

LABORATORY MANUAL FOR PHYSICS 180F

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0. This Manual

This is a newly revised version of the Lab Manual for Physics 180F.

There are currently four available experiments:

1. μ^+ Mean Lifetime and Polarization
2. μ^- Capture
3. Multiple Coulomb Scattering with Spark Chambers
4. μ Spectrometer

This manual describes the hardware setup for the first three experiments, including the logic modules, the logic circuits, PMT operation, HV adjustment, timing issues, debugging, and troubleshooting. The fourth experiment is described in a separate write-up.

The separate document, ***Supplementary Material V1.2***, provides some additional information about the labs, including discussion about backgrounds and analysis strategies.

I. Introduction

The objective of this course is to introduce students to techniques of experimental particle physics, with a particular emphasis on setting up and understanding the hardware (detectors and electronics) and on carrying out detailed analysis to derive meaningful results. This is accomplished by a number of experiments using cosmic-ray muons. Though technical issues abound and must be mastered with the necessary skill, the real point is to learn the art of performing a convincing experiment. Generally this only works when it intimately is combined with a cogent theoretical context. The course also presents the opportunity to work with modern software and ROOT, the widely used data analysis framework developed at CERN. Macros, written in C are provided as templates. *The code macros are intended to be examples only and students must expect to introduce changes to cope with their own specific problems.*

Because muons are relatively long-lived, most of them survive traversing the atmosphere, of which a one square centimeter vertical column has a mass of about a kilogram. This amount of matter is roughly equivalent to 90 cm of lead. Strongly interacting particles like pions generally do not penetrate the atmosphere all the way to the surface of the Earth.

From the time of I. I. Rabi's annoyed comment of "Who ordered that?", muons have taken on an honored position in particle physics. Muons share some of the properties of electrons (same charge, lack of strong nuclear forces), but they are unstable and more massive than electrons. Muons themselves are produced in weak interactions (or in pairs via the electromagnetic interaction). Since they do not interact strongly and their bremsstrahlung is suppressed due to their high mass, muons can penetrate a considerable amount of material and are often used as trigger particles where their presence may reveal the weak decay of a more exotic particle.

The four experiments of Physics 180F study: (1) the decay and polarization of positive muons, (2) the decay and capture of negative muons, (3) multiple Coulomb scattering of both charges, and (4) the direct observation of the two separate charges bending in a magnetic field. This manual covers the first three experiments; the fourth experiment is described in a separate write-up.

Feynman diagrams demonstrate how these processes are related. Figure 1a shows Coulomb scattering, Figure 1b, μ^+ decay, and Figure 1c μ^- capture at the nucleon level. Because μ^- particles disappear via both capture and decay, their disappearance rate exceeds that of μ^+ . In experiment (2) the disappearance and capture rate in various materials are determined. In experiment (4) the decay rates of μ^+ and μ^- can be compared. In experiment (1), μ^+ are preferentially studied since most μ^- will get captured in the copper target.

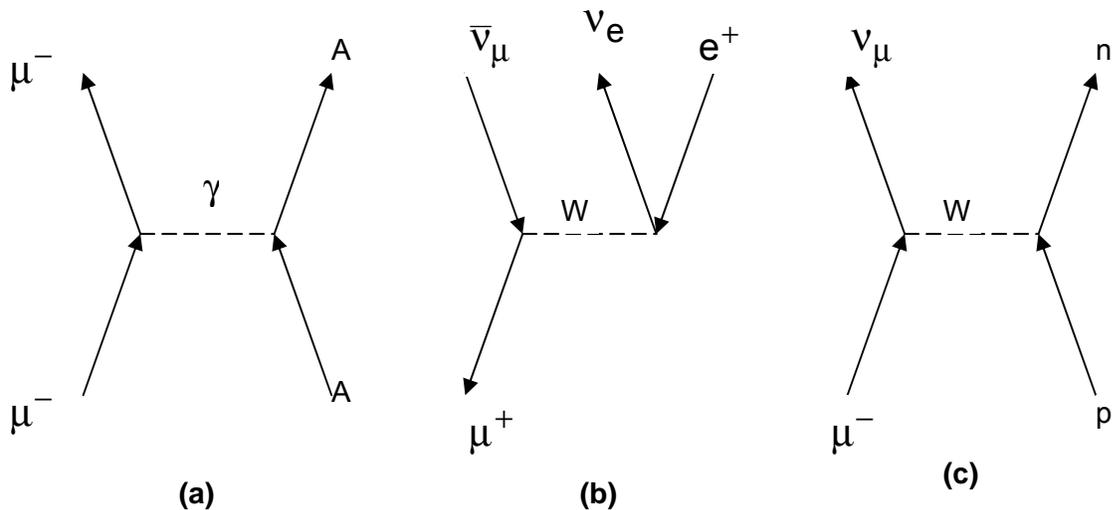


Figure 1: Feynman diagrams for muon interactions:
 (a) Coulomb scattering, (b) μ^+ decay, (c) μ^- capture.

The “exchanged” particle (dashed lines in Figure 1) defines the type of interaction as electromagnetic (1a) via the photon and weak (1b and 1c) via the W^\pm . The electroweak interaction describes the electromagnetic and weak forces in a unified frame work, and the Standard Model combines the three (electromagnetic, weak and strong) forces into one elegant theory. Striking examples of this unified electroweak force include the observed quantum mechanical interference between electromagnetic exchange of a photon and weak exchange of a Z^0 , the neutral companion of the charged W^\pm bosons.

Muons have played an important role in understanding electroweak interactions for many decades, starting with their very existence. Especially significant is the dominance of $\pi \rightarrow \mu$ decays over $\pi \rightarrow e$. The latter would be heavily favored due to its greater phase space, but turns out experimentally to be smaller by four orders of magnitude. This anomaly from the 1950’s was eventually explained as due to neutrino helicity and the V-A nature of weak interactions. Another consequence of this polarization of neutrinos in the $\pi \rightarrow \mu \rightarrow e$ chain of decays makes doable (and interesting) the first of the Physics 180F experiments.

As mentioned earlier, the goal of Physics 180F is to introduce students to a real-life laboratory situation in particle physics. As a result, none of the 180F experiments is easy and by definition this manual is not a simple cookbook. Careful setup and real understanding of the experimental procedure are required. Cosmic-ray rates are low and you have to think about backgrounds. It is critical for each group to keep a careful logbook of their work. Although not a cookbook, the manual does provide complete recommended setups and details on the suggested steps for carrying out the analysis and estimating the backgrounds. The payoff is, of course, the knowledge and satisfaction gained from doing a convincing experiment. *Please pay attention to the text in italics which generally discuss important points or specific tasks that students should carry out.*

II. The Source and Properties of Muons

Figure 2 shows the measured spectrum of cosmic-ray muons on Earth at sea level. When first observed, muons were thought to be the pions predicted by Yukawa in 1934 to mediate his screened inverse square, strong force. Instead, muons do not interact strongly and are completely different particles from pions (hence I.I. Rabi's question). In fact, muons in the cosmic rays originate mainly from the decays of pions (and kaons).

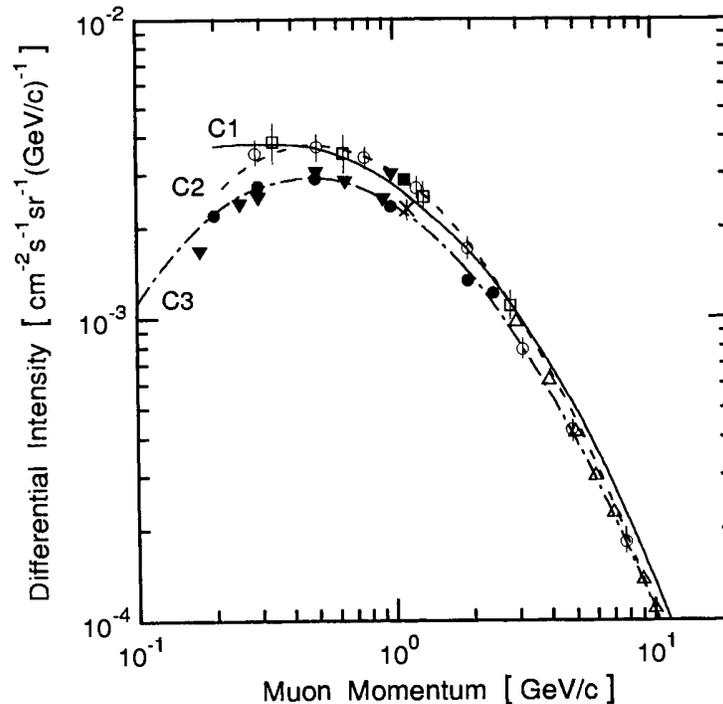


Figure 2: Spectrum of cosmic-ray muons at sea level. The differential intensity or flux (dN/dp) is plotted as a function of the muon momentum p . The points refer to different measurements and the curves are fits to the measurements. From P.K.F. Grieder, *Cosmic Rays at Earth*, Elsevier Science B.V. (2001).

The Earth is bombarded by high-energy and very high-energy cosmic particles (primary cosmic rays, consisting of protons and more massive nuclei). These particles, created in astrophysical sources in the Galaxy and beyond, interact in the upper atmosphere to produce extensive air showers – i.e. extensive electromagnetic and hadronic cascades that propagate at relativistic speeds towards the Earth's surface. Pions are produced in the hadronic component of the shower; these pions come in three charges, π^+ , π^- , π^0 . Unless they interact first, charged pions decay

weakly in flight to charged muons. Neutral pions decay electromagnetically to two photons.¹ Most muons make it to ground level and, to a limited extent, below. Even very energetic muons eventually lose all their kinetic energy to ionization or radiation.

Three properties of muons allow them to be detected and identified: (1) they are charged and therefore generate scintillation light in appropriate material, (2) they do not interact strongly, and (3) they are relatively massive (compared to the electron) and thus do not appreciably radiate when passing through material. Therefore, muons can penetrate a filter material such as iron. A generic muon detector is shown in Figure 3, consisting of two scintillation counters with a slab of iron between. A scintillation counter is a slab of scintillator (wrapped in foil and paper to make it light-tight) that is connected to a photomultiplier tube (PMT). A charged particle going through the counter will produce scintillation light via ionization that is detected by the PMT.

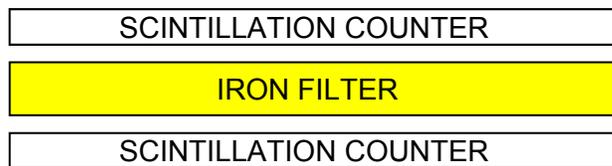


Figure 3: A simplified detector of muons.

Referring to Figure 3, low-energy electrons and photons, coming from above, are easily stopped in the iron. A coincidence of the top and bottom counters (i.e. signals in the two counters within a short time interval) is required so that only a particle that goes through the iron can give a signal.

Before you actually set up the wiring for your lab, you should look at the outputs of the PMTs on an oscilloscope. The clean, relatively large negative signals are the ones due to real muon tracks. The smaller signals occurring at a very high rate (~kHz or greater) are largely due to photocathode quantum noise. You should spend some time learning how the scope functions, including how to adjust trigger, gain, time base, and so on. *Examine the signals from each of the scintillation counters used in your experiment and make sketches of what you see on the oscilloscope.*

¹ These are the most frequent decay modes. Most particles decay to several different final states, with widely varying branching fractions; see Particle Data Group (<http://pdg.lbl.gov/>).

III. Experimental Details

Momentum Selection

The “telescope” of Figure 3 could be used to roughly measure the flux of cosmic rays, but the experiments in 180F require more sophistication, namely to make a selection of the muons based on their momentum. Both the μ^+ decay/polarization experiment and the μ^- capture experiment use muons that stop in a target and subsequently (within a few microseconds) emit a secondary particle. In the multiple Coulomb scattering experiment, we want muons with relatively low momentum in order to maximize the amount of scattering. Thus all three experiments need muons with momenta near 200 MeV/c, which can be achieved in a similar manner. Figure 4 shows an improved telescope that adds an iron slab below the sandwich of Figure 3. The second slab serves as a target and is followed by an “anti-counter” (C3) to reject muons that pass through the target. The anti-counter is the same as a counter, but it is operated in a slightly different manner to achieve a high efficiency (i.e. to veto the through-going muons). Relative to the upper counters (C1 and C2), the anti-counter (C3) is typically operated at a higher high voltage (HV) or at a lower discriminator threshold, and it is possibly thicker or of larger area. Its discriminator output is set wider in time than for C1 or C2 and is usually connected to the veto input of a coincidence unit.

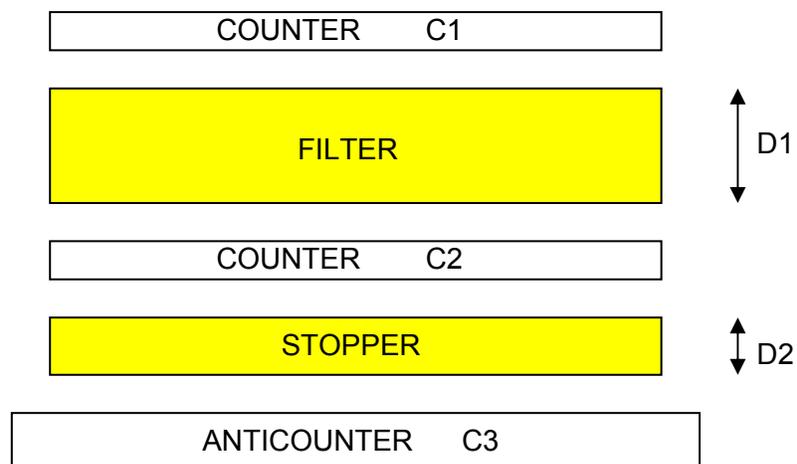


Figure 4: A more sophisticated detector that can select muons in a narrow band of momentum. The anti-counter (C3) vetos the through-going muons that have higher momentum.

To be detected by the condition $1 \otimes 2 \otimes \bar{3}$,² a particle must penetrate at least a thickness D1 but not more than the thickness D1+D2. The relation between energy loss and range is covered in the lecture part of Physics 180F. The momentum that just makes it through D1=7.5 cm of iron (60 g/cm²) is approximately $P_{\min} = 200$ MeV/c. To get through D1+D2 = 7.5+2.5 cm of iron (80 g/cm²), a muon must have $P_{\max} = 230$ MeV/c. If $P > 230$ MeV/c, the particle is detected in C3 and the event is vetoed. The muons that enter C1 and satisfy the trigger $1 \otimes 2 \otimes \bar{3}$ are within the momentum interval of 30 MeV/c centered at approximately 215 MeV/c. In the 180F multiple Coulomb experiment, a detector like that shown in Figure 3 is placed downstream of the spark chamber array so that momentum selection follows the scattering. This is valid because the muons do not lose significant energy in the scattering. We also ignore energy lost in the counter material.

