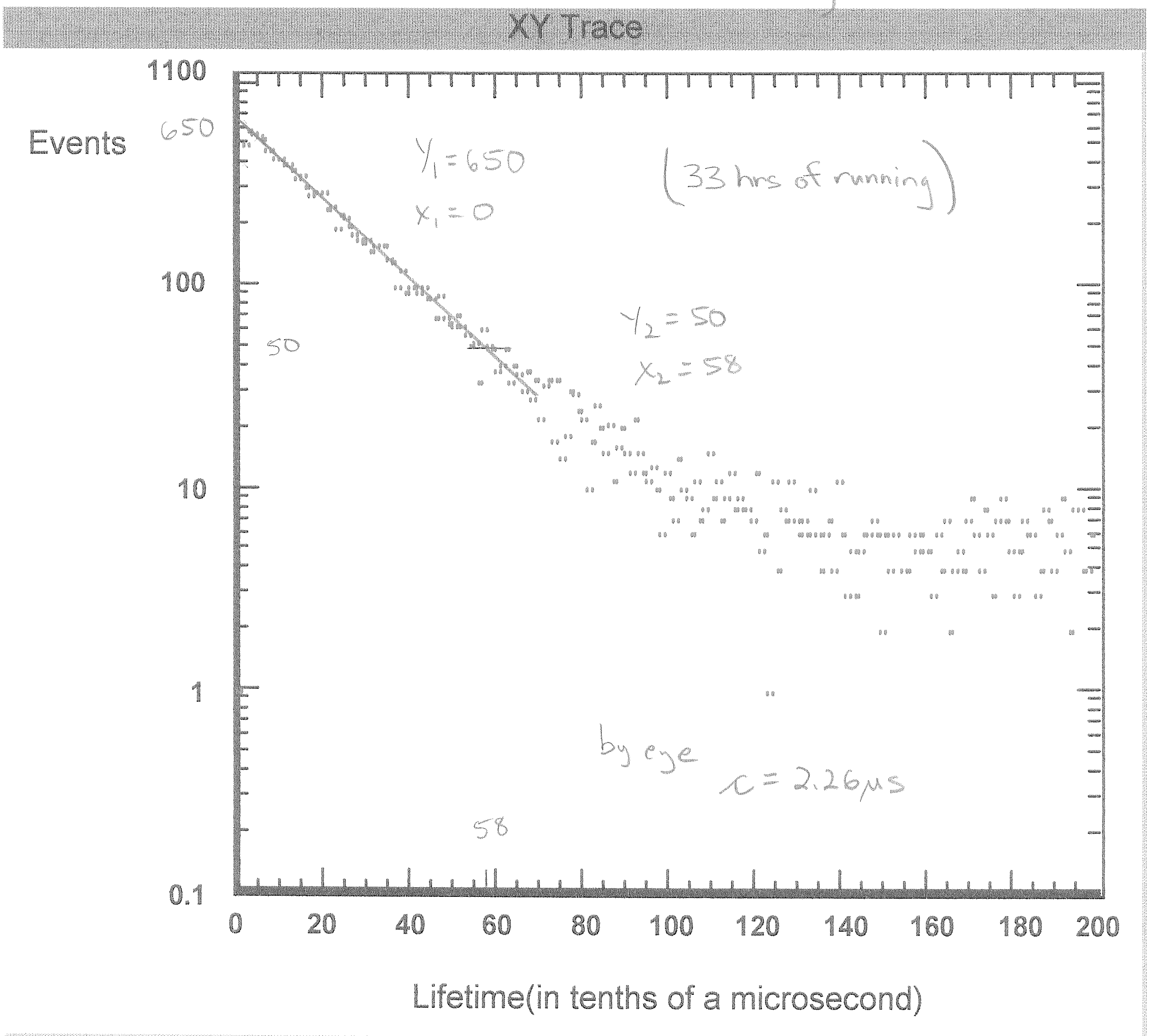
1. Ruler, eyeball method. Put a transparent ruler on the plot and line it up with the straight line portion of the data. Extend to coordinates which are easy to read and determine the constants for this line in the form y = $\mathrm{Ae^{Bt}}$ or $rmlog_{10}y = log_{10}A + Bt$. Substitute for y and t for two points on your line. Dividing one equation by the other eliminates A and leaves you a simple equation for B. The lifetime in nanoseconds is 1/B. Try steeper and flatter lines at the limits of what appear to be acceptable fits and calculate B for each to get some feel for the error on the determination of B.
2. Linear fit method. If you subtract the random background, the plot should become a pure exponential instead of a gracious curve from a straight sloping line to a constant. You can estimate the background from the points at large t. Thus if you make a linear plot of the logarithm of the subtracted numbers of counts *vs.* the time, you have the familiar fit to a straight line problem. However you cannot assume that all points have the same errors. You must assign errors to the log which correspond to the square root of the number of counts in the bin before background subtraction. How do you propagate errors to the log of a number? (Use derivatives just as you do for the square of a variable.) Do you know how to do a linear least squares fit with errors on the transformed measurements? This method basically assumes that the error on the subtracted randoms is negligible while the next method takes the errors on the background determination into account.
3. Nonlinear fit method. This method is able to minimize the sum over all measurements of the square of the difference between the formula and the data divided by the square of the error on the data point. That is, all 3 constants in the formula are varied and the set of three constants which give the smallest value for the sum is selected. By varying the constants, sensitivity of the sum to the individual constants and thus errors to the fitted quantities are determined. In fact, the function is expanded in a series about the current guess at a solution and the problem is then linearized by keeping only linear terms in each variable in the series expansion, this linear problem

