

LABORATORY MANUAL FOR PHYSICS 180F

William E. Slater

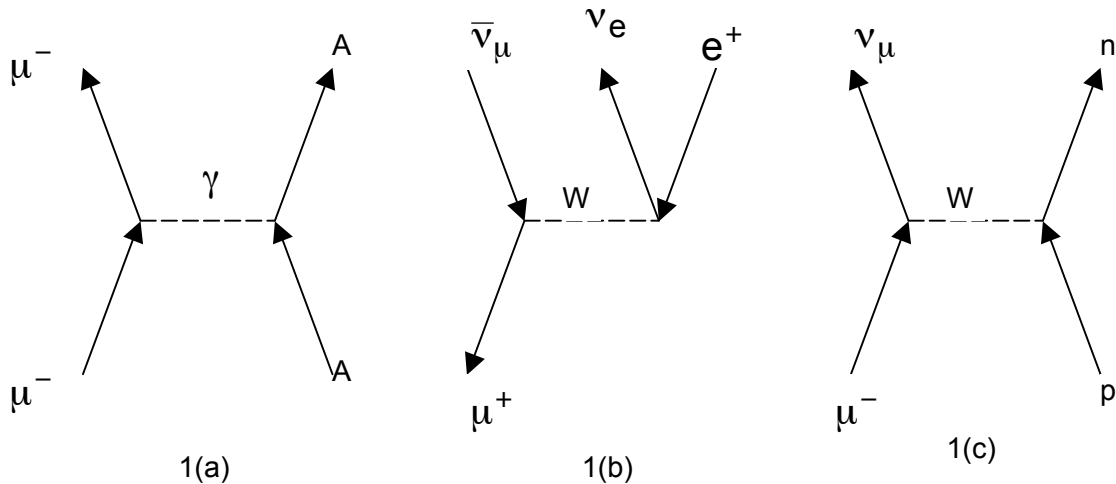
UCLA, February 2004

Version 2.4

I. Introduction

My objective in this course is to introduce students to some experiments with cosmic ray muons. Because they interact weakly, muons usually survive the traversal of 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 a 90-centimeter column of lead. Strongly interacting components of cosmic rays do not generally penetrate the atmosphere all the way to the surface of the earth.

The observations we make in this laboratory have to do with the decay of positive muons, the decay and capture of negative muons, and the multiple coulomb scattering of both. Feynman diagrams, which I will use for illustration only, and not calculation, for these processes are shown in Figure 1a (coulomb scattering), Figure 1b (μ^+ decay), and Figure 1c (μ^- capture).



The “exchanged” particle defines the type of interaction as electromagnetic for photon and weak for W^\pm . The Standard Model of strong and electroweak interactions combines both of these 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.

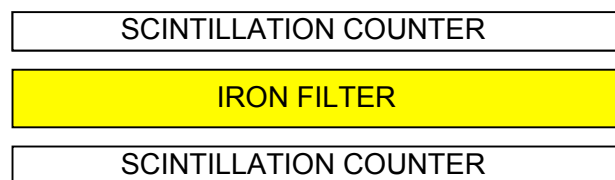
None of the 180F experiments is easy. Cosmic ray rates are low and you have to think about backgrounds. This manual is not a cookbook for the experiments, though a setup of the fast logic is presented for each one and suggestions are given on how to measure the backgrounds. I hope that the manual will be of use in recognizing and solving some of the subtle problems that have to be overcome in order to do a convincing experiment.

II. Source of Particles

The muons we play with in this course originate in pion decay, the particle predicted by Yukawa in 1934 to mediate his screened coulomb force. Pions come in three charges, π^+ , π^- , π^0 . Unless they interact first, the charged pions decay in flight to charged muons. There is no neutral muon; the neutral pion decays to two photons.¹

Two properties of muons allow them to be detected and identified: (1) they are charged and therefore generate scintillation light in appropriate material and (2) they do not interact strongly and therefore only lose energy by ionization and can penetrate a filter material such as iron. A generic muon detector is shown in Figure 2, consisting of two scintillation counters with a slab of iron between. Low energy electrons and photons, which make up a relatively small component of cosmic rays at sea level, are easily stopped in the iron. A coincidence of the two counters is required so that only a particle that goes through the iron can give a signal.

FIGURE 2



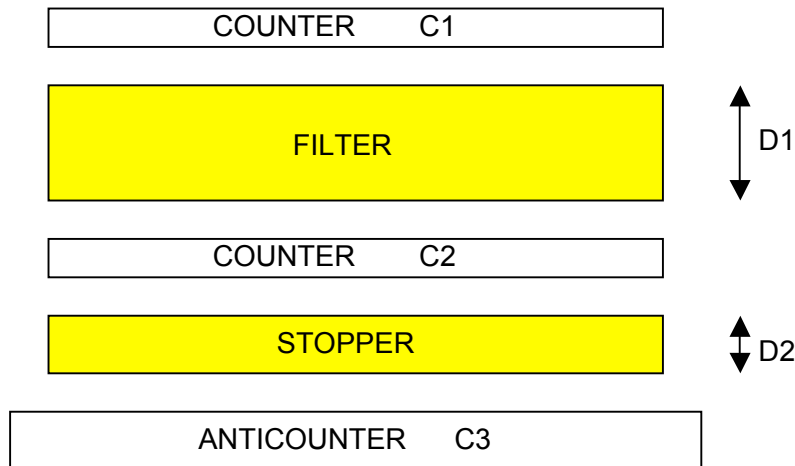
Before you set up anything more elaborate, it will be essential for you to look at the counter outputs with an oscilloscope. The clean, relatively large signals are the ones due to real tracks.

¹ These are the most frequent decay modes. Most particles decay to several different final states, with widely varying branching fractions.

Anything seen a lot more frequently than once every second or so is phototube quantum noise that can give a very high rate, in the megahertz ($10^6 / \text{sec}$) range or higher. Needless to say, you will need to spend some time learning how the scope functions, including how to adjust trigger, gain, time base, and so on.

The “telescope” of Figure 2 could be used to measure roughly the flux of cosmic rays, but the experiments in 180F require more, namely to make an energy selection of the muons. 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 momentum of 200 MeV/c or so. All three can be achieved the same way. Figure 3 shows an improved telescope that adds an iron slab below the sandwich of Figure 2. The second slab serves as a “stopper” and is followed by an “anti-counter”. The anti-counter is the same as a counter, but it may be operated at a slightly higher HV, or lower discriminator threshold, is possibly thicker, and of larger area. It is connected in veto and its discriminator output is set wider in time than the other signals. Efficiency is generally more crucial for an anti- counter.

