Nuclear Physics #2

Notes on Muon Physics Experiments

1. Read the user's manual. Also read up on how a photomultiplier tube (PMT) works.

2. **An important setting**: Make sure the HV Adjust knob on the detector is at position "10".

3. **Detecting muons using the oscilloscope**: Turn on the electronics box and set the Discriminator Conrol knob to "7". The green LED should be blinking several times per second. Connect the Tektronix 3054B oscilloscope to both the Amplifier Output and the Discriminator Output. Set the input impedances of the oscilloscope to 50 Ω, the time scale to ~ 20 ns per division and trigger the sweep with the Discriminator-Output channel. The pulses that you see are mostly associated with ~ 4 GeV muons passing through the detector that have originated at the top of our atmosphere. The different pulse heights are associated with random variations in the energy loss of the muons as they pass through the scintillator. Record the pulse widths, shapes and heights.

The fact that you see these high-energy muons is a demonstration of Einstein's Special Theory of Relativity! At rest a muon has a lifetime of 2.2 μs. So if a muon had this lifetime while traveling near the speed of light, it would only penetrate 660 m of our atmosphere before decaying and never be detected near the surface of the earth since the depth of the atmosphere is ~ 8 km. Thus the fact that muons make it to your detector is proof of time dilation where the effective lifetime of the moving muon is $\geq (8000/660)2.2 \approx 27$ μs.

4. **Detecting muon decays**: Set the oscilloscope to sweep at 2 μs/division and the display persistence to ∞. Muons passing through the detector will only produce a pulse at zero time. When a low-energy muon comes to rest in the scintillator, it will also trigger the sweep; but if the muon decays in the next ~20 μs, you will see another pulse on the screen. These muon decays typically occur about once per minute. Let it run for a while, and you will see that most of the decay pulses occur before ~ 5 μs, as expected.

5. **Measuring the muon lifetime**: Before you finish your evening lab session, you should begin collecting muon-decay data. During one week of counting, you should see about 8,000 muon decays that will give a good measurement of the lifetime. Before running the data acquisition program, look in the folder on the desktop called "Muon Data Acquisition Software". Delete the text file called "muon.data". Now run **muon.exe**. Under preferences, choose **com3** and leave the decay-time histogram scale at 20 μs and the bin number at 20. After you start the program, the manufacturer recommends that you set the muon count rate to about 5/sec using the Discriminator Control knob. At any time you can ask the program to do a fit to your data that will return a value of the lifetime and its uncertainty. The password for this fit is "muon." At the end of your one-week run, pause the program. Write down in your notebook all the important quantities on the screen**—elapsed time, muon lifetime and its uncertainty, number of muons detected, number of muon decays, etc**. Now quit the program; but before it will let you exit, it will ask you if you want to save the data. You should answer yes, and this writes data to two files: (1) with a name that is the date and time when the measurement was originally started and

(2) the **muon.data** file. If you answer no, only the former file will be created. For the latter file, the data are appended; but since you started with no **muon.data** file, this file is created for the first time. **At this point, copy this muon.data file into your separate data folder**, because another student running this program may accidentally append his/her data to your **muon.data** file or erase it. Likewise, you should also copy the former file to your data folder.

6. **Analyzing your results**: Run the program **sift.exe**. It extracts the muon-decay events and places them in a separate file so you can make a histogram of the number of muon decays vs. time. Import this data file into a graphing program. **Warning**: for times < 0.1 μs, the detector significantly undercounts the muon-decay events. Can you guess why? So you should be careful to start your histogram binning for times > ~ 0.1 μs. If you begin your time binning at time = 0, the first bin will have less counts than it should, and this will skew your fit of Eq. (1) to the data, see below. If a given time bin has N counts in it, assume that your data are obeying Poisson statistics and assign an uncertainty of $\sqrt{N}$ for the data in each time bin. So now your plot can show error bars associated with the ordinate values. Fit the following equation to the data, using the error bars to weight the fit:

$$N = N_o e^{-t/\tau} + \Delta \qquad (1)$$

where τ is the lifetime and Δ is a non-zero constant background count. This background count is mostly associated with two non-stopping muons passing through the scintillator within 20 μs of each other. Using the numbers that you wrote down before you quit the program, compute an expected value for Δ and see if it agrees with your value obtained from the fit. Analyze your value of τ in terms of its expected value—see lab manual.

7. **Poisson statistics**: Your fit made use of the $\sqrt{N}$ estimate for the uncertainty of the decay data in each time bin. You should prove that your data obey Poisson statistics. You should do this analysis separately for (1) those muons that didn't stop in the detector and (2) those that stopped and decayed in the scintillator. On the desktop, you will find a folder labeled "Muon Analysis". In that folder there are some Mathcad programs to extract the data that you need. Start with the "Read-this-first" file. You may also want to read Taylor's book on error analysis.

8. **Changing the PMT high voltage**: So far you have only set the HV Adjust knob position to "10". Change this setting to several different values, record the reading on the DVM that is connected to the HV-Monitor, note what happens to the pulses (as seen by oscilloscope) and use the program to record what happens to the average muon count rate. Explain what you see. Would you expect your value of τ to be affected by this HV Adjust knob setting? Perhaps you want to find out.

9. **Systematic uncertainties for τ**: So far, your final value of τ has an uncertainty that is statistical in nature. So what about systematic uncertainties? How accurate is the timing circuit in the electronics? Although you can use the LED pulser on the detector to perform this test, we have found that scintillations from the LED and the muons interfere with each other, making the timing measurements less accurate. Instead you will use the HP 8012B Pulse Generator to check the calibration of the electronics. This generator can put out single or double pulses. First, connect the HP generator to the oscilloscope and set it to put out single negative pulses of < 200 mV height and time width comparable to what you observed in item #3, above. Also connect the

oscilloscope to the Amplifier Output and the Discriminator Output. Set the repetition rate to about 5/sec and all oscilloscope inputs to 50-Ω impedance. **Now make sure the muon electronics is turned off.** Disconnect the cable at the PMT "pulse output" on the top of the detector and connect the cable to the HP pulse generator, leaving the oscilloscope also connected. Be sure to connect 50-Ω "short" to the PMT Output on the detector. Now turn on the muon electronics and observe what happens on the oscilloscope. Next set the pulse generator to double-pulse mode and set the oscilloscope to automatically measure the time between the pulses from the HP generator. You can vary the time between the two pulses and run the program for short periods of time to see how the oscilloscope-measured and the program-measured time intervals agree. Do a really careful job on this! Is the systematic uncertainly less that your statistical uncertainty for τ?

10. **Other properties of muon electronics**: In determining the reliability of your measurement, you want to learn as much as you can about how the electronics works. Put an attenuator on the output of the HP pulse generator and vary the pulse height to measure the gain of the amplifier and to determine what minimum amplifier-output pulse height is needed to trigger the Discriminator—you'll need to keep track of the Discriminator Knob setting and the Reference Monitor (with a DVM).