is solved just as you solved the linear equation in 2). The process is then repeated taking the expansion point as the solution of the previous fit, etc. If the final errors are small enough so that it is legitimate to discard the higher order terms within a few errors for each variable, the process makes sense. This is the method used, employing a CERN program call MINUIT, for the fit with errors shown in the accompanying figure.

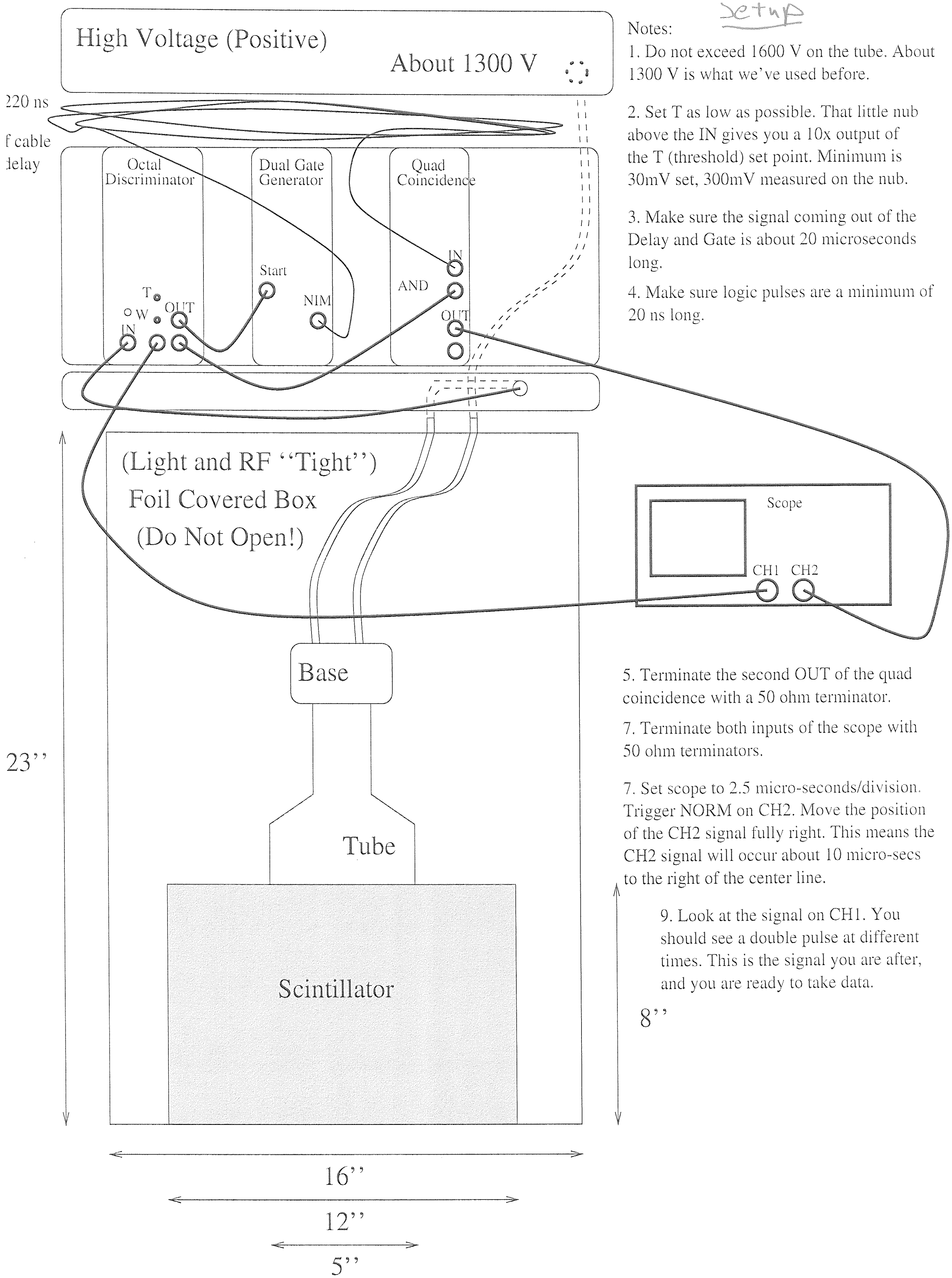
At least for the first set of students, we will discuss how much of this analysis the students should do and how much the instructor should do to help them. The student clearly should do method 1) while 3) is pretty much just using a canned program and there isn't much physics in the operation, so treatment with method 3) may turn out to be done by the instructor.