FIGURE 3



To be detected by the condition $1 \otimes 2 \otimes \bar{3}$,² a particle must penetrate at least a thickness D1 and at most D1+D2. Look at Figure 4, the range-momentum relation for various particles and

²I use the symbol \otimes to designate logical AND and \oplus 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.

materials, and select the curve for muons in iron. The momentum that just makes it through D1=7.5 cm (60 grams) is approximately $P=200$ MeV/c. To get through $D1+D2 = 7.5+2.5$ cm of iron, (80 grams / cm^2) a muon must have $P=230$ MeV/c. If $P>230$ MeV/c, the particle is detected in C3 of Figure 3 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 (or "bite") of 30 MeV/c centered at approximately 215 MeV/c. In the 180F MCS experiment, a telescope like Figure 3 is placed downstream of the spark chamber array so momentum selection follows the scattering events. This is valid because the muons do not lose significant energy in the scattering. We also ignore energy lost in the counter material.

An estimate of the rate at which candidate events will occur can be made from available numbers. The Particle Data Booklet gives cosmic ray fluxes (Ticho's notes have the numbers also); one way to give the result is 80 particles, mostly muons, per second, per steradian, per square meter. In any of our setups, the counters are roughly 1 foot by 2 feet in surface area that is 0.18 m^2 . Using Figure 3 as a generic 180F telescope, suppose that the distance from the top surface of C1 to the bottom of C3 is 30 centimeters, the solid angle (within a factor of ~ 2) is approximately

$$\Omega \approx \frac{0.18 \text{ m}^2}{(0.3 \text{ m})^2} = 2 \text{ steradians. This is about right for the } \mu^+ \text{ experiment, but is an}$$

overestimate for the multiple scattering experiment (MCS) where the counters are farther apart in order to provide space for the chambers. In addition, the momentum bite for the MCS takes a smaller fraction of the total flux. Figure 4 shows the measured spectrum (See the Handbuch der Physik volume 46 in the reference section of the library; since about 1950 it is published in English and titled PH). If you approximate Figure 4 by a flat distribution from 100 MeV/c to 2 GeV/c, a 30 MeV/c bite takes about 1.5% of the total flux. Putting the three factors together gives an estimate of $0.015 \times 2 \times 0.18 \times 80 \approx 0.4$ per second for the number of muons stopping in 1 inch of iron after having already penetrated 3 inches of iron.

FIGURE 4. Copied from Handbuch der Physik (see text)

7. Measurements by the Manchester group. These measurements have been repeated and extended by a similar but larger instrument at Manchester (HYAMS *et al.*, OWEN and WILSON¹). The spectrograph employed counter recording for

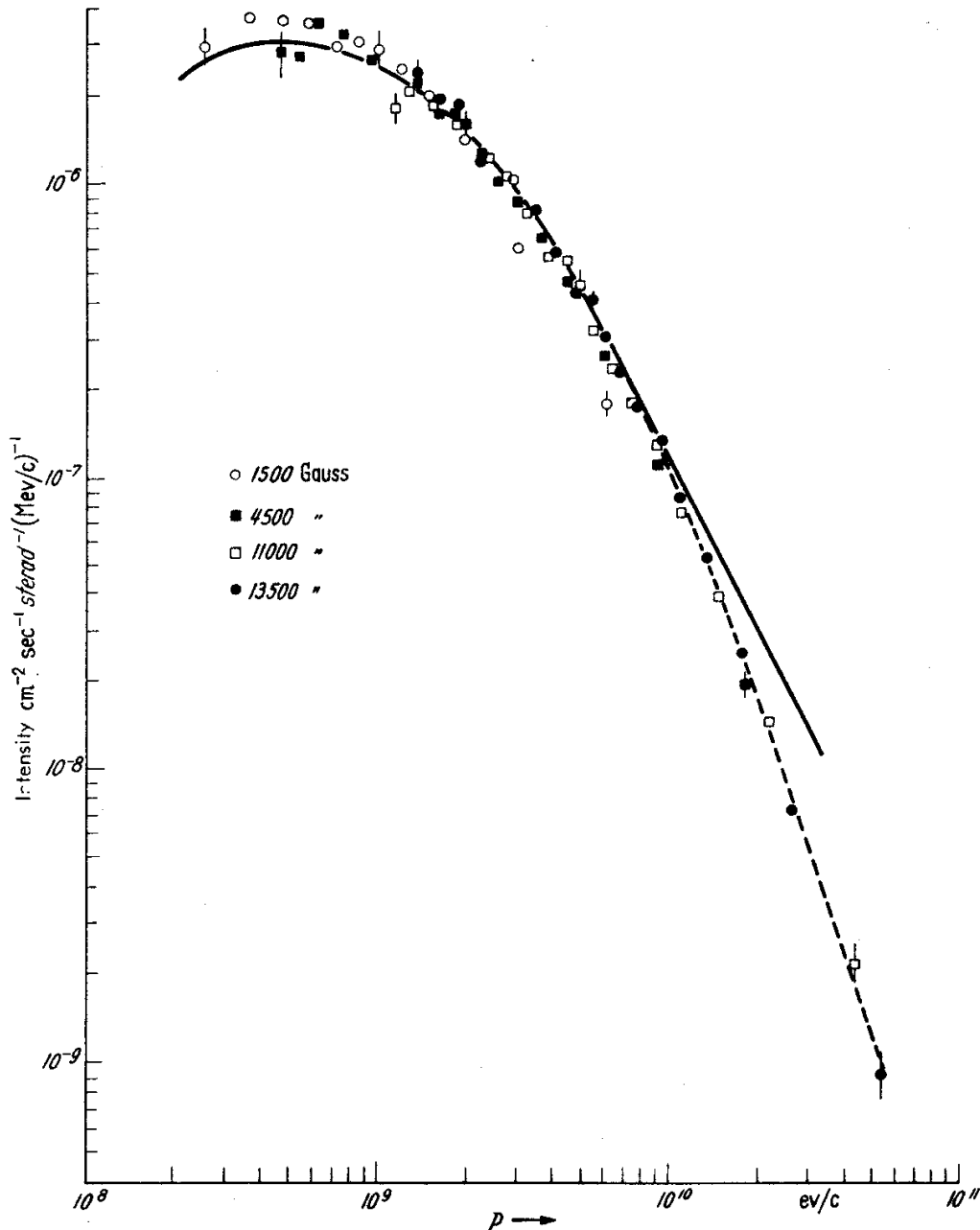


Fig. 3. A comparison of the sea level momentum spectra of CARO *et al.*, see footnote 4, p. 274, (broken line) and Rossi, see footnote 2, p. 274, (full line).

the low momentum measurements, $0.5 < p < 20 \text{ GeV}/c$ and consisted of two electromagnets placed vertically one above the other with three layers of counters symmetrically placed along the trajectories of the particles.