Rate Estimation

An estimate of the rate at which candidate events will occur can be made from available reference data. The Particle Data Group gives the fluxes of cosmic rays; one way to state the result is ~ 70 particles/m²/s/sr (mostly the “hard” component, i.e. muons). In the three labs, the counters are roughly 1 foot by 2 feet in surface area or ~ 0.18 m². Using Figure 4 as a generic 180F telescope, suppose that the distance from the top surface of C1 to the bottom of C3 is 30 cm, the solid angle (within a factor of ~ 2) is approximately $\Omega \approx \frac{0.18 \text{ m}^2}{(0.3 \text{ m})^2} = 2.0$ sr. This is the right ballpark for the μ^+

and μ^- experiments, but is an overestimate for the multiple Coulomb scattering (MCS) experiment where the counters are farther apart. To get a rough estimate for the overall rate, you can assume that the differential flux of muons is flat (i.e. independent of momentum) between 100 MeV/c and 2.0 GeV/c (see Figure 2). A 30 MeV/c momentum slice thus takes about 1.6% of the total flux. Putting the various factors together gives an estimate of $0.016 \times 2.0 \times 0.18 \times 70 \approx 0.4$ Hz for the rate of muons stopping in 1 inch of iron after having already penetrated 3 inches of iron. *Clearly this is a relatively crude estimate and an initial task for each group is to make a better estimate of the expected rate of triggered events for their experiment. Measure the size of the counters and their separation and think a bit more carefully about the solid angle calculation. Then, determine the expected trigger rate for stopping muons in your apparatus.*

²The symbol \otimes designates logical AND and \oplus designates logical OR. A bar above a number $\bar{0}$ means the logical complement of signal 0. Numbers correspond to the counter that produced the signal.

Electronics Overview

a) Discriminator and high voltage adjustments

As discussed earlier, charged particles going through a counter produce scintillation light that is detected by the photomultiplier tube (PMT) that is attached to the end of the counter. The PMT pulses are “analog” in the sense that they vary in amplitude and in duration depending on the amount of light detected. The electronic step in processing the analog PMT signals is to convert them into a standard “digital” shape by putting them into a discriminator. A discriminator is an electronic module that produces a standard NIM level pulse of specified *width* when an input signal crosses the specified *threshold*. Since the PMT produces a negative-going pulse, the discriminator thresholds are actually negative voltage levels and the discriminator fires when the input signal goes below the set voltage level. In this manual, we’ll just refer to the thresholds as positive quantities for simplicity. In terms of the discriminator output, the standard level for a NIM pulse is -0.7 V (into 50 Ω). Thus, when the discriminator fires, a square NIM pulse is produced where the -0.7 V level is held for the specified width. *Put a signal from one of your PMTs into a discriminator and examine the discriminator output (OUT) on the oscilloscope; measure the voltage level and length of the output pulse; look also at the inverting output ($\overline{\text{OUT}}$). Now read Section VI, Fast Electronics.*

Before you can start setting up the wiring for your experiment, you must first set a threshold for each discriminator and a high voltage (HV) for the PMT of each counter. This is called “plateauing” the counter and is discussed in detail in Section IV below. The HV affects the gain of the PMT and hence the size of the PMT output signal. You might think it is completely equivalent to reduce threshold and raise HV. To some extent this is true, but the HV also affects the amount of noise generated in the PMT due to thermal emission of electrons from the photocathode. A more pernicious background due to positive ion feedback is caused when an imperfect vacuum in the PMT contains enough gas molecules that one may be ionized in a collision with one of the many secondary electrons from a dynode. These positive ions then drift back and impinge on the photocathode producing large “after-pulses”.

Generally it is a good idea to set a discriminator threshold, say 30 mV, that exceeds (i.e. is below) any circuit noise, like power supply ripple or noise from fluorescent lights, and that also avoids PMT noise from e.g. thermal electrons emitted by the photocathode. The discriminator generally

has a minimum threshold setting (typically 15 mV, but it depends on the manufacturer and model). A **warning** is in order here: the potentiometer to adjust threshold on each discriminator channel is recessed about $\frac{3}{4}$ inch so it is easy to mis-align the little screwdriver that you use to make the adjustment. **Do not force the discriminator adjustment as you can easily break the potentiometer away from its circuit board.**

Regarding the discriminator widths, It will be easier to get good plateau data if you start with wide discriminator pulses, say ~ 50 ns so that the timing is not critical as you vary the HV. Only after you have determined an acceptable HV for each PMT should you try to reduce the discriminator output widths to be as narrow as possible in order to reduce the rate of accidental coincidences. The shortest practical discriminator width is ~ 10 ns.

The workings of PMTs will be discussed in lecture. The high voltage supplied between the PMT photocathode and PMT anode controls two performance parameters: (1) photocathode efficiency, i.e. the probability to eject a photoelectron when a photon hits the cathode surface and (2) the PMT gain G . The gain is determined by the secondary emission ratio of each dynode and by the number of dynodes. A value of G of 10^5 to 10^6 is typical. This means that for each photoelectron reaching the first dynode a signal of 10^5 to 10^6 electrons is produced at the PMT anode.

Some explanation is in order about the workings of the high voltage (HV) system for each lab setup. The HV originates from a supply unit mounted in a NIM crate, although the unit does not receive power through the NIM bus (i.e. there is a direct AC cable in back that goes to the wall). The μ^- experiment uses two HV supply units. The output from the supply unit goes to a voltage distribution box ("Voltage Distributor") that is basically a set of resistor dividers to permit a single supply to power multiple PMTs at different voltages. The knobs on the front panel of the distribution box allow you to control each individual PMT's voltage within a range of a few hundred volts relative to the output voltage of the supply. The distribution box has a monitoring circuit where the HV for each PMT is divided by 1000 and presented to a front-panel BNC/LEMO connector. A cable running from that connector to an LED display allows you to read the HV (divided by 1000). A rotor switch is used to select which PMT's HV to display.

b) Experiment wiring

After you've plateaued all of your counters, you can start to set up the wiring for your experiment. The wiring diagrams are shown in Figures 11, 13, and 15 for each of the three experiments, respectively. Some general remarks are needed about these diagrams before you begin. It is assumed that you have already read Section VI on Fast Electronics.

Electronic logic is usually described with a block diagram showing NIM or CAMAC modules as boxes connected by lines. It is not always obvious which direction a signal is supposed to go but usually inputs are on the left side of a box and outputs on the right. The trigger-decision process amounts to constructing and testing a Boolean logic expression, e.g. for the apparatus shown in Figure 4, this expression might be: $1 \otimes 2 \otimes \bar{3}$. Logic is a little more complicated in the real world because the input signals that are required to be in coincidence must overlap in time. However, the incoming PMT signals from different counters are not necessarily simultaneous. They jitter relative to each other by a few ns. In addition, the NIM modules (discriminators, logic units, etc.) insert a delay of several ns and cables cause further delay of about 1 ns per 15 cm. You must adjust cable lengths so that the incoming PMT signals are simultaneous to a reasonable degree. Usually, timing at the ~2 ns level is adequate.

Figures 11, 13 and 15 are actually quite similar in that they each employ discriminators and logic units to select low-momentum muons by vetoing the through-going tracks (see Figure 4 and its discussion). *However, in order to properly check the timing of your circuitry, it is recommended that you first select particles going straight through all your counters, including anti-counters such as C3 in Figure 4.* You can do this by removing the vetos produced by the anti-counters or, even better, by putting the anti-counters into coincidence with the other counters. The frequency of straight-through tracks is high enough that you can make timing and pulse duration adjustments with the oscilloscope. You can compare various signals and study both delays and minimum acceptable pulse widths. *Verify the timing of the intended veto signals by remembering that veto signals must precede the other signals by 10 ns or so and must also be wide enough to surround the other inputs in time.*

Taking Data: Data Acquisition (DAQ) and Analysis Programs

The data acquisition (DAQ) programs are closely tied to the hardware and are different for each experiment. For experiments (1), (2), and (4), the DAQ programs are written in C and are run from a command line window on the relevant Linux computer. The programs read numbers from the CAMAC modules, e.g., a TDC, and pass them to the online computer. The programs are named “muplus” for the μ^+ experiment (1), “muminus” for the μ^- experiment (2) and “muspec” for the spectrometer (4). The source code files for the programs carry a file extension of “.c”; for example, the source code for the μ^+ experiment is in the file “muplus.c”. The executable programs that you actually run in the command window (e.g. “muplus” with no file extension) are built with the utility called “make”. “make” is a standard utility in Unix that compiles source code and links the object code to the required drivers and utilities. Both the C code and the “Makefile” must be present in your working directory to rebuild any of the executables. However, most likely you will *not* need to rebuild the executable programs as the setups have been stable for a few years and have taken many weeks of data. The DAQ for the MCS experiment (3) is done with a Labview program on a Windows machine. Again, this program is stable and should work reliably.

You will often make different runs with specific conditions like target material, state of the magnetic field, trigger conditions and so on. Be sure to name each run uniquely and write down the conditions with sufficient detail so that you can reproduce the conditions if needed. Don’t rely on a mnemonic file name to describe the conditions.

For each of the labs, the DAQ programs produce output files that then require analysis. In principle, various analysis packages could be used, e.g. MATLAB, Mathematica, or even Excel. However, you are strongly encouraged to use the ROOT package from CERN that is a powerful and standard analysis tool in high-energy physics (<https://root.cern.ch/drupal/>). There is some ramp-up to using ROOT, but payoff is substantial in terms of its ability to analyze event-based data that are common in particle physics, nuclear physics and astrophysics.