Figure 1

about 55 hrs of running



Setup



Notes:

1. Do not exceed 1600 V on the tube. About 1300 V is what we've used before.

2. Set T as low as possible. That little nub above the IN gives you a 10x output of the T (threshold) set point. Minimum is 30mV set, 300mV measured on the nub.

3. Make sure the signal coming out of the Delay and Gate is about 20 microseconds long.

4. Make sure logic pulses are a minimum of 20 ns long.

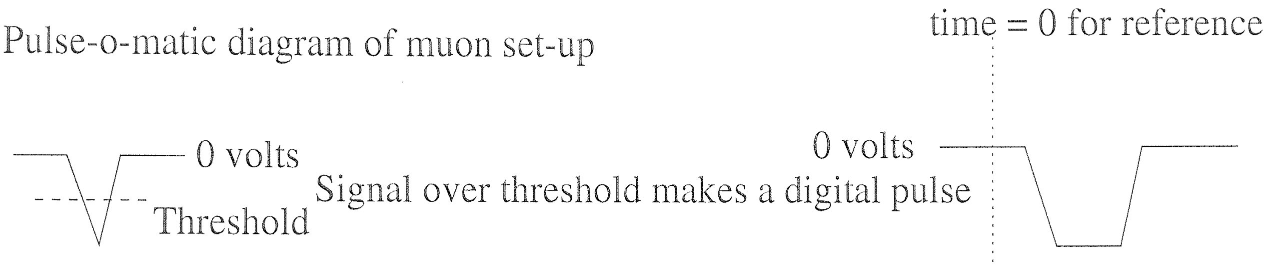
5. Terminate the second OUT of the quad coincidence with a 50 ohm terminator.

7. Terminate both inputs of the scope with 50 ohm terminators.

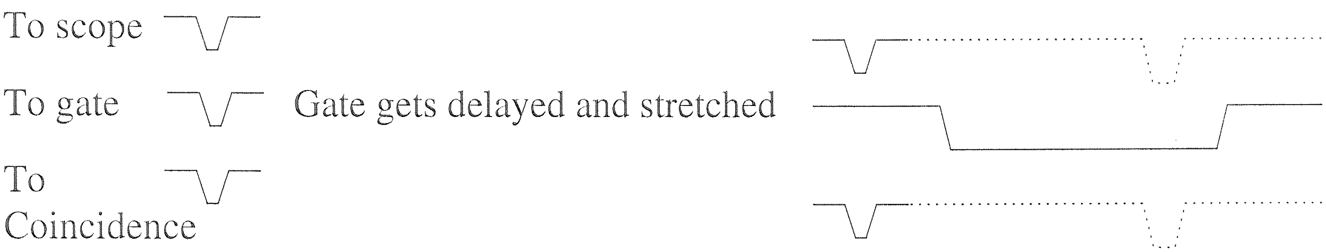
7. Set scope to 2.5 micro-seconds/division. Trigger NORM on CH2. Move the position of the CH2 signal fully right. This means the CH2 signal will occur about 10 micro-secs to the right of the center line.