In setting up any of the experiments, before you try to take data, it is essential to use tracks going straight through your apparatus. You must arrange to do this as simply as possible, for example by just moving a cable from a veto to a normal input because you may need to do some debugging after you begin to take data. Most logic modules have both inverting inputs (vetoes) and inverting outputs (usually labeled $\overline{\text{OUT}}$) that can be used for this purpose. The frequency of straight-through tracks is high enough to observe them with an oscilloscope so that you can make rough timing and pulse duration adjustments. The “digital phosphor” scopes make timing adjustments very easy if you use the infinity setting of persistence because you are able to compare two signals in a large sample of cases to see what delays may be needed as well as what the pulse width settings need to be. You can also view single pulses on the scope without turning off room lights.

Before you can do any useful work with counter signals, you have to convert them to a standard shape by running them into a discriminator. The standard “true” level for the output is -700 millivolts. You must decide on a threshold for each discriminator and a high voltage (HV) setting for the PMT of the counter. The HV affects the gain of the PMT and 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 noise level generated in the PMT due to thermal emission of electrons from the photocathode.

Generally it is a good idea to adopt a reasonable threshold setting, say 50 millivolts, where the discriminator circuit operates reliably. Then using two counters and a coincidence module you can run a HV plateau curve to establish a reasonable operating point. However, in order to make a coincidence at all, the signals going into the coincidence must overlap in time. Timing is adjusted by means of cable length between PMT and discriminator. As mentioned this is easy to adjust with the aid of the infinite persistence feature of the oscilloscopes.

III. The Experiments

A. μ^+ Mean life and Polarization

Figure 5 is a sketch of the telescope used to measure the meanlife and polarization in μ^+ decay.

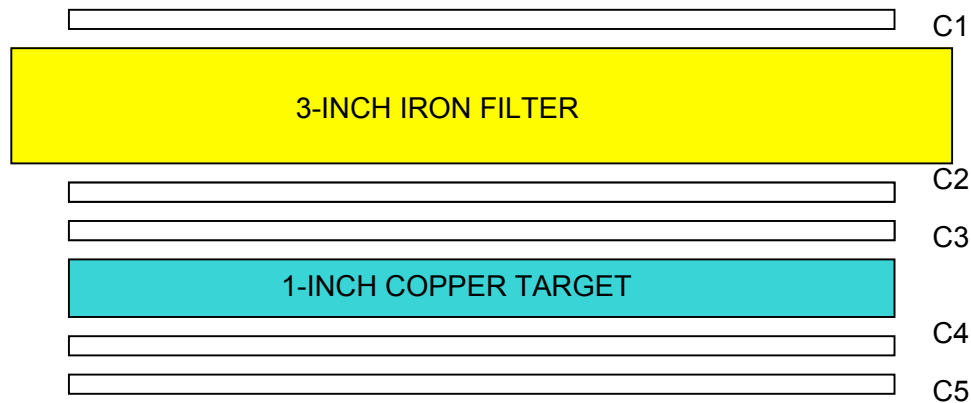


FIGURE 5. μ^+ TELESCOPE

You select stopping muons with the signal $M = 1 \otimes 2 \otimes 3 \otimes \bar{4}$. This signal is used to start a “gate” of ~20 microseconds during which you want to detect and record electrons from the muon decay. Both upward and downward moving decay electrons are needed and you want to detect them separately and measure the time interval between M and the electron. Figure 6 suggests a way to make the signals you need. Outputs from the B-discriminators for C1, C2, C3 along with a veto signal from the A-discriminator for C4 go to a coincidence module, labeled MSTOP. The A-B discriminator tactic is a way to generate properly timed and sequenced “TRUE”³ and “VETO” signals. This is incorporated in the logic diagram, Figure 6. **The analog signals from the PMT’s must arrive at the same time at the A-discriminator inputs.** Before you construct the logic

³ To avoid confusion between signal polarity and the use of the signal in a boolean logical sense, logical signals will be called TRUE and FALSE (or VETO). A TRUE NIM signal is a -.7 volt level, while a FALSE NIM signal is ground. TRUE and FALSE are COMPLEMENTARY.

circuit but after you plateau the counters to set HV, you will use straight through muons to establish this timing.