In addition to the three Linux computers for experiments (1), (2), and (4), there are two machines running Linux that are intended for you to use for analysis; these are located to your left when you enter the lab room. To log onto any of the Linux machines, use the following:

```
username=  p180f
password =  fall15
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IV. Discriminator and HV Adjustment: the “Plateau”

In order to use a scintillation counter effectively, two quantities must be adjusted: the PMT high voltage (HV) and the discriminator threshold. The goal for these adjustments is to have the discriminator fully efficient in triggering on real charged particle signals while triggering as little as possible on spurious PMT noise. Ideally, for a fixed discriminator setting, there should be a range of HV values for which the triggering efficiency is roughly constant, i.e. a “plateau”.

The gain (amplification) of the PMT strongly depends on the supply voltage ($G \propto V^n$ approximately, with n the number of dynode stages, often 10 to 12); thus, at the typical operating voltages the gain can double with every 50-100 V increase in supply voltage. The dark current noise (thermally emitted electrons from the photocathode that mimic photoelectrons) also increases with supply voltage and is an undesirable background. Thus, if the discriminator threshold is set too high (i.e. too negative), legitimate signals will be missed, while if it is set too low, spurious triggers at high rates from both PMT noise and other low-level noise will trigger the circuit. For each lab, a suggested threshold setting is given in the setup instructions, but this is only a guide. You may find that something a bit higher is necessary for stability. Also, 15 mV is the typical limit (i.e. the smallest absolute threshold value) for discriminator operation, depending on the discriminator module.

Three different methods are outlined below for plateauing your counters. Given unlimited time it would be a good exercise to do all three methods on each counter. However, that will probably take too much time, and so try to do method 1 and method 2 on all counters. You can try method 3 on a few counters if you have time. Scaler units (and a watch) can be used to measure counter and coincidence rates. Remember that if the rates are high (i.e. 100's of Hz or more), you can get a good measure of the rate in a relatively short time period (e.g. 10 s). See Section VI for a description of configuring the Jorway scaler so that multiple sections can be controlled simultaneously.

Method 1: Singles Rates

The first method outlined is the most straightforward to understand conceptually. A reasonable discriminator threshold is chosen (usually 20 mV or 30 mV, but see your setup suggestions), and the trigger rate for one PMT (the singles rate) is plotted as a function of high voltage. This method has the advantage of using just one counter at a time, so it should be a good way to get a first

guess for operating voltages. Figure 5 shows how an ideal plateau curve for a single counter should look. For most actual counters, the curves will not look as good as this – i.e. the plateau region may be harder to make out or not evident at all.

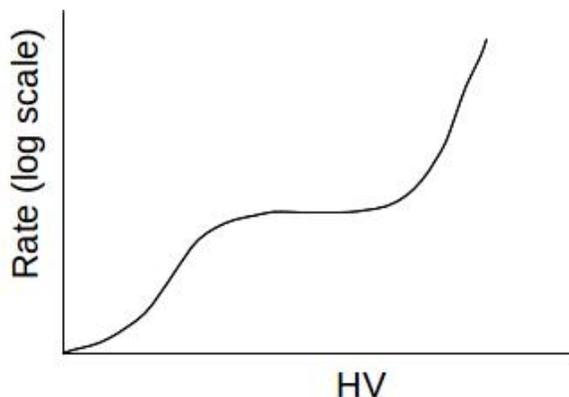


Figure 5: The idealized behavior of a scintillation counter; counter rate is plotted as a function of high voltage (HV). The flat region in the center is the “plateau” where charged particles are detected at full efficiency and where noise pulses are below threshold.

The idealized behavior we qualitatively expect is shown in Figure 5. At lower voltages, the PMT gain is too small for charged particle signals to be efficiently detected (i.e. the smaller pulses don't cross threshold). As the HV is raised, a 'plateau' region of operation is reached where the trigger rate increases slowly with HV. In the middle of the plateau is the ideal place to operate your counters. As a sanity check, the rate you get in this region should be within a factor of a few of the rate estimated for whatever counter you are using. Finally, if the HV is raised sufficiently, a region of rapidly increasing rate is entered where most of the triggers are noise pulses.

Regarding the rates you should expect, the rule-of-thumb is that muons at sea level have a flux of about 1 per cm^2 per minute (integrated over all angles). As an example, the smaller-sized counters in the μ^+ experiment are about 0.62 m x 0.31 m in size, and thus we can expect a total muon singles rate per counter of ~ 30 Hz. Since this is integrated over all angles, once you make a coincidence of two layers the rate will go down. There is also a soft (electron) component to the cosmic-ray flux at sea level, but since you are indoors most of that has been absorbed in the building above you. There is also natural radioactive background, some of which you will trigger on as well. For a counter of this size, a rate between 25 and 250 Hz is roughly what we can expect. Keep in mind that the actual scintillator sizes may be larger or smaller than this example.

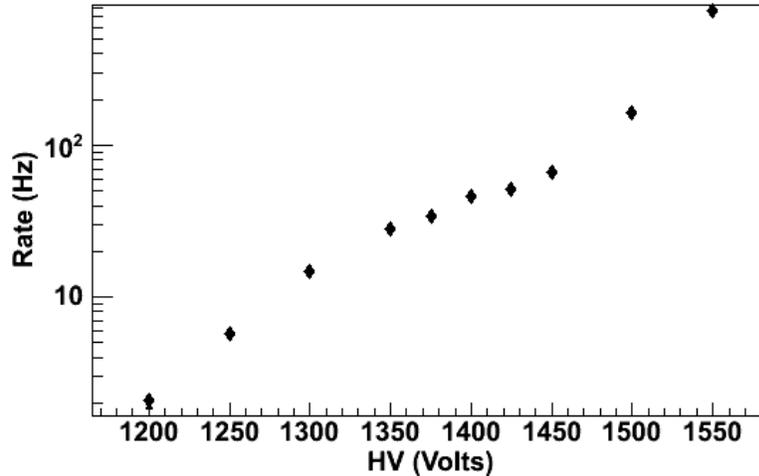


Figure 6: Recorded rates for one of the actual scintillation counters of the μ^+ experiment. A reasonable operating voltage for this counter would be ~ 1400 V.

As with most things, the real world is usually not quite this ideal. Figure 6 shows actual data from a counter in one of the 180F experiments. Qualitatively it is similar to Figure 5, but the “plateau” region is not nearly as flat or as well defined as in the ideal case. What this means is that some noise pulses are always present, but do not dominate until the HV is raised sufficiently high.

Our general preference is to allow more noise triggers to ensure that no legitimate signals are missed. Once two or more counters are operated in coincidence, the rate of accidental noise is greatly eliminated. There is of course a practical upper limit to this, either because the operating voltage of the PMT becomes too high (unsafe for it), or because the noise pulses start to contribute to a high accidental (chance coincidence) rate.

Method 2: Coincidence

If three scintillation counters can be operated in coincidence, the HV of any one of them can be optimized. The setup is shown schematically in Figure 7. This method requires that two of the counters have their HV’s set to reasonable values already (e.g. by using Method 1).

As the HV for C2 is raised (and it becomes fully efficient at detecting muons), the ratio of the coincidences will approach a constant:

$$R = \frac{C1 \otimes C2 \otimes C3}{C1 \otimes C3}$$

In this expression, the numerator is the rate of three-fold coincidences of C1, C2 and C3, and the denominator is the rate of two-fold coincidences of C1 and C3.

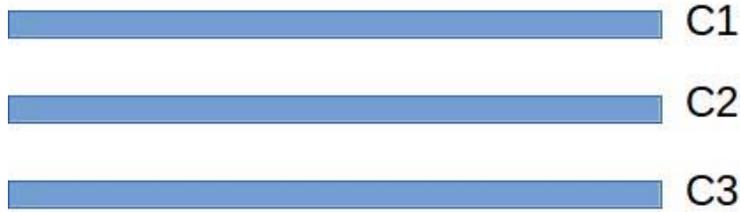


Figure 7: Schematic of three counters (C1, C2, and C3) used to plateau counter C2.

The coincidence method was used with the counters in the μ^+ experiment, and the results for one counter are shown in Figure 8. Note that if the counters are not fully aligned (or if the counter under test is C1 or C3 instead of C2), then the ratio will still approach a constant, but something less than 1.

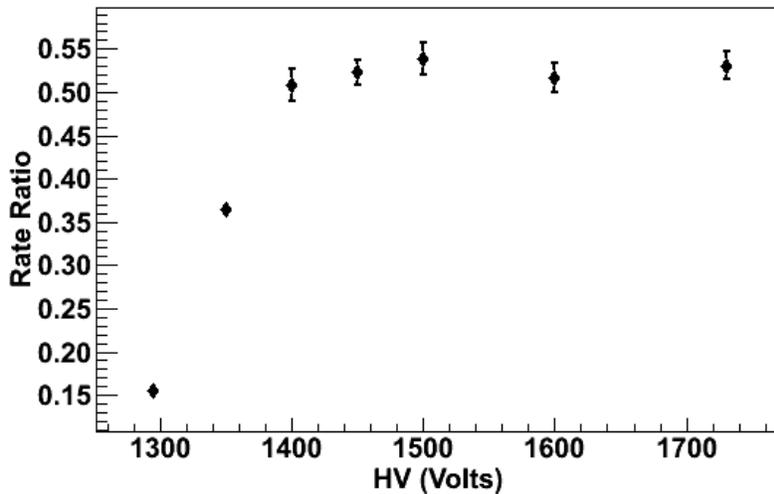


Figure 8: Coincidence method for determining a counter plateau using three actual counters in the μ^+ experiment of Physics 180F. The ratio of the three-fold coincidences to the two-fold coincidences is plotted as a function of the HV for the counter being studied. A reasonable operating voltage for the studied counter would be ~ 1500 V.

Method 3: Dual Discriminator

A third method of plateauing a single counter is to split its PMT signal with a NIM amplifier module (e.g. Phillips 776) or a linear fan in/out module (e.g. Phillips 748) and to then discriminate the two

signals at different thresholds (your normal threshold and a somewhat higher value, for example, 20 mV and 30 mV). Then, you measure the ratio of the high threshold count rate to the low. The ratio will start out small for low HV (more real signals will cross the low threshold than the high one). As the HV is raised, the ratio will increase (most real pulses will cross both thresholds). Eventually for even higher HV values, noise pulses will begin to cross the lower threshold, and the ratio will fall. The plateau region is near the peak of the rate ratio. Figure 9 shows actual data taken with one of the counters in the μ^+ experiment. The dual discriminator method is relatively quick to do and generally provides more incisive data than Method 1.

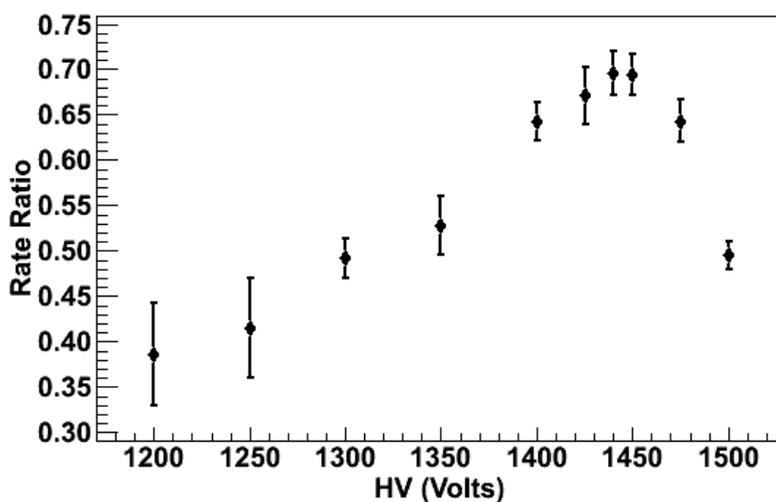


Figure 9: Results from the dual-discriminator method as applied to one of the scintillation counters in the μ^+ experiment. The ratio of the high-threshold (30 mV) discriminator over the low-threshold (20 mV) discriminator is shown as a function of the PMT high voltage. A reasonable operating voltage for the counter would be ~ 1450 V.

Final Comments on Plateauing

Figures 6, 8, and 9 are all for the same PMT. All three methods suggest an operating voltage of ~ 1450 V for a good efficiency for detection of muons with limited background from noise. In practice, it is usually desirable to operate somewhat above this voltage to be sure to get all legitimate signals at the cost of some extra noise pulses. Noise pulses do not typically happen in coincidence with pulses in other counters and so, in the final setup, they may not necessarily be a problem. Also note that some PMTs in some experiments have different instructions for plateauing because the desired use is different (e.g. the neutron detectors in the u^- experiment).

V. The Experiments

A. μ^+ Mean lifetime and Polarization

Experiment Outline

The discovery of parity violation in the weak interactions was one of the most important results in modern physics. The background to this discovery, and the ramifications resulting from it, are discussed in the lecture part of the course. In this experiment, parity violation is demonstrated in the decays of positively charged muons that exhibit a net polarization. Along the way, we also get a measurement of the mean muon lifetime.

Figure 10 shows the apparatus used in this experiment.

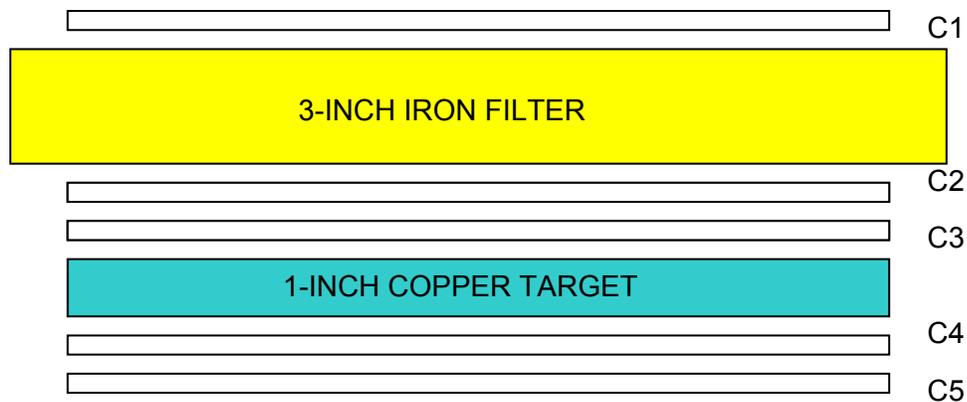


Figure 10: Sketch of μ^+ apparatus.

Cosmic-ray μ^+ particles with relatively low momenta are selected by the apparatus shown above. These particles stop in the copper target and subsequently decay via the weak interaction. The positron from the decay can be detected either by the counters above the target (an “UP” event) or by the counters below the target (a “DOWN” event). The muon lifetime is measured from the time difference between the event START, due to the initial passage of the muon, and the event STOP, due to the detection of the positron. Parity violation leads to a non-zero value of $\langle \vec{\sigma} \cdot \vec{p} \rangle$, where $\vec{\sigma}$ is the spin vector of the muon and \vec{p} is the momentum vector. Experimentally, a non-zero $\langle \vec{\sigma} \cdot \vec{p} \rangle$ is demonstrated by measuring an asymmetry in the direction of the emitted positron (i.e. an

asymmetry in the measured UP and DOWN rates). The asymmetry is made clearer by the application of an external magnetic field. This causes the magnetic moment of the muon (i.e. its spin) to precess around the field direction.

The detection of parity violation in cosmic-ray muons relies on the fact that there is a net spin polarization for the muons arriving at the surface of the Earth (i.e. that the spins from many arriving muons do *not* average out to zero). As discussed in the lecture, the fact that muons are predominantly created from the weak interaction decays of *downward* going pions and kaons leads to a net spin polarization of about 20% directed up. *For those groups doing this lab, it would be important to do some background reading on parity violation – especially by consulting the additional books listed in the syllabus for the course.*

It is important to remember that μ^- particles can stop in the target just as well as μ^+ . However, a μ^- can undergo a capture interaction in addition to decay. Since the capture rate in copper is significantly larger than the decay rate ($1/\Gamma_c \sim 160$ ns, as compared to $1/\Gamma_d \sim 2.2$ μ s), most μ^- will capture in the target and the resulting neutron will generally be missed by the thin scintillation counters that surround it. This is why the apparatus is most sensitive to μ^+ decays, especially at times greater than several capture lifetimes.

Getting Set Up

First make sure to read Section III Electronics Overview and Section VI Fast Electronics. Then you can start to plateau the five counters C1-C5, using the procedures discussed in Section IV. When doing these plateaus, set the discriminator thresholds to 20 mV and adjust the HV of each counter. A good initial guess for the HV is ~ 1300 V. When you are happy with your HV settings, you are ready to start wiring up the basic logic, shown in the block diagram of Figure 11.

A muon that stops in the target makes the signal: $M = \overline{C4} \otimes C1 \otimes C2 \otimes C3$. Electronically, this is done by putting outputs from the B-discriminators for C1, C2, and C3, along with a veto signal from the A-discriminator for C4, into a coincidence module, labeled **M** in Figure 11. Another signal into **M** is a lockout signal (**L/O**) as discussed in the caption of Figure 11. **M** feeds **S** which starts two time-to-digital converters (TDC's) and two identical 20 μ s gates (**G1** and **G2**). One TDC is subsequently stopped by up-moving particles (presumably positrons) and the other TDC by down-moving ones. To restrict these to positrons from muon decay, the particles are recorded only if