9. Look at the signal on CH1. You should see a double pulse at different times. This is the signal you are after, and you are ready to take data.

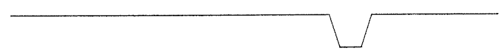
Pulse-o-matic diagram of muon set-up



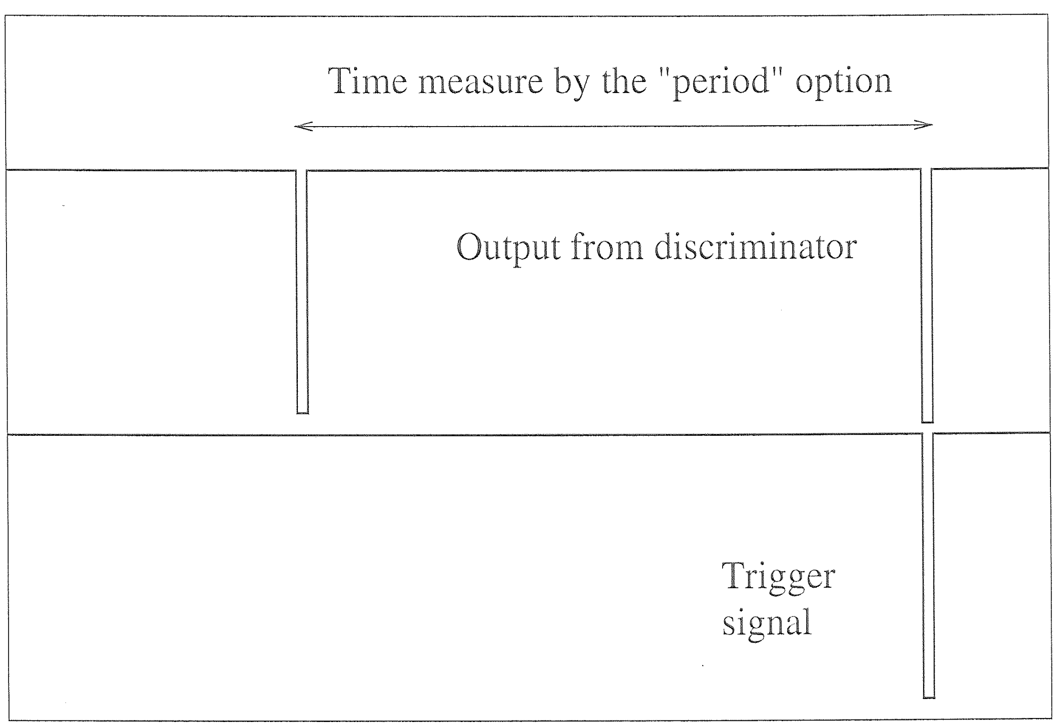
Digial pulse is split 3 ways:



So if we get a second pulse (indicated by dotted line) the result from the coincidence unit looks like:



And your Scope picture look like:



Getting started on the computer:

1. Login as student. Your teacher has the password.

2. go to the area D:\users\student\muon

3. click on the icon muonlifetime, a visual program with little wires connecting obtects should appear.