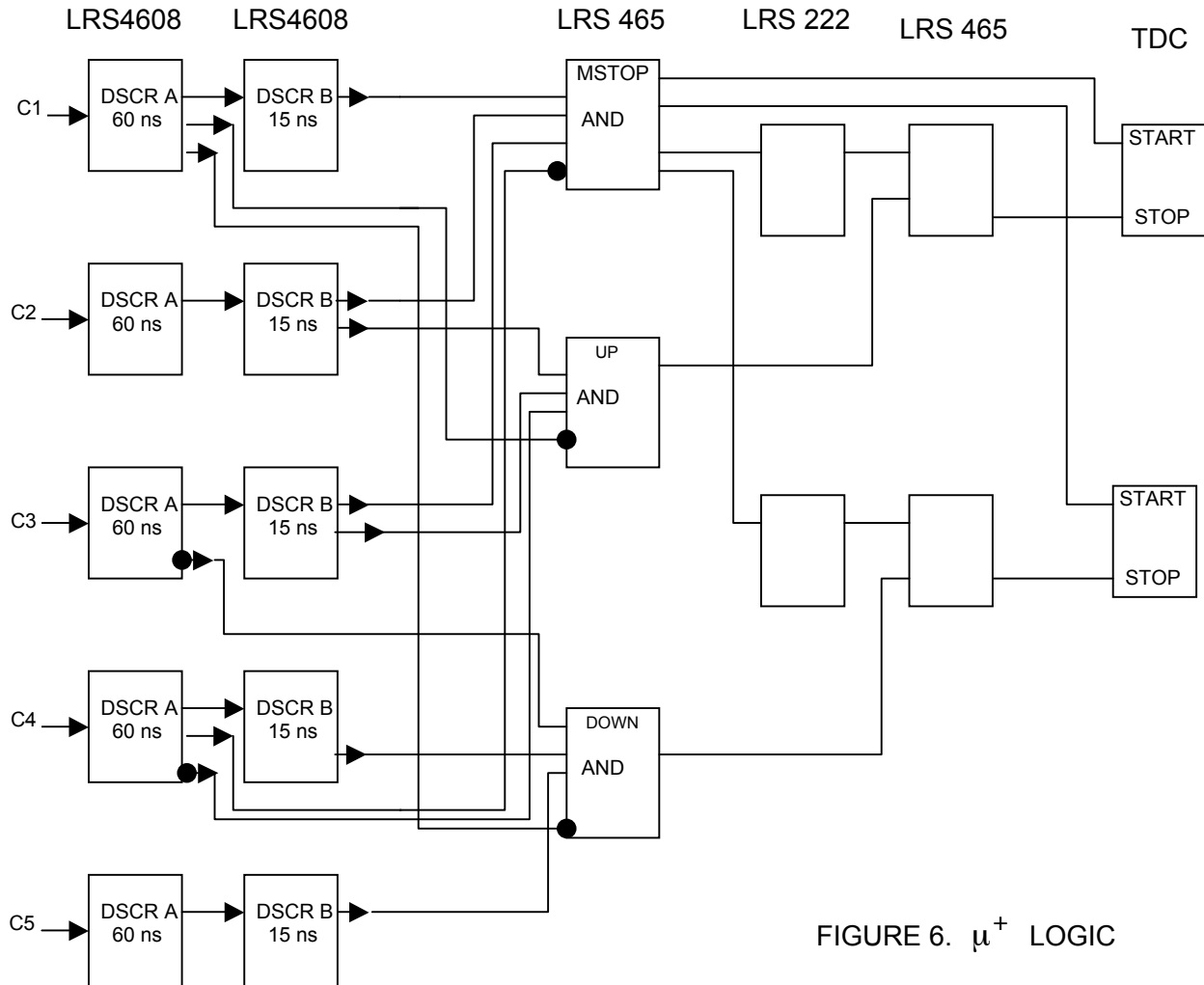


FIGURE 6. μ^+ LOGIC

Downward decay candidates are identified by $D = \bar{1} \otimes \bar{3} \otimes 4 \otimes 5$ and upward candidates by $U = \bar{1} \otimes 2 \otimes 3 \otimes \bar{4}$. U and D are made in additional LeCroy 465 coincidence units. Since there is only one veto input in the LRS 465, only one of the two complementary inputs for U and D can be formed from an A-discriminator OUT to the LRS465 veto input. The other is done with $\overline{\text{OUT}}$ from the corresponding A-discriminator to a normal input of the LRS465. Although you do not need vetoes from all the counters, it is necessary to cable all the signals alike with both wide A-discriminator outputs and narrow B-discriminator outputs, retarded by the ~10 nanosecond circuit delay of the B-discriminators.

As mentioned above, the stopping muon signal (MSTOP in Figure 6) is used to generate a gate signal (M-gate) of ~30 microseconds duration. The coincidence of the M-gate with U or D formed in the LRS465's (5th column of Fig.6) is the way you select decay candidates that are correlated with a stopped muon within the time-length of the gate.

Besides starting the M-gates, MSTOP also starts both TDC's. A U (D) decay candidate that occurs within the M-gate stops the up(down) TDC; the other TDC overflows and can be recognized in the recorded data as having done so because it sets all bits of its digital output true when it overflows. All bits on is read out as 65535. The TDC counts are written to disk by the data acquisition program. This program executes a loop that checks the LAM register and exits the loop if there is a LAM. If not, the loop repeats. When there is a LAM, the program checks to see which TDC set the LAM and reads that TDC's output register. After the information is written to disk, the loop is re-entered. In addition to the LAM check, there is a check to see if the F1 key has been pressed on the terminal. If so, the program pauses to present a choice of stopping the run or restarting the loop. This is the only way to stop a data run and save the recorded data. If you control-C out of a run, the output file is lost. See section IV-B for a listing of this program.

To observe the beginning of the muon decay time distribution, you should put several nanoseconds delay cable between the U and D outputs from the LRS465 majority logic units before their ANDs with the M-gate. Cable and logic delays are less in U and D than in M-gate and you can only observe the early part of the time distributions by delaying U and D.

There are at least three important backgrounds in this experiment. (1) Accidentals from straight-through muons may be present in this part of the distribution, depending on how efficient are the vetoes. Similar triggers when one muon hits C1, C2, and C3 near one side but misses the target and also misses C4 and C5. Then a second muon misses C1, C2, and C3 but hits C4 and C5. These decay times have a random, flat distribution. They can be counted from the late part of the time distribution. After 10 mean life times, the real muon decays are reduced by a factor of $\exp(-10)$ so remaining events are random accidentals. You can do a good background subtraction with data beyond 10 microseconds; the TDC's make this job easy. Run with M-gate set to approximately 30 microseconds. Since PAW can fit an arbitrary function to data, you should construct a function with adjustable accidental level and let the fitting program simultaneously determine the signal and accidental levels.

(2) Counters are not sensitive to the sign of a particle's charge. There is background from μ^- decay and capture which exhibit a shorter effective mean "life" due to the capture channel, which is not present for μ^+ . Cutting the data at the low numbered TDC bins can eliminate them. A cut at bin 8 eliminates 98% of the μ^- decays.⁴ One way to deal with both (1) and (2) is to histogram the combined UP and DOWN TDC values to assess the accidental level. With the M-gate set to 30 μ SEC which is nearly 15 mean life times; the bins from 500 to 1500 can be used to measure the accidental rate, which can then be subtracted from each bin. A histogram from bin 10 to bin 300 should be a clean exponential after the subtraction.