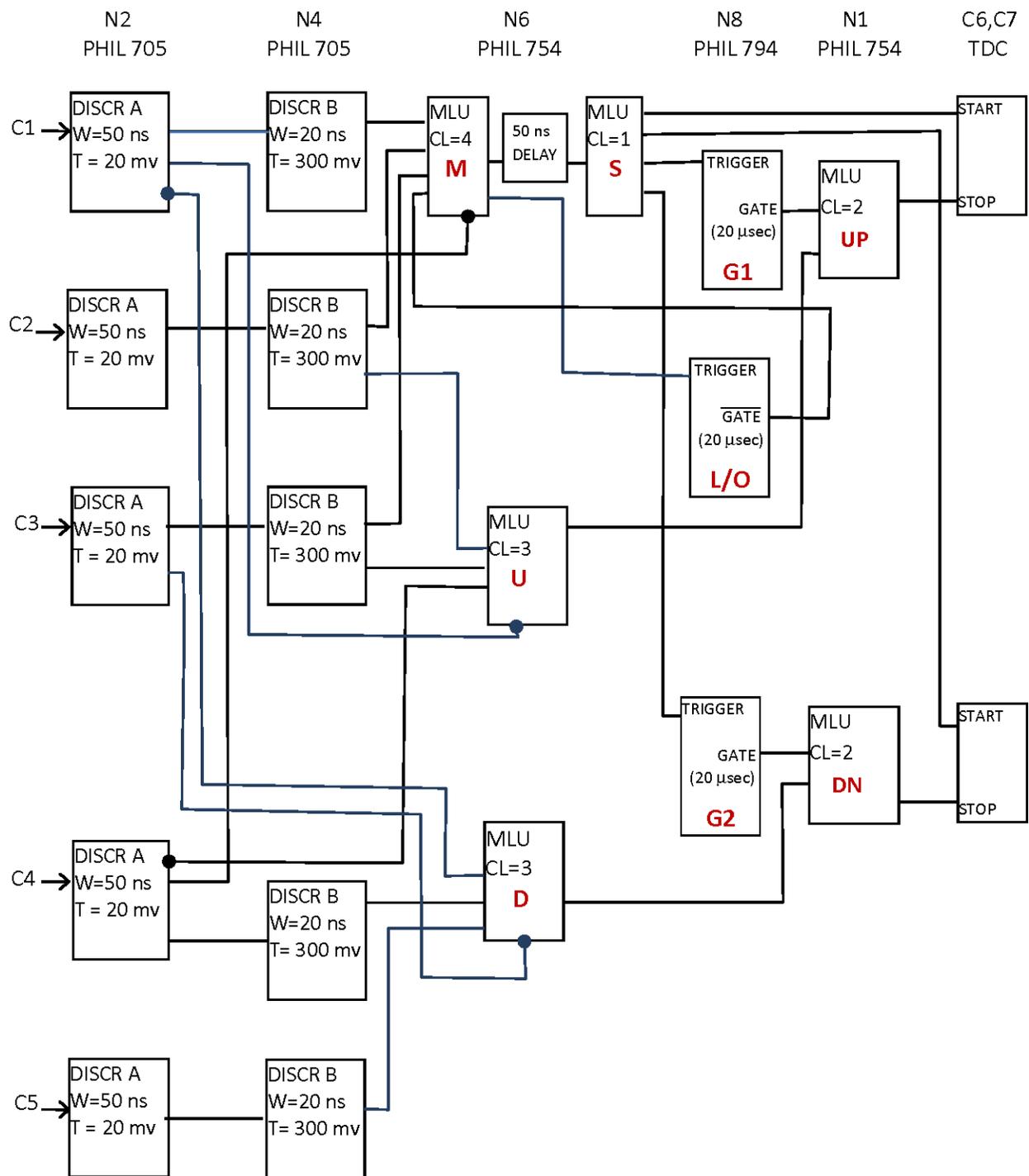


Figure 11: Logic diagram for the μ^+ experiment. The text on the top two lines indicates the module type and which slot in the NIM (N) or CAMAC (C) crate to use. The PMT outputs are C1, C2, C3, C4, and C5. For the discriminators, W stands for output width and T stands for threshold. For the multiple logic units (MLU's), CL indicates the coincidence level. The signals **M, U, D, S, G1, G2, UP** and **DN** are discussed in the text. **L/O** is a signal that locks-out new triggers until the current event is done. The 50 ns delay is achieved by a portable delay box with switches. The filled circle indicates an inverted output or an input on the veto line.

they occur during the 20 μ s gates, i.e., within about 10 mean muon lifetimes. The time intervals are flagged according to which TDC stopped and recorded. We use two discriminators in series to make sure that the vetos come before the "TRUE" signals³. Also, the analog signals from the PMTs must arrive simultaneously (with respect to each other) at the A-discriminator inputs for things to work correctly. After you plateau the counters, but before you finalize the logic circuit, you should use straight-through muons to adjust this timing as accurately as possible. Precision is ultimately limited by the size of the scintillators and the jitter introduced from the propagation of light to the PMT.

Downward positron candidates are identified by $D = \overline{C1} \otimes \overline{C3} \otimes C4 \otimes C5$ and upward candidates by $U = \overline{C1} \otimes C2 \otimes C3 \otimes \overline{C4}$. **U** and **D** are made in Phillips 754 majority logic units. Two veto's are needed for both **U** and **D**, but there is only one hardware veto input in the Phillips 754 and it is assigned to C1 in **U** and to C3 in **D**. The other veto is done with an \overline{OUT} from the appropriate A-discriminator (C4 for **U** and C1 for **D**) to a normal input of the Phillips 754.

As mentioned above, the stopping muon signal (**M**) is used to start two identical gate signals (**G1**, **G2**) of 20 μ s duration. Coincidences **G1*U** and **G2*D** in two channels of a Phillips 754 (Figure 11) make the TDC stop signals for secondary positron candidates because of the time correlation with the stopped muon. In other words, we only stop the TDC's when there is a coincidence between the positron signal and the (delayed) signal of the stopped muon. When either TDC receives no stop signal, it overflows to return a 16-bit word with all bits on, i.e., 65535. That shows up as -1 in the computer data stream. When both TDC's overflow, the DAQ does not write the event to the data stream. So, events appear in the data only when a TDC has been stopped.

Once you have completed the basic wiring shown in Figure 11, you should check that you are getting signals at all points of the electronics chain and that the signals are what you expect (i.e. the rates are moderate, the signals have the correct polarity and width, etc.). Rates can be measured by putting the **S**, **U** and **D** signals into a scaler unit. *Check that the rate of stopped muon events (the **M** rate) is consistent with the calculation you were asked to do in Section III Rate Estimation.*

³ A TRUE NIM signal is a -0.7 volt level, while a FALSE NIM signal is ground. TRUE and FALSE are complementary signals.

Taking Data

Make sure to read Section III Taking Data: Data Acquisition (DAQ) and Analysis Programs.

The DAQ program for this experiment is called “muplus”. This program runs in a command window on the muplus Linux computer next to the muplus electronics rack; you have to be logged onto this machine to take data. The source code for the DAQ program is “muplus.c”. As discussed in Section III, the executable program “muplus” can be rebuilt using the “make” utility, but chances are you will never have to do this. If you have any difficulties with the software, consult with the instructor or the TA.

To start the DAQ program do: `./muplus &`. Two information lines (“Return from cccl, cccC, cccZ”, “upTDC in slot 6, dnTDC in slot 7”) should appear on the screen. Then, within several (~5) minutes you should see a line of data appear on your screen that indicates that you got an event. If a line does not appear and you have your electronics set up properly, something is wrong that must be fixed before you can do anything else. To begin a data run, enter `./muplus > filename &`. This command redirects the output of “muplus” in the file “filename”. The “filename” can anything you want, e.g. “12mar2016.txt”, and the lines of data will go into that file. (The ampersand, &, puts the process in the background and returns your terminal window to you). You should keep a careful record of: (1) the filenames, along with (2) the conditions of your experiment at the time, (3) what was the point of the run, and (4) who was leading the run. A chronological record of this information can be indispensable if you have to reconstruct conditions during early runs when mistakes are most prevalent.

When you run the “muplus” program it first initializes the system and then enters a loop while it waits for an **M** trigger. While waiting, it periodically tests to see whether a TDC has been stopped; if one has, the program exits the loop, reads the TDC that was stopped and writes a line of output to “standard output”. The output includes a time stamp. Then the loop is re-started. So, as your experiment runs, the two single-channel TDC’s are read, depending on which TDC detected the decay signal. The TDC module in slot 6 of the CAMAC crate gives the decay time for UP events and in slot 7 for DOWN events. The unit of time is 20 ns; in other words, each TDC count equals 20 ns. The data rate is low; 20-40 evts/hr is a typical rate.

The “muplus” program prints one line for each triggered event in which there is a stopping muon and a TDC hit (i.e. evidence of a decay positron). The output format is five integer values per line:

CAMAC_SLOT_ID NUMBER NEVENT TDC_VALUE UNIX_TIME

where:

CAMAC_SLOT_ID =	6 (up) or 7 (down)
NUMBER =	Loop number (not really needed)
NEVENT=	Event number
TDC_VALUE =	TDC time (20 ns units)
UNIX_TIME=	Computer clock time in secs in Unix format

Do not close the terminal window while you have a run going; that will delete the run process. To stop the data run, type “touch stop”. This creates a zero length file named “stop”. In its loop that checks for TDC output, “muplus” tests for the presence of a file named “stop”. If the file is found, the data acquisition ends properly. Be sure to delete the “stop” file (“rm stop”) after you stop a run. Otherwise any new muplus runs you try to start will not start. Since the data files are written in ASCII format you can read them with a text editor. To analyze the data it’s best to use ROOT. The Physics 180F software manual has some example macros and typical output plots.

Normally there is some debugging to do before it is possible to collect usable data. This can only be done by taking short runs and carrying out rudimentary analysis. If you have not used UNIX or LINUX before, now is the time to learn how. It is very important to keep an adequate written record of your goals supported with plots to back up any conclusions you draw. A careful and thorough log book is essential later on if you must retrace steps to explain anomalies that always show up in real experiments.

Required Data

The basic quantities you will be analyzing are the two TDC distributions (for UP and DOWN decays) for several different experimental configurations. You should see the effect of the muon precession only when the magnetic field is turned on. Since the data rate will be low, it will take a fair amount of data taken over multiple days to build up enough statistics. Thus, the bulk of the data taking should be with the magnet on. However, to do proper background subtractions, you need data with the magnet off, but installed and with the magnet and target out (i.e. uninstalled – actually the magnet swings down). Thus, the following data sets are required:

- A. Magnet Off
- B. Magnet On
- C. Magnet/target Out

It is recommended that you start with taking data set A and check that the lifetime distributions for UP and DOWN have reasonable statistics and make sense. Then move to taking data set B where a minimum of two weeks of data collection will be required. Analyze these data as they are being taken; multiple data runs can be added together to produce a longer data set. When you have sufficient data to see the precession, take some data with the magnet and target out. The magnet/target is hinged to swing down without being removed. The bottom counter must be removed to allow this, however, and then reinstalled after the magnet/target is adjusted.

The principal analysis step is to make histograms of the two TDC values but since the 20 ns TDC resolution is too fine to produce statistically useful results, a coarser binning is better. For example, 200 ns binning is reasonable. The tradeoff is to make bins large enough to reduce the statistical uncertainty of the quantity (U -D), but small enough to see the structure of the distribution. Of course, in a real experiment you would not know what precession frequency to expect and thus would not *a priori* be able to set the time binning. However, for this lab the strength of the magnetic field is chosen to make the expected precession period approximately equal to the μ^+ mean life of 2.2 μs , which corresponds to 11 bins if you use 200 ns bins. Ticho's write-up (1972) includes a calculation of the magnetic field based on a model of oppositely directed current sheets for the magnet in your apparatus. The desired current is 3.84 A. You should monitor and record the current value daily to be sure it is constant over the length of a run.

Additional Comments

One timing issue should be understood before you try to analyze any TDC data. The time=zero (T_0) point, defined by the muon stop, will not coincide with a TDC output of zero. Even though you synchronize incoming signals as well as possible, signal delays in the logic modules often amount to 10 ns or more and the sizes of the counters introduce some irreducible timing ambiguity. The veto signal from the A-discriminators in Figure 11 must be wide enough to surround the B-discriminator width by 10 ns or so both preceding and following it. The B-width cannot be much less than 15-20 ns because of the counter sizes and travel time along different paths of muons from one counter to another. The most obvious consequence is that you will see TDC numbers in your data that are never are less than a T_{min} of about 5 (or 100 ns). But the one or two bins above T_{min} may contain invalid events where a false decay signal is generated by the muon itself. In Figure 11, the box labeled "DELAY" following **M** is there to delay the TDC start long enough to preclude recording these events. A setting of about 50 ns is usually adequate for normal running,

but you will have to judge for your setup where to set this parameter. And, in the end, you may need to cut away the first few bins of your lifetime distributions if you see a pile-up of events there.

On the other hand, the muon precession starts at T_0 and you should remove this source of a systematic error in your analysis of the TDC distributions. To locate T_0 to within one TDC count, you can temporarily modify the circuit in Figure 11 as follows. Uncable the inputs into **U** and set $CL=1$. Replace one input with a 16 ns cable coming from the **M** output to generate T_0+16ns . Then run “./muplus &” and write down some TDC values from the data stream. Repeat this for a few other delay values, up to 80ns, in 16ns steps. You will probably see nothing from the initial 16ns step. Once you start to see TDC outputs in the data stream, plot their average reading against the cable delay time. Then you can extrapolate to a value corresponding to T_0 . Add to T_0 the circuit delay for the Phillips 754 itself that you can find in the 754 specification sheet. This all measures T_0 in nanoseconds and implies a correction of $nint(T_0/20)$ that you should add to your TDC value before you fit to the form $A+B(\cos \omega T)$. “nint()” means “nearest integer”.

Determination of Muon Polarization and Decay Asymmetry

The polarization measurement depends on the fact that the muon magnetic dipole moment $\vec{\mu}$ precesses in the presence of the magnetic field, \vec{B} . The \vec{B} vector lies in the horizontal plane of the target, so the precession axis is also horizontal. The behavior is analogous to a mechanical gyroscope whose spin axis traces out a cone, the axis of which is aligned with gravity. The projection of the gyro's spin vector on the cone-axis is constant. Similarly, the projection $\vec{\mu} \cdot \vec{B}$ remains constant as the μ^+ spin vector traces out a cone whose axis is along \vec{B} , i.e., horizontal. As a result, $\vec{\mu} \cdot \hat{z}$ changes sign periodically, where \hat{z} is a vector *perpendicular* to the target plane. Since the positron momentum is correlated with its spin direction, you can observe an oscillation in the difference of (U-D). The frequency of the (U-D) oscillation measures the dipole moment and the asymmetry (U-D)/(U+D) measures the muon polarization. Reviewing the notes by H. Ticho (1972), it can be shown that the distribution you expect for (U-D) is $\exp(-\Gamma T) * (A+B(\cos \omega T))$, where A, B, ω and Γ are determined from a fit to the data. You should make distributions of (U-D), (U+D), and the asymmetry. You should also check that the measured oscillation frequency ω agrees with what you expect from the known muon magnetic moment and the value of the B field.