4. Connect a TDS210 scope to the centronics like GBIB cable

5. Follow the lab setup as described in the write-up and the set-up diagram.

6. Click button to start acquisition. Events should appear.

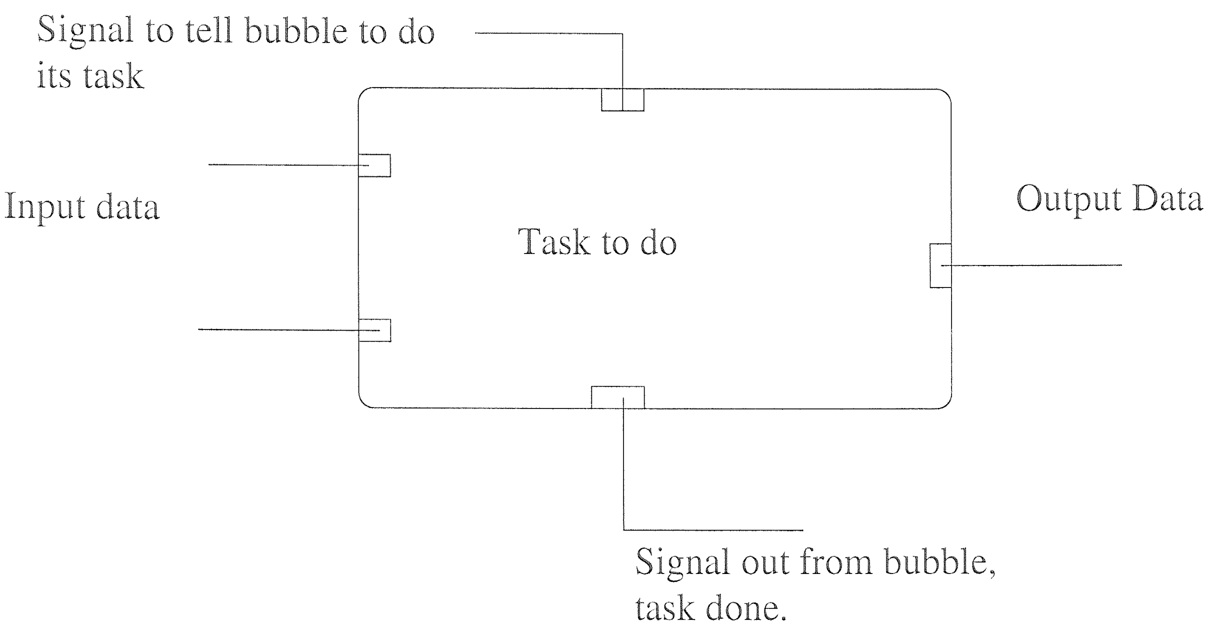
7. Data output file is slectable, the default is called myfile. It contains the data you are acquiring. You need to be a little careful, some of the fake data generator programs can overwrite this file.

8. You can view your progress on the web. See instructions.

Note on HPVEE:

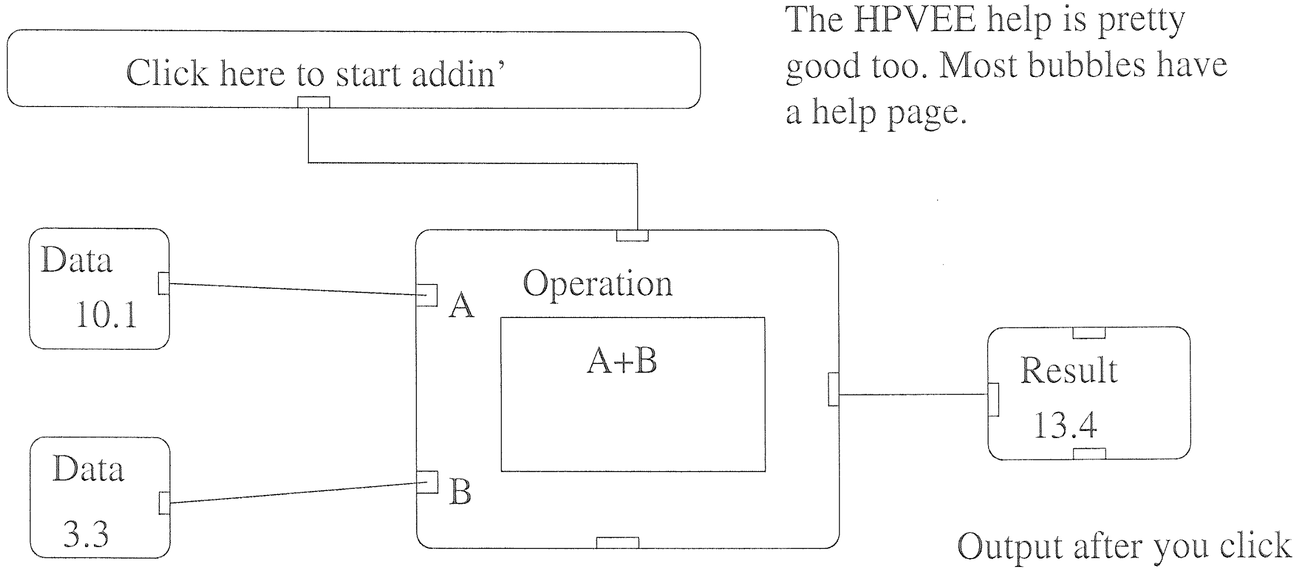
HPVEE is a visual programming language that is supposed to make your life a little easier if you are trying to record data from an instument. Here's pretty much how it works:

Bubbles perform tasks, here's a picture



If you leave off the signals to tell the bubble to do something, it will do it's job if the data on the inputs change. Here's a program that adds two numbers together: (the more complicated programs you can follow in the same way)

The HPVEE help is pretty good too. Most bubbles have a help page.