(3) Sometimes a muon will stop in C3, decay there, and appear as a real event. Since there is no magnetic field, there is no precession. The polarization signal is therefore washed out somewhat. There is no way to distinguish these from decays within the copper target except to remove the target and count the bin by bin rate of apparent events. Therefore, you should do a target-out run to correct for stops in C3. These events are a mixture of true μ^+ and μ^- . It could be argued that this is irrelevant for the μ^+ which have the same mean life in copper and scintillator, but the μ^- will have a longer effective mean life in scintillator than in copper and can therefore distort your time distribution when you correct for C3 stops.

To do the polarization measurement, you use the fact that the muon magnetic dipole moments $\vec{\mu}$ precess in the presence of a magnetic field, \vec{B} , within the copper target. The field direction is in the plane of the target, so the muon magnetic dipoles precess around \vec{B} . This is analogous to a mechanical gyroscope whose spin axis traces a cone whose own axis is vertical so that the projection of the spin on the cone-axis is constant. Similarly, the dot product $\vec{\mu} \cdot \vec{B}$ remains constant as the spin vector traces out the surface of a cone whose axis is horizontal, along \vec{B} .

⁴ You get a factor of e reduction in one mean life; 8 bins = 160 ns = τ_- in copper. If the rate of capture is Γ_C and the rate of decay is Γ_D , then the effective mean life is given by

$$\frac{1}{\tau} = \Gamma = \Gamma_C + \Gamma_D. \text{ The branching ratio of decays to captures is } \Gamma_D / \Gamma_C \approx 0.08. \text{ I assume}$$

Thus $\vec{\mu} \cdot \hat{Z}$ changes sign periodically, where \hat{Z} is a vector **perpendicular** to the target plane and \vec{B} is **in** the target plane. Since the decay electron momentum is correlated with its spin direction, you can observe an oscillation in the ratio of UP decays to DOWN decays. To optimize the observable signal, the strength of the magnetic field is chosen to make one precession period approximately equal to the μ^+ mean life. If the precession period is a lot smaller than the mean life, your statistical accuracy will be limited in successive up and down intervals. If the period is much larger, then accuracy will correspondingly be different for up and down events and the up-down difference will lose statistical sensitivity.

Signal events are from μ^+ that stop in the target. As mentioned above, μ^+ that stop in counter 3 and decay UP must be corrected for by running with the target swung out of the path. Since it is unlikely that you will run with target out for the same number of incident muons as you do with target in place, you must record the run time in both cases so that you can normalize the background distribution to the running time with target in place. The procedure seems quite straightforward at first glance but the target-out run will contain DOWN as well as UP decays. The capture material of such events is not obvious. If the origin is μ^+ that stop in C3 near enough to the exit face that the decay positron is left with a very short path. It can fail to generate a signal in C3 but do so in C4 and C5. It is then wrong to subtract them because similar positrons would not have enough energy to penetrate the copper target if it were present. On the other hand if they originate with μ^+ that stop in C4 so near the entrance surface as not to be detected, then μ^+ (with slightly different energy) would be present in target-in data. This problem is complicated even more because some muons will stop in the support structure.

I was troubled enough by this ambiguity to write a GEANT simulation of the experiment. Compare two possibilities: (1) a μ^+ near the end of its range where dE/dx is large will produce a large signal while its daughter, a downward moving decay positron has little path in which to generate scintillation light; (2) a μ^+ that stops in a very limited thickness of C4 (so as to be missed) has

$\Gamma_d = 1/(2.2 \mu \text{ SEC})$ is the same for μ^+, μ^- . The fraction of all μ^- that decay is therefore $f = .08/1.08 = .07$. The fraction of μ^- that decay later than τ_- is $.07/e = .025$.

maximum specific ionization since it is at the end of its range. Even though C4 should always detect the decay positron if it is emitted DOWN, scenario (1) seems more likely in view of the muon track. The simulation bears out this guess. Based on the simulation, I believe the correct procedure is to subtract the UP target OUT time distribution from the UP target IN distribution. However, the DOWN target-OUT events are not relevant and should be discarded.

In fact, the target IN simulation also generates electrons emitted DOWN some of which scatter inside the copper target in a way to move back upstream towards C3, thereby faking an UP event. Thus, some number of DOWN decays will end up satisfying the UP trigger; they ought to be subtracted but you have no way to identify them.

Figure 7 shows the simulated distributions of the μ^+ decay position for target IN/OUT and decay UP/DOWN. C3 lies between $z=11.3$ and $z=12.3$ cm. As you can see in the IN/UP plot, μ^+ stops in C3 are about 20% of stops in the target. The OUT/DOWN plot shows that C3 is the main source, by roughly 17 to 1 compared with C4. In raw data (see IN plots) the monte-carlo UP decays number about 4/3 for the DOWN decays. Subtraction of OUT/UP events from IN/UP gives Figure 8. The subtraction removes about 95% of the background.

Figure 9 compares apparent UP detected, DOWN generated events (the positron evidently has a hard scattering) for IN and OUT runs. The difference consists of events that when target is IN scatter from it. When that target is OUT, there are still such events, and in this case the positrons must scatter from C4. The difference between these plots make up the difference noted in Figure 8. Figure 10 shows that the last little 5% is reproduced about right.

To complicate matters further, the background from μ^- is characterized by an effective mean life of about 160 ns if the stopping material is copper and 1800 ns if the material has low atomic number like carbon (6) or oxygen (8) which are similar to the constituents of scintillator.

The experiment was run in Winter 200 for over 400 hours of each IN and OUT events. Table 1 summarizes the data taking and Figure 11 shows the precession after subtracting UP/OUT background and then doing UP-DOWN subtraction. The 2.2 microsecond exponential was not divided out.