The relatively tiny precession amplitude B requires that you devote as much time as possible to the target-in run. Target-out data are required to estimate the non-target backgrounds. B is relatively immune to non-target events, but, muons that stop outside the target do contribute to the denominator, $U+D$, of the asymmetry and you need to correct for these. Using the target-out data, you need to verify that a single exponential distribution plus accidentals is an adequate representation. The non-target material closest to the target is nearly all scintillator (plastic) or aluminum and so negative muons will interact differently in this material than they would in the target. Thus, the time constant of the exponential seen in the target-out data is not necessarily the muon lifetime and you should measure it. The target-out subtraction from your real data should then be based on the fitted time constant and amplitude of the exponential function.

B. μ^- Capture

Experiment Outline

In empty space, μ^+ and μ^- , being antiparticles, decay at the same rate, $\Gamma_d = (10^6/2.297) \text{ s}^{-1}$, so that the number decaying, dN , in time dt is $dN = -N(t) \Gamma_d dt$. If you integrate this, you get $N(t) = N_0 \exp(-\Gamma_d t)$, for N_0 the starting number of muons and Γ_d the decay rate. If those muons stop in matter, the behavior is very different. The μ^- particles disappear at a greater rate because they can also be captured, as shown in Figure 1c. One then gets the number of muons as a function of time $N(t) = N_0 \exp(-\Gamma t)$, for $\Gamma = \Gamma_d + \Gamma_c$ and Γ_c being the capture rate. The capture rate depends strongly on the atomic number of the material; it varies by a factor of 30 from Li to Nd. In this experiment, you will measure the capture rates for negative muons in three materials: Al, Fe, Pb. You also measure the muon decay rate and can thus compare the relative strength of diagrams (b) and (c) of Figure 1.

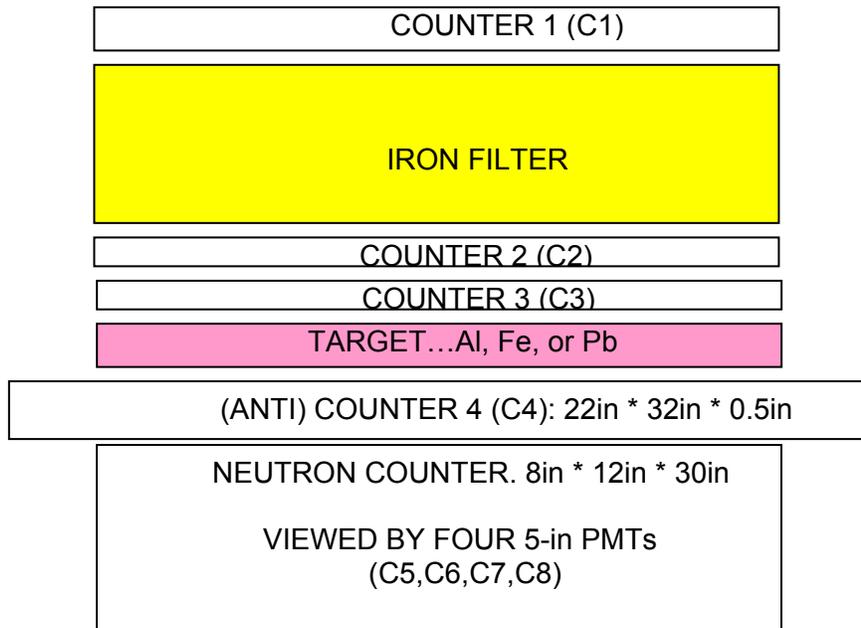


Figure 12: Sketch of μ^- apparatus.

The apparatus is shown in Figure 12. Stopping muons are selected with counters C1-C4 using the logic: $M = \overline{C4} \otimes C1 \otimes C2 \otimes C3$. Muons that decay can be detected by a delayed signal in C3, indicating the passage of an upward going electron/positron. Muons that capture in the target can

be detected by signals in C5-C8; these are large (5-inch) PMTs that view a large block of scintillator that is sensitive to the passage of low-energy neutrons. These counters are also sensitive to electrons/positrons that arrive after the anti-coincidence veto of C4 is released.

Getting Set Up

First make sure to read Section III Electronics Overview and Section VI Fast Electronics. Then take a look at Figure 13 which shows the suggested wiring for this experiment. You won't be setting this up right away, but it helps to have a general understanding of the circuitry.

There are eight scintillation counters C1-C8. The outputs from the counters are fed into the Phillips 705 discriminator. Note the suggested discriminator widths and thresholds in Figure 13. Counters C4 and C5-C8 need to be very efficient because they serve as the anti-coincidence and neutron detectors, respectively. Thus, the signals from these counters go through an amplifier stage (Phillips 776) on their way to the discriminator. The discriminated signals from C1-C4 form the stopped muon trigger $M = \overline{C4} \otimes C1 \otimes C2 \otimes C3$ in one section of the Phillips 754 coincidence unit. This primary trigger for the experiment (**M**) provides the common start for the Philips 7186 TDC. Individual TDC channels are stopped by signals from counters C3 and C5-C8. The TDC records the differences in time (in 4 ns units) between the start signal and the stop signals on those channels that recorded stops. A data acquisition program on the "muplus" Linux computer reads out the TDC values for each event trigger. The additional circuitry in Figure 13 and some added electronic details will be discussed later in this section.

Your first task is to plateau the scintillation counters, using the procedures discussed in Section IV. Start with the counters above the target, C1-C3. Set the discriminator thresholds to 30 mV and adjust the HV values to plateau the counters. A good initial guess for the HV is 1300 V. You will be starting, stopping, and clearing the scaler channels many times while you plateau the counters. For convenience you can gang the gate inputs of a dual scaler to guarantee that both sections are turned on together. You can use a gate generator under manual control to do this.

When you are happy with your discriminator and HV settings for C1-C3, you should check their timing. You want the timing such that the discriminator outputs for C1, C2, and C3 all arrive at the Phillips 754 coincidence unit at the same time (as closely as possible). This is non-trivial because each scintillator has a surface area of many cm² so the time for scintillation light to travel to the

PMT varies by several ns, depending on where the muon hit. This timing variation limits the narrowness of the discriminator widths that you can set and still have an efficient trigger. Examine the discriminator outputs of two counters on the oscilloscope. If you trigger the oscilloscope on the signal from one counter, you will see that the signal from the second jitters slightly. The discriminator output widths must be large enough to satisfy the coincidence, taking into account this jitter. A discriminator width of 30 ns for C1-C3 is reasonable. On the oscilloscope, you will also see any systematic shift between the two signals. This shift should be minimized by adjusting the cable lengths of C1-C3 before they reach the discriminator. You may be satisfied with the timing, in which case no adjustments are needed.

After completing the adjustments for C1-C3, move on to the remaining counters. The anti-counter, C4, and the four neutron-counter PMTs (C5, C6, C7, C8) require special care to achieve sensitivity to weak signals; they hence operate close to their thermal noise level. You must set the HV values and discriminator thresholds with consideration of both efficiency and sensitivity to noise. Plateau C4 using the singles rates and coincidence techniques of Section IV. When doing the coincidence method, use counters C2 and C3 to provide the coincidence and vary the HV on C4. After you determine a standard plateau point (HV value) for C4, choose an operating point for C4 that is above the standard point by as much as possible (150-200 V), but still below the onset of the sharply increasing noise spectrum.

Now move on to the four PMTs (C5-C8) in the neutron detector. Signals from these PMTs are all intentionally delayed by 96 ns cables before they reach the 776 amplifier. These delays are needed to achieve optimal performance from the Phillips 7186 16-channel TDC (see below). Do the plateaus for these PMTs via the same methods you used for C4 above, choosing operating points for each counter that are above the standard plateau point by as much as possible. Once you've selected operating points, the C5-C8 counters should be fully sensitive to neutron signals. (Note that C5 is different from C6, C7, and C8 because it has two parallel outputs. Use only one of them and leave the other un-terminated. If you terminate the second output, the signal is split into two half-sized signals).

Many muons enter the apparatus; some stop, both in the target and elsewhere, but most do not. Some of the stopping muons decay to electrons or positrons that can have energies up to 55 MeV and some of these can lead to signals in the neutron counter if they arrive after the C4 veto. The neutron counter therefore has to accommodate a very large dynamic range.

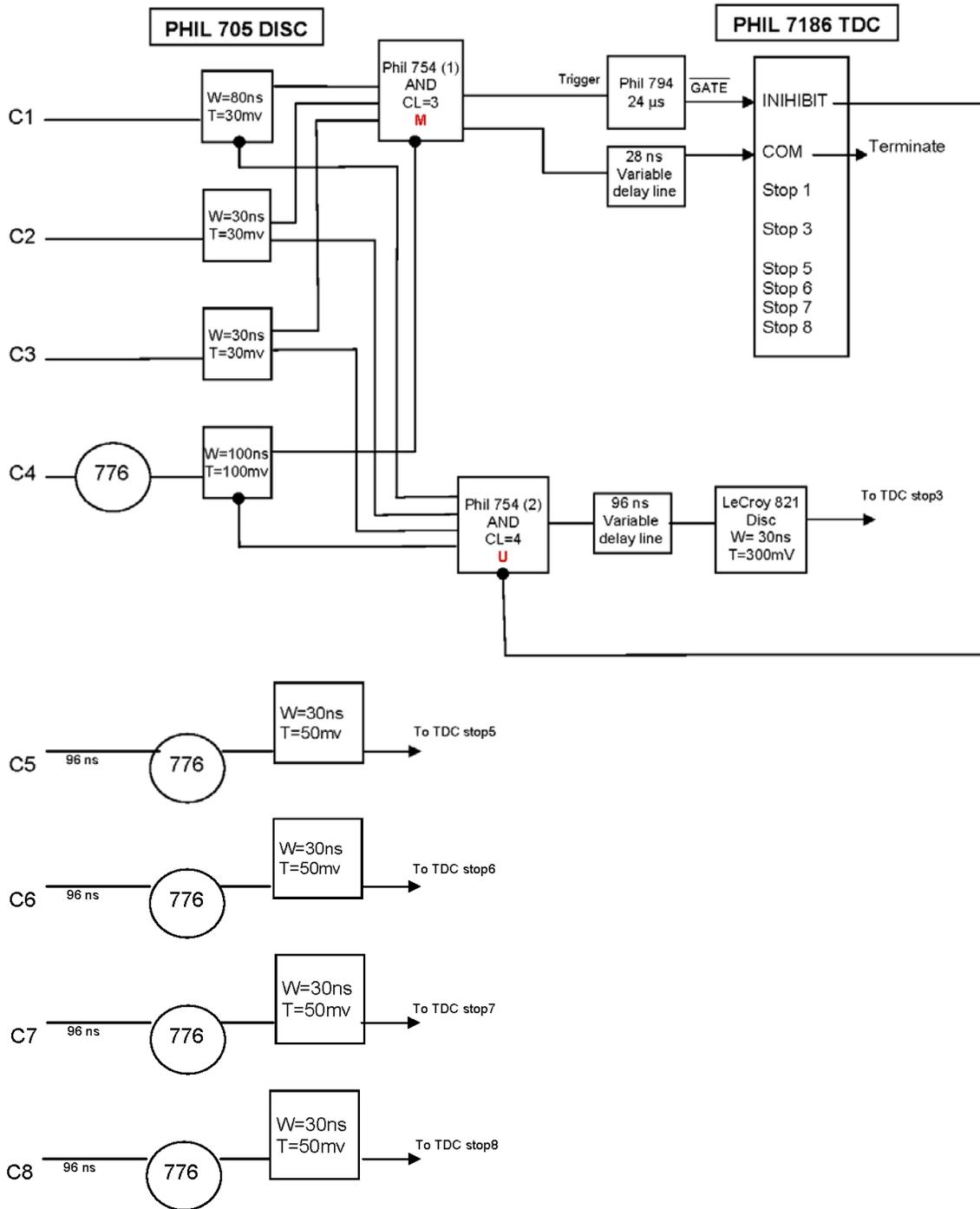


Figure 13: Logic diagram for the μ^- experiment. PMT signals from the eight counters, C1-C8, are discriminated in the Phillips 705 discriminator (W stands for output width and T stands for threshold). Signals from C5-C8 are amplified by the Phillips 776 before they reach the discriminator. The stopped muon trigger **M** is formed in the Phillips 754 by the logic: $M = \overline{C4} \otimes C1 \otimes C2 \otimes C3$. The trigger lifts the INHIBIT line and starts the Phillips 7186 TDC. An upward decay signal **U** is formed by $U = \overline{C4} \otimes \overline{C1} \otimes \overline{C2} \otimes C3$. TDC stops are provided by signals from C5-C8 and **U**. The 28 and 96 ns delays are achieved by portable cable delay boxes with switches. A filled circle indicates an inverted output or an input on the veto line.

Once you have determined reasonable HV values for all the counters, you can set up the logic in Figure 13. Returning to this diagram, remember that the event trigger (**M**) is generated when a muon is detected by C1, C2, and C3, but not C4. When an event trigger occurs, the logic starts two control signals for the Phillips 7186 TDC. One of these removes the INHIBIT signal, and the second provides the common start pulse (COM) for all TDC channels. The 28 ns delay satisfies the manufacturer's specification that the start pulse comes after the removal of the INHIBIT. The INHIBIT line is kept OFF for the gate width of the Phillips 794 gate generator (set to 24 μ s) and is then restored to ON. It will stay ON until the next muon is detected. This prevents extraneous signals from the neutron counters getting into the TDC between real events. The signal **U** for upward-going electrons/positrons is formed by $U = \overline{C4} \otimes \overline{C1} \otimes C2 \otimes C3$. This signal is then delayed by 96 ns (see below) and the delayed signal is put through another discriminator to sharpen the timing. **U** is then fed into the C3 gate of the TDC.

After the common TDC start, any individual input signals will stop the associated TDC channel. We record stop signals from **U** and from counters C5-C8. The TDC values for each channel are in 4 ns units – e.g. a count of 20 corresponds to a time of 80 ns. Only stop signals that arrive at the TDC later than ~ 100 ns after the TDC start will be properly detected.⁴ Thus, signals from the neutron capture PMTs (C5-C8) and **U** are intentionally delayed by 96 ns.

Once you have completed the basic wiring shown in Figure 13, you should check that you are getting signals at all points of the electronics chain and that the signals are what you expect (i.e. the rates are moderate, the signals have the correct polarity and width, etc.). Rates can be measured by putting the **M** and **U** signals into a scaler unit. *Check that the rate of stopped muon events (the **M** rate) is consistent with the calculation you were asked to do in Section III Rate Estimation.*

Taking Data

Make sure to read Section III Taking Data: Data Acquisition (DAQ) and Analysis Programs.

The DAQ program for this experiment is called “muminus”. This program runs in a command line window on the muminus Linux computer next to the muminus electronics rack; you have to be

⁴ The TDC uses a Wilkenson rundown design that charges a precision capacitor for each channel at a fixed rate during the time between the start and stop signals. The capacitor is then measured by an ADC in the 7186. The capacitor output is quite linear above a minimum value that corresponds to a minimum time called the “pedestal” that varies from one channel to another.

logged into this computer to take data. The source code for the DAQ program is in the file “muminus.c”. As discussed in Section III, the executable program “muminus” can be rebuilt using the “make” utility, but chances are you will never have to do this. If you have any difficulties with the software, consult with the instructor or the TA.

To start the DAQ program do: `./muminus &`. You should see 5 lines of initialization information. Then, after a minute you should see lines of TDC data appear on your screen indicating that you are getting events. If those lines never appear and you have your electronics set up properly, something is wrong that must be fixed before you can do anything else. To begin a data run, enter `./muminus > filename &`. This command redirects the output of “muminus” in the file “filename”. The “filename” can be anything you want, e.g. “12mar2016.txt”, and the lines of data will go into that file. (The ampersand, &, puts the process in the background and returns your terminal window to you). You should keep a careful record of: (1) the filenames, along with (2) the conditions of your experiment at the time, (3) what was the point of the run, and (4) who was leading the run. A chronological record of this information can be indispensable if you have to reconstruct conditions during early runs when mistakes are most prevalent.

The “muminus” program prints one line for each triggered event in which there is a stopping muon. The output format is nine integer values per line:

```
TDC1 TDC2 TDC3 TDC4 TDC5 TDC6 TDC7 TDC8 UNIX_TIME
```

where:

TDCX =	TDC value for channel X in 4 ns units (X=1 to 8)
UNIX_TIME=	Computer clock time in secs in Unix format

Do not close the terminal window while you have a run going; that will delete the run process. To stop the data run, type “touch stop”. This creates a zero length file named “stop”. In its loop that checks for TDC output, “muminus” tests for the presence of a file named “stop”. If the file is found, the data acquisition ends properly. Be sure to delete the “stop” file (“rm stop”) after you stop a run. Otherwise any new muminus runs you try to start will not start. Since the data files are written in ASCII format you can read them with a text editor. To analyze the data it’s best to use ROOT. The Physics 180F software manual has some example macros and typical output plots.

Normally there is some debugging to do before it is possible to collect usable data. This can only be done by taking short runs and carrying out rudimentary analysis. If you have not used UNIX or LINUX before, now is the time to learn how. It is very important to keep an adequate written record of your goals supported with plots to back up any conclusions you draw. A careful and thorough log book is essential later on if you must retrace steps to explain anomalies that always show up in real experiments.

Required Data

The goal of the experiment is to measure the capture rates of μ^- in three materials, Al, Fe, and Pb, and to compare those rates to the muon decay rate which you will also measure. Before you take a lot of data, it would be good to look up experimental values for the capture rates so that you know where in the TDC distributions to see an effect. Remember that: 1) the **U** trigger should be sensitive to upward going particles, presumably electrons/positrons, that come from the target and that do not penetrate the iron filter and 2) the neutron counters will be sensitive to the passage of both low-energy neutrons and electrons/positrons that arrive after the C4 veto is lifted. Finally, do not forget that all the counters are sensitive to various types of backgrounds, such as through-going muons coming after the C4 veto and particles coming in from the side, etc.

The basic data you are acquiring are the TDC distributions for **U** and the four neutron counters. These data will allow you to determine both the decay and capture rates for muons. Once you are fully set up, take a short (~day) run with no target in place to make sure that you are seeing TDC hits on those channels where you expect to have signals. If something does not look right (e.g. one of the neutron counters appears to very insensitive), it would be good to try to fix the problem before taking long data runs.

When you think that things are working reasonably well, take a long run (multiple days) with one of the targets in place. You probably want to pick a target that has a high capture rate, relative to the decay rate. Analyze this run to check that you are getting reasonable results. Then remove the target and take a long run to get an understanding of the backgrounds. Finally, complete the data taking by taking long runs with the other two targets. Thus your basic data set should consist of four long runs: no target, Al, Fe, and Pb.

Note: there are rails that hold the targets. For the Pb sheets that do not fit the rails, use the black sheet of honeycomb carbon fiber to support the sheets. **Do not place any targets directly on the scintillator counters.**

C. Multiple Coulomb Scattering with Spark Chambers

Experiment Outline

When a muon enters material, it can undergo a number of interactions. Being a charged particle, it can lose energy via ionization and bremsstrahlung. It can also interact with the electric field of nuclei of the material and scatter. This process is known as Coulomb scattering and was used by Rutherford, Geiger and Marsden to demonstrate the validity of the nuclear model of the atom. The Feynman diagram for Coulomb scattering is shown in Figure 1a; a muon passing near a nucleus exchanges a virtual photon and in the process has its direction altered. Thus, passing by a nucleus essentially gives the muon a small “kick”. In passing through some bulk material the muon’s trajectory is changed by the incoherent sum of many “kicks”. This is the process of *multiple Coulomb scattering* that you will measure in this experiment. It is important to remember that any of the various interactions available to the muon (i.e. ionization, bremsstrahlung, Coulomb scattering, and even weak interaction) can occur as it passes through material and the relative likelihood for each to occur is discussed in the lecture for the course. See also the review of the “Passage of Particle through Matter” of the Particle Data Group (<http://pdg.lbl.gov/>).

The basic design of the experiment is as follows. Downward-going muons enter the apparatus which consists of planes of scintillation counters, spark chambers and metal absorbers. The scintillation counters provide a trigger signal for low momentum muons as discussed in Section III and illustrated in Figure 4. These muons also interact in the spark chambers which provide a visual record of the muon’s trajectory. A thin plane of dense material (e.g. Pb or Fe) placed in the middle of the apparatus leads to multiple Coulomb scattering and the amount of scattering can be measured for different material thicknesses.

Figure 14 shows the actual setup of the experiment. Muons that go through the apparatus ionize the helium gas in the spark chambers and are also detected in the scintillation counters at the top, middle and bottom of the chamber stack. A trigger signal is derived from the counters and is sent to a high voltage switch which pulses the spark chambers with about 4 kV to produce the sparks. A picture of the sparks is recorded by a video camera and computer. Note that in reality, multiple Coulomb scattering (MCS) happens in three dimensions, but the distribution of projected angles in two dimensions can be predicted for comparison with this experiment.



Figure 14: Sketch of the multiple-Coulomb scattering experiment. The four spark chambers are labeled SC1-SC4 and the five scintillation counters are C1-C5.

Your task for this experiment is to set up the electronics connected to the scintillation counters to selection muons that you wish to study with the spark chambers. When you are happy with your electronics and the muon trigger rate seems reasonable, you should turn on the spark chambers and look for sparks. Then you'll want to take data with a variety of different material thicknesses in the middle of the apparatus to study the amount of multiple Coulomb scattering as a function of thickness. You will measure the distribution of projected (two-dimensional) scattering angles and compare to the expected distribution. Along the way you'll need to develop a way to analyze the images that the camera takes in order to determine the muon trajectory and to measure the scattering angle.

Some points about the spark chambers need mentioning. The spark chambers are aimed so that a straight line starting from the camera lens will trace through each chamber. Aiming the chambers

is more problematic than it might look and should not be attempted unless absolutely necessary. NEVER grasp a chamber along the edge with the mylar window. A squeeze here is just about certain to break the seal of the window to the chamber planes, in which case the apparatus is down for at least several days for repair.

Getting Set Up

First make sure to read Section III Electronics Overview and Section VI Fast Electronics. Then you can start to plateau the five counters C1-C5, using the procedures discussed in Section IV. When doing these plateaus, use the LeCroy 4608C discriminator; set the discriminator widths to 60 ns and the thresholds to 20 MV and adjust the HV of each counter.

Choosing high voltages for the MCS counters is complicated by the extended vertical geometry and the restricted size of C1, C2, and C3. A reasonable procedure would be to start with single-counter plateaus (Method 1 of Section IV) to get an approximate starting value for each of the counters. A good initial guess for the HV is ~1300 V. It also helps to use the oscilloscope on each channel to understand the typical signal for muon events as compared to the noise level.

When you have initial HV values for C1 and C4 (or C5), you can use the coincidence of $C1 \otimes C4$ to make a cleaner selection of muons because this coincidence preferentially selects particles that penetrate several inches of Fe. In this manner, you can use the coincidence technique (Method 2 of Section IV) to check the plateaus for C2 and C3. For example, to plateau C2, you would examine $[C1 \otimes C2 \otimes C4] / [C1 \otimes C4]$ as a function of the C2 high voltage.

When you are happy with your HV settings, you are ready to start wiring up the basic logic, shown in the block diagram of Figure 15. The width and threshold values of the discriminator-A channels are the same as for the plateau work. A low-momentum muon that stops in the bottom piece of steel ("Steel Stopper" in Figure 14) is selected by the logic $M = C1 \otimes C2 \otimes C3 \otimes \overline{C4} \otimes \overline{C5}$. Then, gates are provided to trigger the HV on the spark chambers and to initiate computer readout of the camera. For more details on the setup, see the caption of Figure 15.

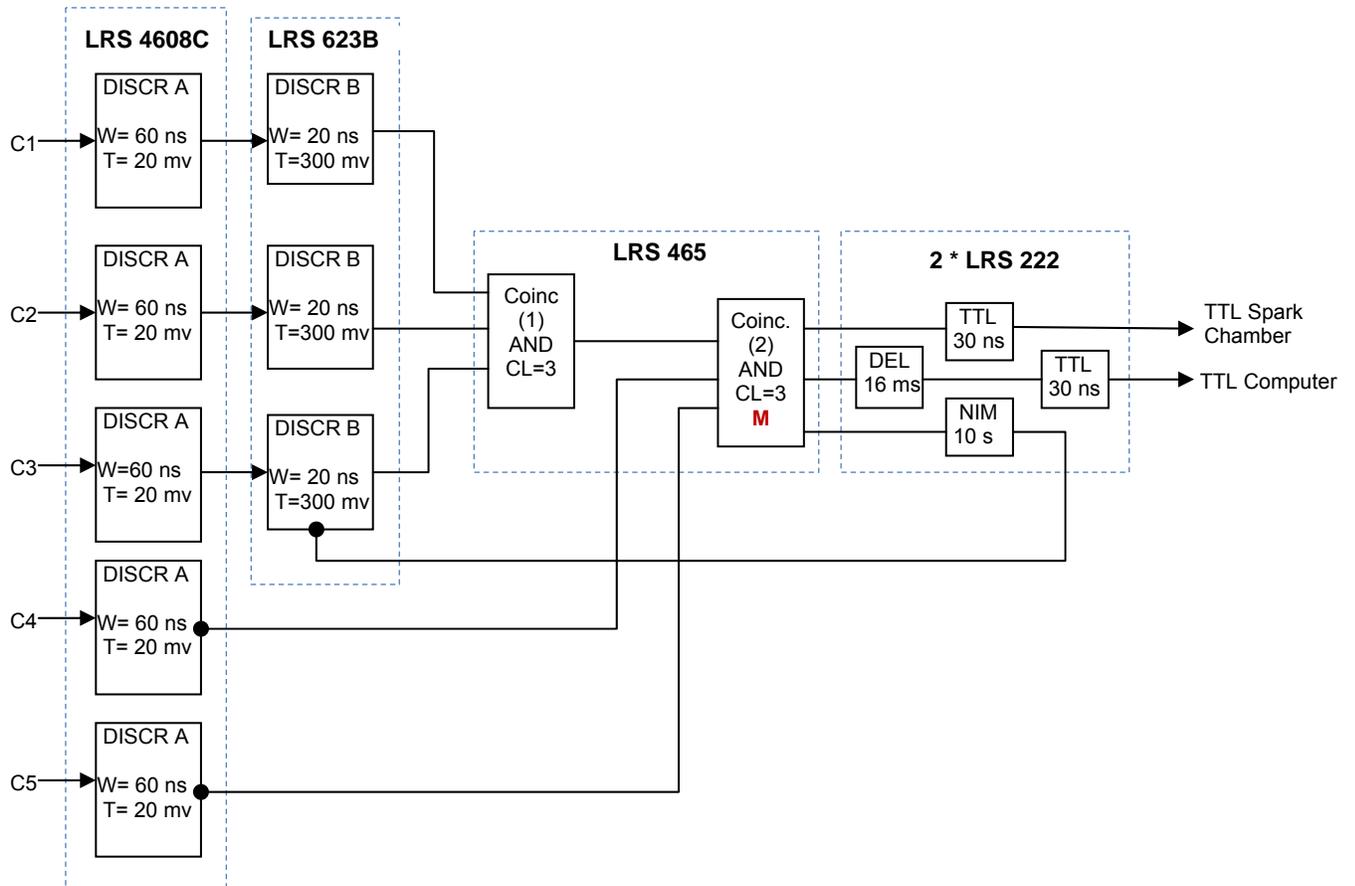


Figure 15: Logic diagram for MCS experiment. The PMT signals, C1-C5, are discriminated by Discriminator A (LRS 4608C, W= output width, T= threshold). Additional delay is given to C1-C3 in the form of Discriminator B (LRS 623B). The coincidence unit (LRS 465) gives two independent channels of majority logic (CL= coincidence level); the overall **M** trigger is formed in the second channel. Two gate generator units (LRS 222) provide signals for the HV switch of the spark chamber (TTL Spark Chamber), the PC readout trigger (TTL Computer), and the veto (Common Inhibit) of the LRS 623B. In the LRS 222, input signals go to START and the output signals and relevant delays are indicated in the diagram. A filled circle indicates an inverted output or an input on the veto line.

Connect the C1, C2, and C3 discriminator-B's as shown in the figure. For the anti-coincidence signals C4 and C5, start by initially using the normal outputs from the discriminator-A into the LRS 465 logic unit. This will allow you have a reasonable rate of through-going muons to check the timing.

To verify the timing, use the discriminator-A outputs and trigger a 4-channel oscilloscope with the signal C3. Display simultaneously on the oscilloscope the C1, C2, C4, and C5 signals with screen persistence set to maximum. Adjust cable lengths so the signals overlap as well as possible. Then

trigger the oscilloscope with C2 and check the timing for C3. When you are satisfied with the timing, change the cabling for C4 and C5 so that the inverted outputs from discriminator-A are used. In this way, when either C4 or C5 are hit, the event will be vetoed and your trigger will be set up to measure muons stopping in the absorber above C4/C5. *Check that the rate of stopped muon events (the **M** rate) is consistent with the calculation you were asked to do in Section III Rate Estimation.*

Camera Setup

The camera digitizer (NI 1405b) is on the PC's internal bus. It has two inputs from the experiment: (1) the TTL trigger line and (2) the composite video signal from the camera which continuously transmits the analog video. To provide enough time between events for the PC to read the digitizer and write its output to disk, dead-time is generated by a LeCroy 222 module. Ten seconds is adequate and you can do that with a single gate generator whose output is connected to the veto/inhibit line of the LRS 623B discriminator. In this way the time period between successive event triggers is forced to be 10 s or more. A second Lecroy 222 channel makes the TTL signal needed to actuate the HTS150 HV switch that fires the spark chambers. Two more 222 channels connected in series make the trigger for the video digitizer readout into the PC; one of them provides 16 milliseconds delay to complete the camera scan following the muon trigger and its DEL output starts the second 222 whose TTL output starts the NI 1405b memory dump.

Spark coordinates must be digitized and recorded. We use an Edmund Optics U53-152 wide angle zoom lens coupled with a Sony XC-ST50 monochrome camera. With reasonable quality helium in the chambers, the fully open ($f/1.2$) lens aperture gives excellent images with little dark noise. The sparks are the source of light but they also make electronic noise. For this reason the experiment is isolated inside a Faraday cage. The cage is also dark and the sensitivity of the camera is such that you need not cover up small reading lights and so on, but you should obviously close and hook the door of the cage when taking data.

The CCD camera sensor is reasonably robust and is not damaged if the lights are on but you should not aim anything as strong as a flashlight into the lens. Data are secured with a NI 1405b digitizer; it is basically an eight-bit ADC with a PCI bus interface and is controlled with Labview software.

There are four camera adjustments: lens aperture, zoom, focus and rotation of the camera about a vertical axis. Height and tilt are fixed. The adjustments are easiest to make if you watch a display of what the camera sees.

Data Acquisition (DAQ) Software

The DAQ software, written in Labview, is on the Windows computer closest to the door of the MCS Farady cage. Clicking on the “virtual instrument” (VI) icon labeled **wsring** starts Labview and displays a front panel of the VI. You can cycle between this front panel and the block diagram of the application program. To execute the program, click the little arrow in the upper left corner. The VI loops continuously, reading and displaying the camera field on the PC screen just like a CCTV setup. If you get an error message to the effect that “no device is detected” it probably means the camera is unplugged or turned off. When the camera is running you will see the spark chamber array on the PC screen.