Viewing your experiment's progress on the web.

1. Make sure you are hooked up to the internet. Try opening internet explorer. If it finds microsoft, the internet is connected.

2. In the file menu of HPVEE, select preferences and follow the windows to enable the web server.

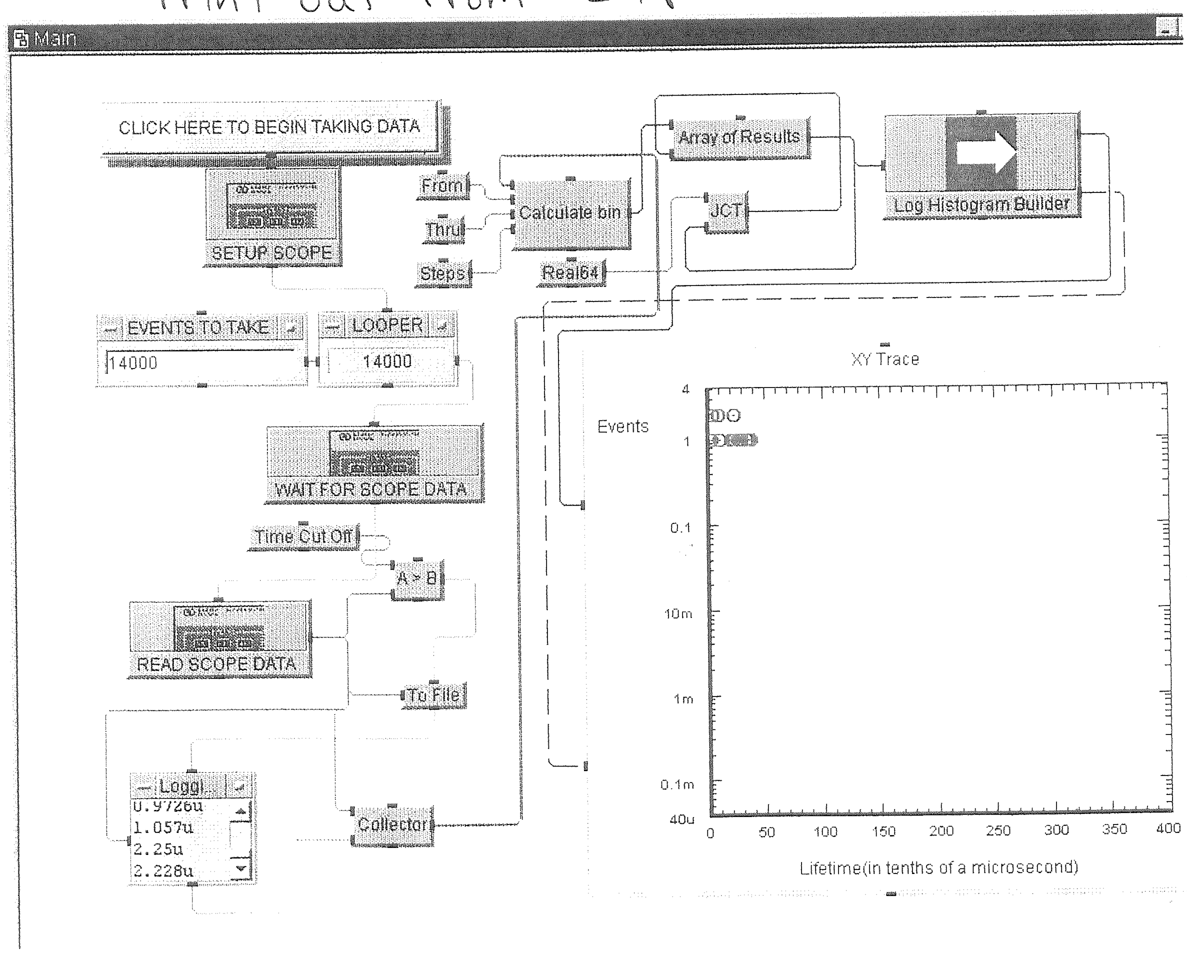
3. Get an MSDos command promt and enter the command   ipconfig.