Figure 7

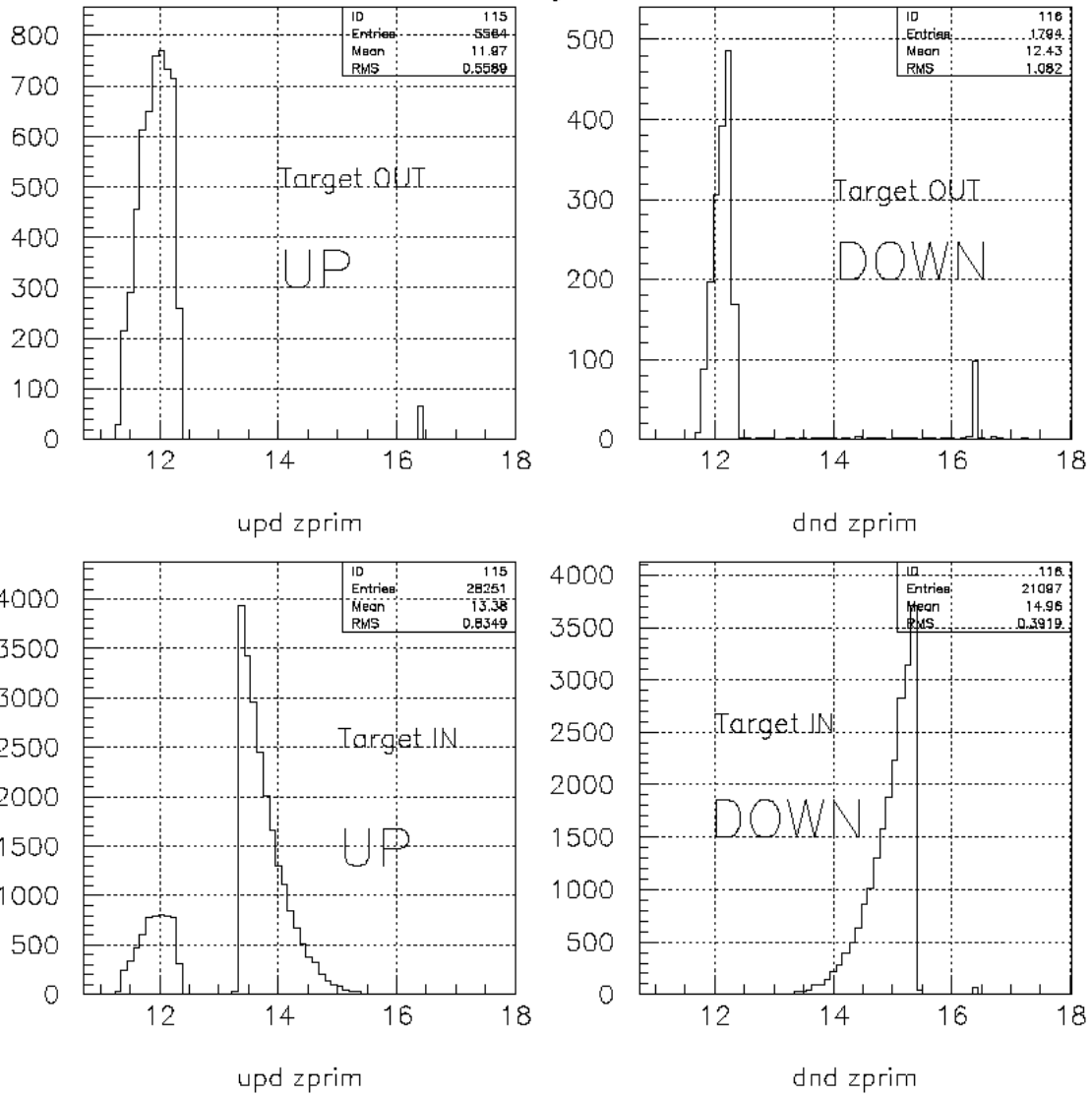


Figure 7

Figure 8

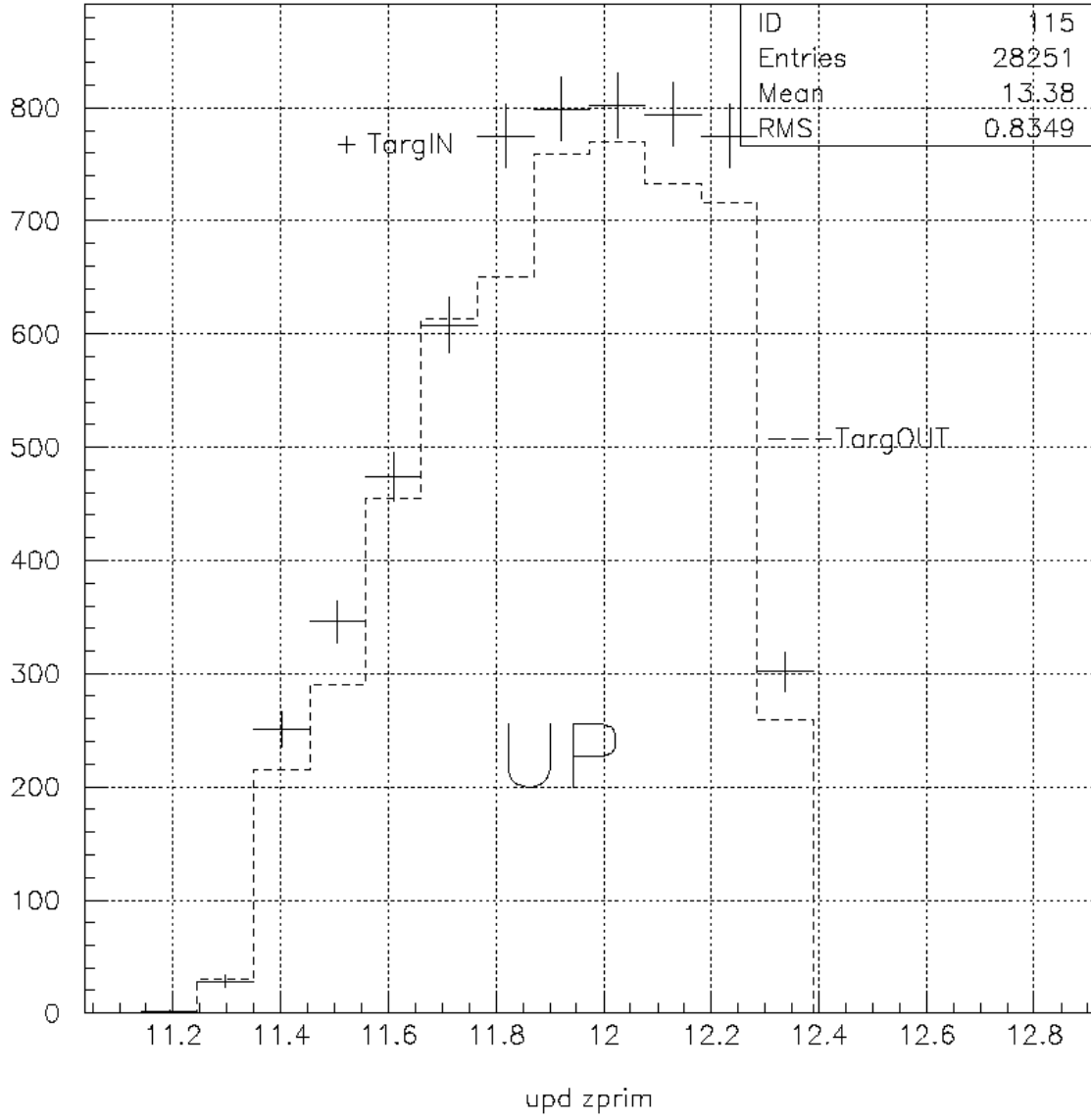


Figure 8.