When you set up the camera for the first time, it may not be necessary to adjust anything. Be sure the aperture (f-number) of the camera is wide open at f/1.2 and the image is centered horizontally. The spark chambers should all be easily visible in the frame. Focus can best be judged by looking at the edges of the center planes. You can make the best adjustment if you move the PC monitor so that one person can both see the display and reach the camera simultaneously.

The XC-ST50 camera has a widescreen aspect ratio whereas the chamber array is higher than it is wide. The camera is therefore mounted on its side so that the image matches the CCD sensor as well as possible and can give the optimum resolution. As a result, the display appears rotated by 90 degrees. In image space the chamber planes are parallel to the y-axis, so a chamber is defined in image space by $x=\text{constant}$. The scale in image space corresponds roughly to 1 pixel per millimeter in lab space when the zoom is adjusted so that the chamber array fits within about 80% of the sensor. You can see that the distance in one of the spark chambers between a center chamber plane and either ground plane is about 1 cm, corresponding to about 10 pixels in image space.

The icon to launch the data acquisition is labeled **wsGrab0**. It continuously reads the camera sensor into the local memory of the 1405b. When a trigger signal is received by the NI 1405b digitizer card, its memory contents are transmitted to the PC. Because there is low optical

distortion in this setup and the dark noise is nearly non-existent, one can use nearly the whole dynamic range (8 bits) of the ADC. The VI cuts signals below 5 on a scale of 0 to 255 (full scale for 8 bits). Events are written to a single file called “picout.txt” as long as the VI is running. Events are separated by a line with “0 0 255” in the data stream. Events are not displayed during a data run though if you click on “picout.txt” it will open the file in Notepad so you can read through some of the numbers.

Taking Data and Analysis

The DAQ program **wsGrab0** does not display an event image on the PC screen but instead it writes the image data to the file named “picout.txt”. All data you take are written to the same file “picout.txt”. If you leave a “picout.txt” file in place when you start **wsGrab0**, any new events will be appended to that file. To separate different runs into different files, you must rename each completed “picout.txt” file to something appropriate. A name that incorporates the date is often the best choice, e.g. “picout-11nov2015.txt”. It is very easy to confuse the runs for different operating conditions so make sure that your log book keeps track of which runs were taken at which times and under which conditions. You should also adopt a file naming scheme that unambiguously associates a data file with the run that produced it.

The image data is stored in “picout.txt” in a reasonably compact format and it is quick to copy it over to one of the Linux machines (‘p180f-a’ or ‘p180f-b’) using the FTP/SCP transfer utility. You should do your analysis on the Linux machines using ROOT. ‘p180f-a’ and ‘p180f-b’ are the machines on your left when you enter the lab room. To transfer the file “picout-11nov2015.txt” to the appropriate directory on one of these machines, you do the following:

- Bring up a command line window (‘Start’ and select ‘Command Line’)
- ‘cd Desktop’
- ‘psftp 169.232.152.124’ for computer ‘p180f-a’ (or 169.232.152.125 for ‘p180f-b’)
- Log in as user ‘p180f’ and password ‘fall15’.
- ‘cd data/fall2015/mcs’
- ‘put picout-11nov2015.txt’
- ‘quit’

The data analysis is best done using ROOT’. You first need a program that will determine ‘tracks’ in the spark chambers – i.e. that will try to reconstruct the trajectory of the muon passing through the chambers. In laboratory space, the x-coordinates of the sparks are determined at the y-

positions of the four chamber planes. The first two sparks (two upper chambers) define one track segment, as does the second pair of sparks (two lower chambers). The angle between the two segments is the scattering angle that needs to be determined. For genuine events where the scattering occurs in the lead sheet in the middle of the apparatus, the two segments intersect in the lead. Sample analysis macros are written in C and can be executed in ROOT. You can model your code after these macros. Once you have a program that can calculate the scattering angle for each event, you can write those angles to a file and read them in with ROOT to make a histogram to study the distribution of many scattering angles.

Required Data

Once you are set up, take some initial data with no lead sheets in the center. Verify visually that you are getting some four spark events. If you are only getting 3 (or less) spark events, you may need to purge the spark chambers longer and you probably want to discuss things with the instructor/TA. There is also a program that can determine the chamber occupancies; this can help you determine if a chamber is weak. Once you are sure that you are getting 4-spark events, verify that the tracks are straight (visually) and work on the program that determines tracks in the chambers and measures the scattering angle. Write out a number of scattering angles and check that what you are getting is making sense.

If you think that you are getting reasonable values for the scattering angles, take a long (multiple day) run to get a good baseline for the “no scattering” case. Then insert the full amount of lead (all sheets available) and take some data to check visually that there is some deflection in the track between the upper and lower chambers. If things look good, take a long run to get good statistics for the scattering effect. Then take additional runs with intermediate amounts of lead. Four different configurations (including no lead) will provide sufficient data to do a good analysis of the RMS scattering angle versus material thickness. At all steps along the way, make sure to carefully record what the conditions were (e.g. the amount of lead) for each data run.

HHV (high high voltage) pulsing and Helium flow

The optical spark chamber is a very direct (though out-dated) way to observe tracks. A charged particle leaves an ion trail in the chamber gas and if a strong enough electric field is applied, a spark will form along the ionized path. To avoid continuous discharge, the electric field must be

pulsed. In the days when these chambers were used in research, a thyratron tube or a sparkgap functioned as a HHV switch to dump the charge on a capacitor across the spark chambers. In the 180F experiment, we use a MOSFET high voltage switch (HTS150) manufactured by Behlke Electronic GmbH that has a fixed pulse length of 3 μ s. The switch is rated for 30 A at 15 kV.

The pulse distribution and isolation circuit is shown in Figure 17. It is mounted in a panel on the experiment frame near the spark chambers. A small toggle switch controls logic power and must be on for the HTS150 to operate. There is a monitor point on this panel where the HTS150 output, attenuated by a factor of 1000, can be observed on an oscilloscope. There are additionally separate monitor points, one for each chamber. The chambers may discharge at slightly different times; the first spark usually occurs about 1 μ s into the pulse (whose rise time is about 100 ns). Isolation circuitry prevents the first-firing chamber from taking all the stored charge; a spark in the first chamber effectively short-circuits its electrodes and its isolation resistor prevents this short from being connected across the switch output. Thus the HHV is maintained on the remaining chambers until they also spark. The chambers work very reliably at about 4 kV. This corresponds to a reading of about 20 on the meter. The monitor points can be connected to the four channels of an oscilloscope; they tell you that the chambers are operating properly during a data run.

The spark chamber uses helium gas and the spark quality is affected by chamber helium purity. Bottles may fluctuate in quality. With air in the chambers, you will see no sparks at 4 kV. As helium purges the chambers, sparks will appear in one chamber at a time. It will take about an hour for all the chambers to flush with He gas and to stabilize. The best way to judge the quality of operation is to examine the four HHV monitor signals on the oscilloscope. Compare Figure 16a where the chambers are not ready with Figure 16b where the helium is clean and the chambers are ready. This display of the HHV pulses is the only way to verify that the chamber system is working well enough to take good data.

Helium flow can be set to a relatively high level while purging and then adjusted lower once good signals are observed on the oscilloscope. Reasonable flow rates are a few bubbles/sec while purging and a bubble every few seconds for regular operation. Gas tanks will need to be replaced after 3-4 full days of operation. Tanks are exchanged at the loading dock of Knudsen which is open during regular business hours (i.e. not on weekends).

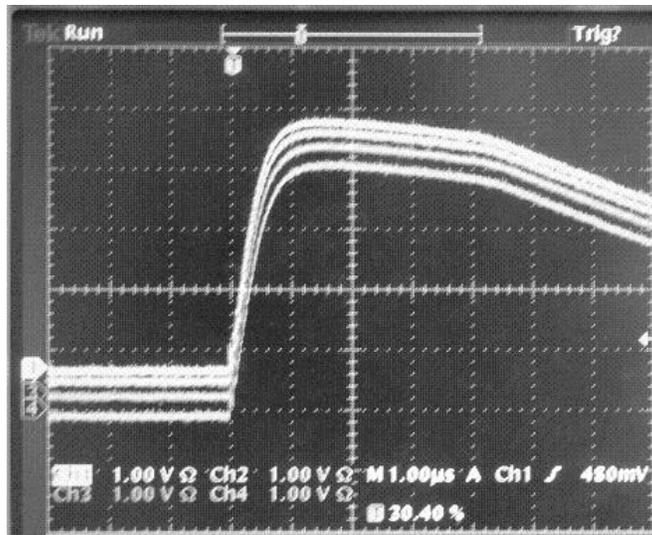


Figure 16a: The four HHV monitor traces before the helium in the chambers is clean enough. The pulses persist beyond 4 microseconds and slowly decay.

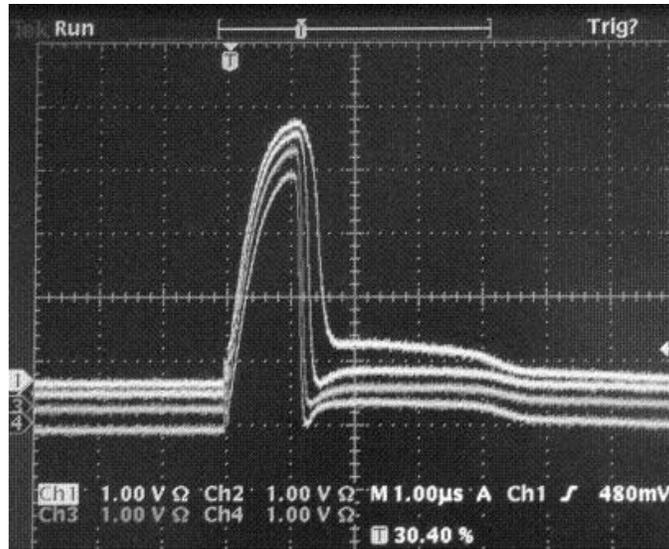


Figure 16b: The four HHV signals when the gas purity is adequate (after at least ~ 1 hr of purging with He). The pulses all fall rapidly after about 1.2 μs when the sparks discharge the capacitors. Notice that the scope can be triggered by the leading edge of any chamber.

VI. Fast Electronics

A. Signal Transmission

All the logic circuits in the 180F experiments are 50Ω impedance systems. The output and input impedances of the logic modules are 50Ω and the cables, both BNC and LEMO, have a characteristic impedance of 50Ω . To see why this is important, we derive the wave equation for a typical *lossless* transmission line; it does not quite match the real world but it introduces the important issues. The cables have coaxial geometry with a dielectric medium between the center conductor and the outer shield. This is relevant to a calculation of the capacitance and inductance per unit length of cable.

Figure 18(a) represents a coaxial cable as two parallel conductors where x is the distance along the cable and t is time. We assume the conductors carry equal and opposite currents, $I(x,t)$ and that the potential difference between them is $V(x,t)$. Both $I(x,t)$ and $V(x,t)$ are functions of position and time. Assume that the cable of Figure 18a is infinitely long and ignore the ends for the moment. A small length (Δx) is shown in Figure 18b where the inductance and capacitance are lumped into discrete components and the long cable is built up by stringing these “T-sections” together in a kind of ladder. The current and potential change from the input side of a T at x to the output side at $x+\Delta x$. (An alert skeptic will ask how it is that this ladder of T’s is general enough to be equivalent to a real cable; to learn the answer you will have to consult a textbook on transmission lines).

The cable is characterized by its capacitance per unit length, C_ℓ , and its inductance per unit length, L_ℓ . The discrete components of the T are the capacitor $C = C_\ell \times \Delta x$ and the inductor $L = L_\ell \times \Delta x$. The current $I(x,t)$ and potential $V(x,t)$ change by small amounts across the small length of cable; some current goes to charge up C and there is a voltage drop across L due to $\Delta V = L \times \frac{\partial I(x,t)}{\partial t}$. To find another relation between $V(x,t)$ and $I(x,t)$, we need the charge on the capacitor, so introduce the charge per unit length, λ , and write $Q(x,t) = \lambda(x,t)\Delta x$. In a short time interval, Δt , the charge that flows into the little T input side is $I(x,t)\Delta t$ and it can go to only two places, to charge C or to the output of the T.

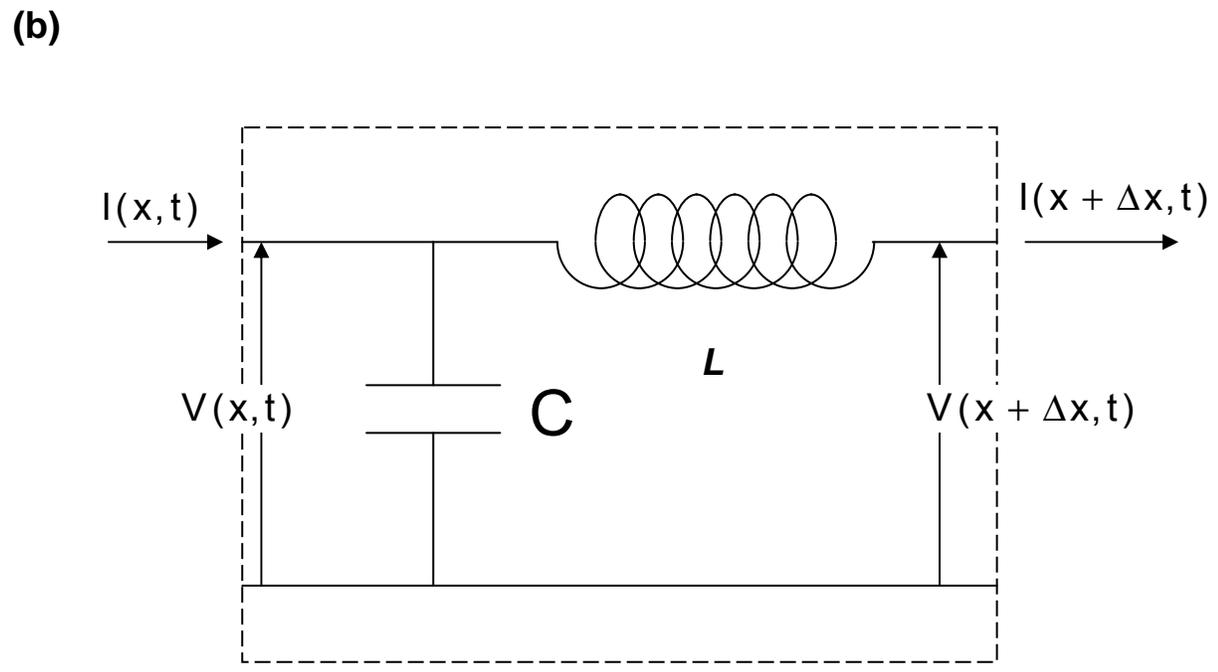
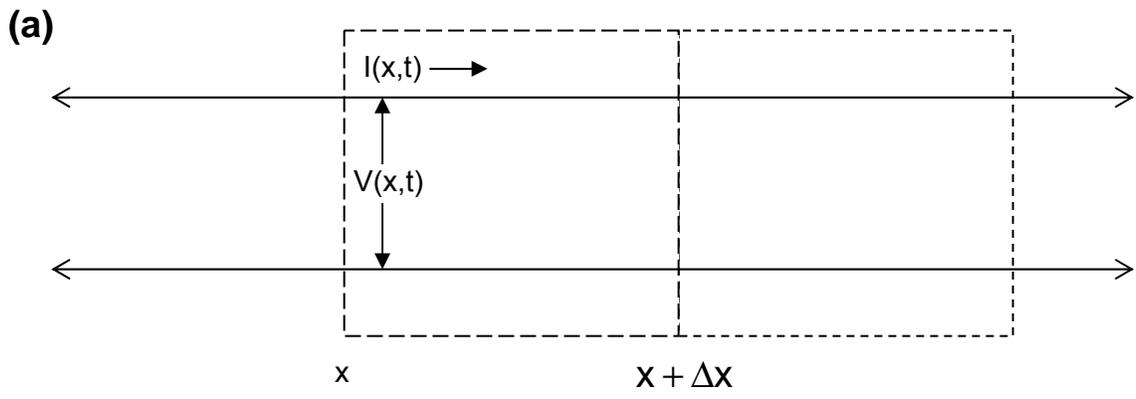


Figure 18: Schematic of a transmission line.

Write this as an equation:

$$I(x, t)\Delta t = I(x + \Delta x, t)\Delta t + \Delta\lambda\Delta x \quad (1)$$

The potential drop across the capacitor is:

$$V(x, t) = \frac{Q}{C} = \frac{\lambda(x, t)\Delta x}{C_\ell\Delta x} = \frac{\lambda(x, t)}{C_\ell} \quad (2)$$

The voltage change across the inductor gives:

$$V(x, t) = L \frac{\partial I}{\partial t} + V(x + \Delta x, t) = L_\ell\Delta x \frac{\partial I}{\partial t} + V(x + \Delta x, t) \quad (3)$$

Divide Equation (1) by Δt and approximate $\frac{\Delta\lambda}{\Delta t} \approx \frac{\partial\lambda}{\partial t}$.

Then Taylor expand $I(x, t)$ in x : $I(x + \Delta x, t) \approx I(x, t) + \frac{\partial I}{\partial x}\Delta x$ and you get $\frac{\partial\lambda}{\partial t} + \frac{\partial I}{\partial x} = 0$.

Take $\frac{\partial}{\partial t}$ of Eq. 2: $\frac{\partial\lambda}{\partial t} = C_\ell \frac{\partial V}{\partial t}$

and eliminate $\frac{\partial\lambda}{\partial t}$ between the last two equations:

$$C_\ell \frac{\partial V}{\partial t} + \frac{\partial I}{\partial x} = 0 \quad (4)$$

Taylor-expand $V(x + \Delta x, t) \approx V(x, t) + \frac{\partial V}{\partial x}\Delta x$ and substitute in Eq. (3):

$$V(x, t) = L_\ell\Delta x \frac{\partial I}{\partial t} + V(x, t) + \frac{\partial V}{\partial x}\Delta x \quad \text{or} \quad L_\ell\Delta x \frac{\partial I}{\partial t} + \frac{\partial V}{\partial x}\Delta x = 0$$

Thus, $\left(L_\ell \frac{\partial I}{\partial t} + \frac{\partial V}{\partial x}\right)\Delta x = 0$ which means:

$$L_\ell \frac{\partial I}{\partial t} + \frac{\partial V}{\partial x} = 0 \quad (5)$$

Now differentiate Eq (4) by t and Eq (5) by x :

$$C_\ell \frac{\partial^2 V}{\partial t^2} + \frac{\partial^2 I}{\partial x \partial t} = 0 \quad \text{and} \quad L_\ell \frac{\partial^2 I}{\partial t \partial x} + \frac{\partial^2 V}{\partial x^2} = 0$$

Eliminate the mixed derivative and you have the wave equation for the voltage, $V(x, t)$:

$$L_\ell C_\ell \frac{\partial^2 V}{\partial t^2} - \frac{\partial^2 V}{\partial x^2} = 0 \quad (6)$$

The current $I(x,t)$ also obeys this wave equation. The general solution to Eq (6) (as you learn for transverse mechanical waves in a string) is $V(x,t) = f(y)$ where $f(y)$ is any (differentiable) function of the argument $y \equiv x + ut$ where $u^2 = 1/C_\ell L_\ell$. The phase velocity u can be either positive or negative, corresponding to disturbances that propagate to the left or to the right. Its magnitude is fixed by the specific C_ℓ, L_ℓ of the cable. The fact that $f(y)$ can be any function means that an arbitrary pulse shape will propagate with the same velocity. However, we have not yet considered the ends of the cable.

B. End Effects and Equivalent Circuits

End effects are an important part of cabling and circuit modules that have to handle fast pulses without distortion. The wave equation (6) with a solution $V(x,t) = f(x-ut)$ holds for pulses. From

$$\text{Eq.(4): } \frac{1}{C_\ell} \frac{\partial I}{\partial x} = -\frac{\partial V}{\partial t} = u f'(x-ut);$$

f' denotes differentiation of $f(y)$ with respect to its argument $y = x-ut$.

$$\text{For the current: } \frac{\partial I}{\partial x} = u C_\ell f'(x-ut)$$

which we can easily integrate: $I(x,t) = u C_\ell \int dx f'(x-ut) + g(t) = u C_\ell f(x-ut) + g(t)$

The function $g(t)$ is an arbitrary function of time something like the arbitrary integration constant in a single variable indefinite integral. $g(t)$ simply raises the current everywhere in the cable by an amount that is independent of position. It is not part of a typical pulse, so we set it to zero for pulses.

$$\text{It follows that: } I(x,t) = u C_\ell V(x,t) = \sqrt{\frac{C_\ell}{L_\ell}} V(x,t) \equiv \frac{V(x,t)}{Z_0}$$

This linear relationship between I and V looks just like Ohm's law for simple direct currents. More importantly, it tells us what to do about the ends of a finite cable. If we attach a resistance of magnitude Z_0 to each end, the finite cable acts like a piece of an infinitely long cable extending in both directions. A signal of any shape will propagate with the same velocity, u . The notion of replacing a semi-infinite piece of cable by a resistor Z_0 is an example of an equivalent circuit. The rule is to terminate any finite cable with its characteristic impedance. All the 180F logic modules are terminated in 50 ohms both for input and output sockets and all the cables have $Z_0 = 50\Omega$.

A circuit element for which you know the equation that connects I and V can be represented by an equivalent circuit that follows the same equation. Typically this means a voltage generator with series resistance or a current generator with a shunt resistance. If a pulse propagates from the left to right toward a short-circuited end at $x = x_0$ of a cable, the short by definition means that the voltage at the point at $x = x_0$ is zero, for any time: $V(x = x_0, t) = 0$. We can reproduce (equivalent circuit) that situation by arranging for a pulse of opposite polarity moving right to left to hit the point $x = x_0$ at the same time as the original pulse; it is called a reflection. It can be observed at the $x=0$ end at a time $\Delta t = 2x_0 / u$ after the real pulse passes $x=0$.

The case of an open circuit at the point $x = x_0$ is a little less intuitive, because the rule to apply is $I(x = x_0, t) = 0$. Consider a test pulse moving to the right toward positive x . A left-moving pulse of the *same* polarity as the test pulse that arrives at $x = x_0$ at the same time as the test pulse has a voltage that is always the same as that of the test pulse. In other words, there is no potential difference between the pair of conductors at the point $x = x_0$, and therefore no current. Thus the reflection from an *open unterminated* cable has the same polarity as the incident pulse. To verify these reflected pulses, you should connect a pulser and a length of cable to an oscilloscope input with a Tee and look at the initial and reflected pulses when the free end of the cable is a) open, b) shorted, and c) terminated with 50 ohms.

C. NIM and CAMAC Modules

Important: the manuals for all the various NIM and CAMAC electronic modules can be found in binders or folders on the table to the left when you enter the lab room.

Discriminators

These modules convert the analog signals from the PMTs to pulses of a standard level (NIM) and controllable duration. You have control over the discriminator *threshold* and *width*. However, depending on the type of discriminator, you may be able to set the output width only for all the channels on the module, and in some cases you may be forced to set a common threshold for all

the channels. Generally, an octal (eight-channel) discriminator will have less flexibility per channel than a quad or dual discriminator. A discriminator also may be useful in reshaping a logic pulse if it goes through a long delay cable and it may be used to fan out a signal when several replications are needed. Remember that a single output can drive only one load. If you attempt to drive multiple loads with a “tee” structure, you violate the 50Ω termination condition and produce reflections (and pulse distortion). However, most of the modules have separate output stages to produce more than one NIM-level output (indicated by two “OUT” spigots connected by a small white line).

The threshold adjustment is usually a small potentiometer recessed behind a screw-hole. The level is presented to test points that you can connect to a voltmeter. On some discriminators the level reads a factor of 10 high, so a 1 V reading means the threshold is set to 100 mV. *The LRS 4608C is direct reading; the Phillips 705 reads 10X the threshold.* (Note that one of the pull-out data sheets for the 4608C is incorrect).

Discriminator speed has two somewhat different specifications: (1) double pulse resolution (DPR), meaning the shortest interval between the leading edges of two pulses that give two distinct output pulses. For this to make sense, all the pulses have to be shorter than the DPR, and (2) reciprocal of the maximum frequency of operation for a continuous pulse train. The DPR is the parameter of most interest in a counting experiment. Experiments with cosmic rays usually do not suffer from an excessive event rate. Note that some discriminators have a toggle switch between “BG” (burst guard) and “UP” (updating). Make sure that those use the “UP” setting.

“Time slewing” has several meanings. It may refer to the variation with input amplitude of the interval between the arrival of the analog input and the generation of the digital output. Intrinsic slewing is a property of the discriminator itself and could be measured if you imagine connecting the same input signal to two separate identical discriminator channels. Then if you measure the time difference of the channel outputs with a precision TDC, you will get a distribution whose variance measures this slewing $2 \times \sigma^2$, if you assume Gaussian distributions. The total time slewing also has a contribution due to the risetime (often defined as the time from 10% to 90% of maximum amplitude). A small signal will take longer to reach the threshold level of the discriminator than will a larger signal. Finally, slewing can refer to a property of all PMTs that the transit time through the dynode chain depends on the effective velocity and therefore on the kinetic energy of the secondary electrons at each stage. Since this directly depends on the potential

difference between dynodes and thus on the HV, you can expect that when you lower the HV you will increase the transit time.

Logic Modules

Most of the “logical” operations are concerned with implementing a decision that you can express in words, e.g.: If (A and B) or (not C), then do something. But it has to be done within a short time with signal processing of some kind. AND, OR, and NOT are typical functions you may want to perform. These are done very flexibly with electronic modules that plug into a NIM (no computer readout) or CAMAC (computer readout) crate. Signals are NIM level: 0 = false, -0.7 volts = true.

In symbolic logic one usually thinks of binary operations that may be combined to make more complicated propositions. In our electronics, the modules typically have more than two inputs.

Coincidence modules

The LeCroy model 465 which has three sections is labeled a coincidence unit and can form a 2, 3, or 4 fold AND of the inputs, depending on the settings of the pushbuttons associated with each input. This module has a “linear output” as well as normal outputs. The width of the linear output signal is the interval during which all the selected inputs are true. The width of the other outputs is set by the usual potentiometer accessible from the front panel. The most important distinction between fast electronic logical expressions and simple symbolic logic propositions is that proper timing is vital. What works if two cables are the same length may not work if their lengths differ by a meter. In addition, what works if the fast pulse widths are 20 ns may not work if they are only 10 ns, and, to make matters more critical, *vice versa*.

Majority Logic Units

These modules can perform both AND and OR functions with several inputs. For Physics 180F, “several” means five or fewer. The LeCroy model 365 has two channels or sections. The setup is accomplished by plugging little pins into appropriate holes. The first set selects which inputs are to be tested and which to be ignored. If an input is “pinned off” it is not considered. The “CL” or coincidence level defines how many inputs must be true to make an output. So if there are two inputs and neither is pinned off, a selection of CL=2 makes an AND while CL=1 makes an OR. There is a “veto” input that kills any positive output. The Phillips 754 has four sections and no pins,

so to exclude a signal you have to unplug it. There is a rotary switch to determine the coincidence level. Each section also has a veto input.

Jorway 1880B Scaler

A scaler is used to count pulses. The Jorway 1880B is a dual unit which is used for making high voltage plateau plots for the phototubes. The sections operate independently but there are inputs for external start/stop and reset. These signals can be chained to control both sections simultaneously, as is convenient for doing the plateau runs. A scaler is also useful for monitoring your experiment as it can count events that come in continuously, without having to stop the run and analyze the data output.

Phillips 776 PMT preamp

Although one of the strong points of a PMT is its high gain, there are many applications in which additional gain is needed without the risk of added noise from photocathode emission of thermal electrons. Both the μ^- and spectrometer experiments require very small signals to be reliably detected and the 776 module is used to do this.

CAMAC ADC and TDC

The spectrometer experiment uses both Phillips 7166 (charge ADC = QDC) and 7186 (TDC) modules. The QDC in particular is very convenient compared to a spectroscopy ADC because its gate signal can be derived from merely a discriminator or gate generator output. The Phillips 7166 QDC and 7186 TDC are actually somewhat similar because the TDC is built around a so-called Wilkinson rundown circuit. Basically this circuit allows you to rapidly charge a precision capacitor and then slowly discharge it to determine the stored charge by measuring the potential with an ADC circuit. To make the module into a QDC you simply dump the whole PMT signal into this capacitor and thus the charge Q is equal to $\int CV dt$. To make it a TDC, you dump a known current I into the capacitor for the time interval between a start and stop signal. The reason to use this complicated scheme to measure times is that the time interval involved is too short to measure directly, but the act of charging the capacitor can be done quickly while the readout or conversion can be done at a relatively leisurely pace. The critical circuitry is the same for either QDC or TDC. Because of the similarity, the circuits have the same calibration constants that must be measured and applied in software: linearity and pedestal, i.e., the slope and intercept of the best fit of

capacitor voltage to discharge time at a fixed rate. To extract the best results from either circuit you have to devise a method to measure the response to the input of a known time interval or a known charge. A procedure and the circuit setups required are discussed in the software manual.

Level Translator

Both NIM (Phillips 726) and CAMAC (7126) versions exist, depending on where it is convenient to find power. The functions are identical. Level translators are used to make ECL (emitter coupled logic) signals for the 4448 latch. An advantage of ECL is the ability to use twisted/flat ribbon cable that can easily and economically provide a delay of many nanoseconds.

Fanout

A Phillips 748 Linear Fanout module is useful in case you need to copy one source to multiple outputs. Novices occasionally will do this with cables strung out with a “tee” dropping off the signal here and there. This violates the 50 ohm termination rule and leads to signal distortion and attenuation. A fanout is used in the μ^- experiment to feed a gate to use with the counters for a TDC stop signal to be correlated with a muon stop.

Lecroy 4448 Latch

This circuit is used in the spectrometer experiment to record all the target counter signals when there is an event trigger.