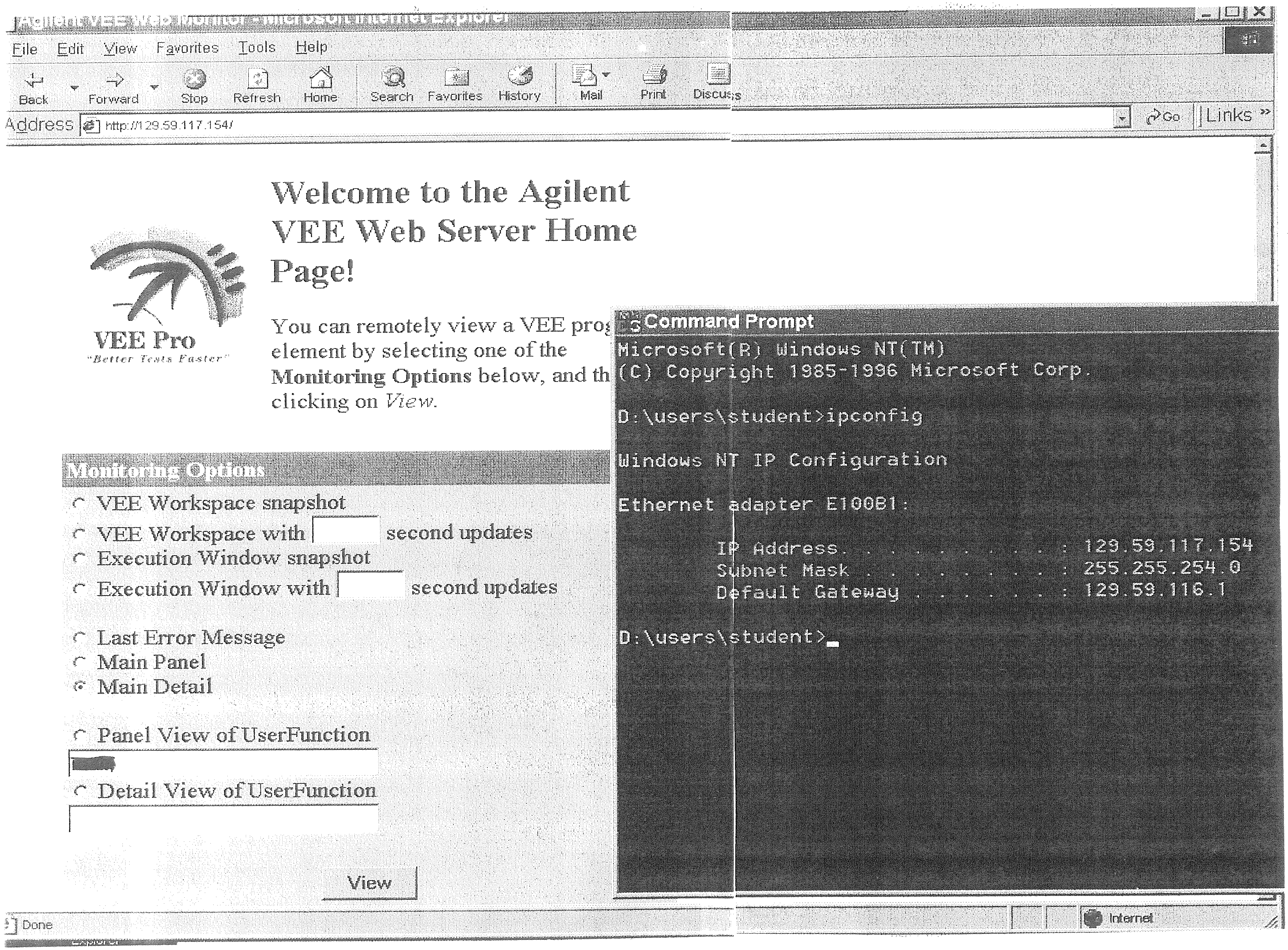
4. You can now access your experiment from your home to see how it is doing. A screen dump of the greeting page is shown:

    a: Select Main Detail on the browser page

    b: Hit View, your screen should show the below picture.
    (note: this is just a screen dump, no commands are allowed!)

Print out from Explorer

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Main Detail
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Detail View of UserFunction
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Windows NT IP Configuration
Ethernet adapter E100B1:
IP Address. . . . . : 129.59.117.154
Subnet Mask . . . . : 255.255.254.0
Default Gateway . . . . . . : 129.59.116.1
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