Figure 9

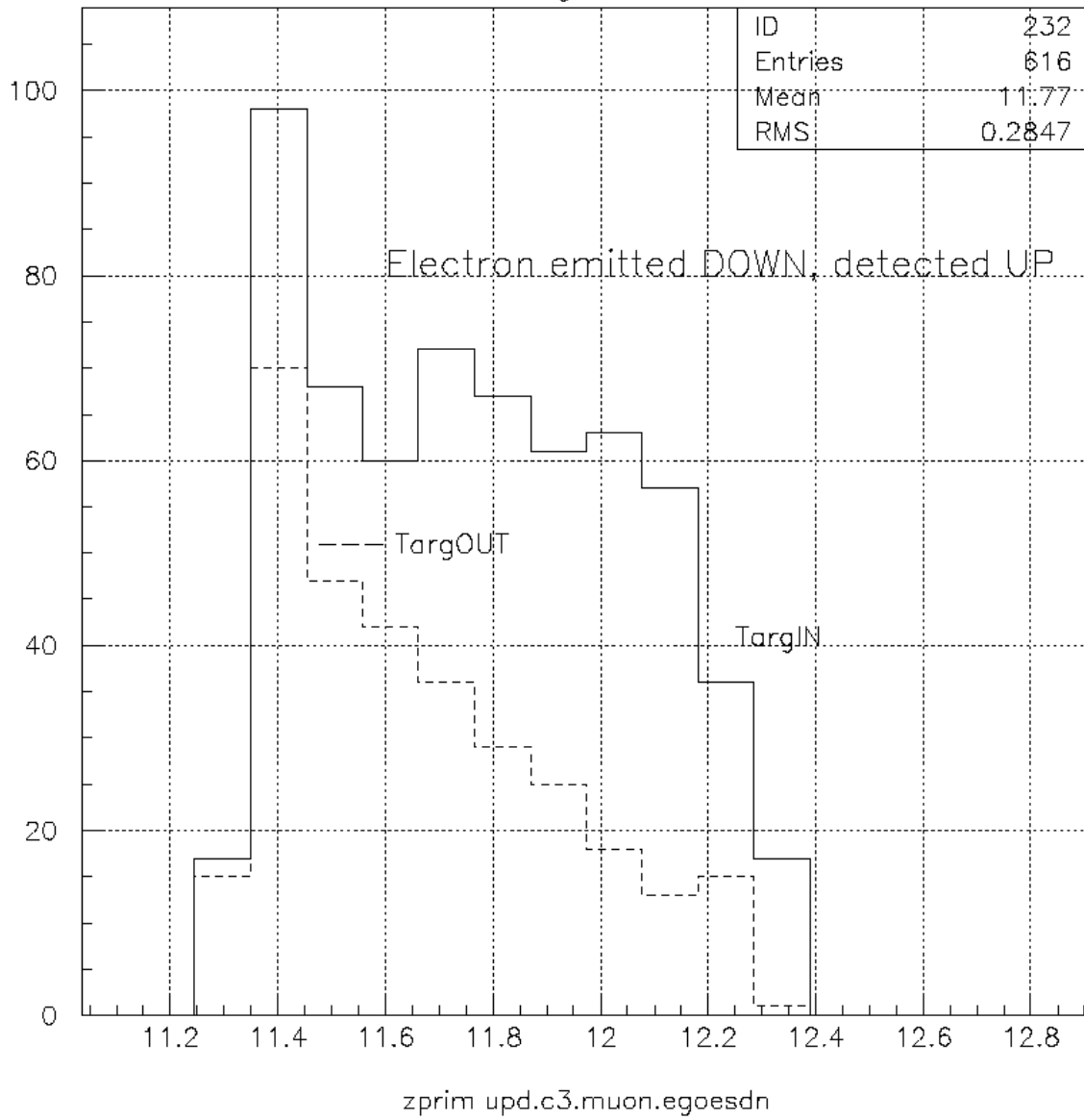


Figure 9

Figure 10

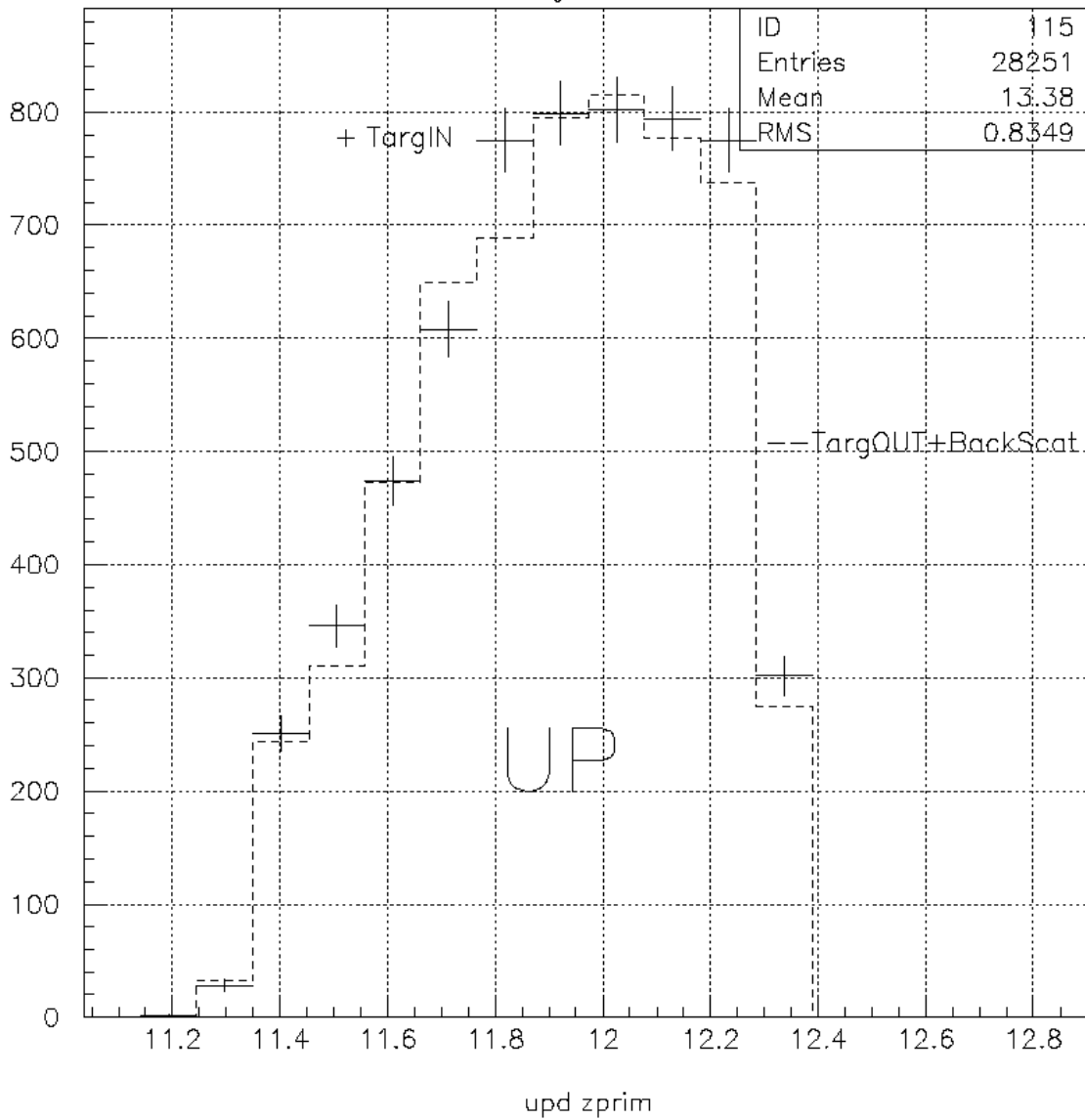


Figure 10

New running, July 2000 after new target (24") is in place with guard coils attached.																		
file	start	stop	up	down	runtime	up rate	dn rate	c2 thr	c3 thr	mustop	1*2*4*5	target temp	l beg	l end				
25jul00	25-Jul	8:00	26-Jul	8:45	904	585	24.75	36.53	23.64	50	50							
26jul00	26-Jul	8:55	27-Jul	8:45	676	616	23.83	26.36	25.85	50	50	199212	676878	in	3.85 rev	3.85 rev		
27jul00	27-Jul	8:48	This run and the ones above probably had a cable not solidly plugged in. I saw no T1 in 2 hours. Note rate change above.															
27jul00	27-Jul	11:00	28-Jul	16:30	1040	716	29.50			50	50	293556	831263			3.85 rev		
At this point power was removed for electricians to work in vault west of Khudsen Hall. The hard disk did not survive power off/on.																		
Hard disk replaced. Up and running 3 Aug																		
													24.7	pwrOFF				
3aug00	3-Aug	10:25	4-Aug	9:55	847	596	23.50	36.04	25.36	50	50	197322	672965	in	32.9 3.85rev	3.85rev	3.41	1.42
4aug00	4-Aug	10:00	5-Aug	16:50	1085	776	30.50	35.57	25.44	50	50	256363	874104	in	31.9 3.85rev	3.85rev	3.41	1.40
5aug00	5-Aug	16:55	7-Aug	8:50	1383	980	39.92	34.65	24.55	50	50	332559	1133843	in	31.5 3.85rev	3.85rev	3.41	1.41
7aug00	7-Aug	8:55	8-Aug	17:05	1138	785	32.17	35.38	24.40	50	50	269818	913002	in	32.1 3.85rev	3.85 rev	3.38	1.45
8aug00	8-Aug	17:10	10-Aug	15:55	1612	1129	46.75	34.48	24.15	50	50	391990	1328089	in	31.7 3.85 rev	3.85 rev	3.39	1.43
power off																		
15aug00	15-Aug	17:40	18-Aug	15:25	2488	1788	69.25	35.93	25.82	50	50	584263	1983897	in	31.6 3.85 rev		3.40	1.39
18aug00	18-Aug	15:30	pc power supply failed															
22aug00	22-Aug	16:50	24-Aug	10:05	1468	1052	41.25	35.59	25.50	50	50	348990	1184780	in	31.6 3.85 rev		3.39	1.40
24aug00	24-Aug	10:10	28-Aug	9:00	3438	2478	95.80	35.89	25.87	50	50	803611	2726635	in	32 3.85 rev		3.39	1.39
28aug00	28-Aug	9:05	31-Aug	16:10	2959	2007	79.08	37.42	25.38	50	50	673472	2286145	in	31.4 3.85 rev		3.39	1.47
31aug00	31-Aug	16:14	5-Sep	9:10	4145	3036	112.93	36.70	26.88	50	50	961982	3271857	in	31.6 3.85 rev		3.40	1.37
5sep00	5-Sep	9:20	6-Sep	8:30	915	637	23.83	38.40	26.73	50	50	197346	670941	in	31.6		3.40	1.44
							594.97											
6sep00	6-Sep	8:43	7-Sep	9:25	363	161	24.70	14.70	6.52	50	50	179619	739870	out	31.6		4.12	2.25
7sep00	7-Sep	9:30	8-Sep	14:55	436	145	29.42	14.82	4.93	50	50	215596	883679	out			4.10	3.01
8sep00	8-Sep	15:00	10-Sep	15:08	759	277	48.03	15.80	5.77	50	50	352335	1444106	out			4.10	2.74
10sep00	10-Sep	15:10	12-Sep	16:57	787	267	49.78	15.81	5.36	50	50	362227	1481186	out			4.09	2.95
12sep00	12-Sep	17:00	15-Sep	17:03	1034	409	72.05	14.35	5.68	50	50	523746	2142704	out			4.09	2.53
15sep00	15-Sep	17:15	18-Sep	8:30	897	334	63.34	14.16	5.27	50	50	456805	1875967	out			4.11	2.69
							287.32											
Correction for counter 3 mustops:																		
							2.07											

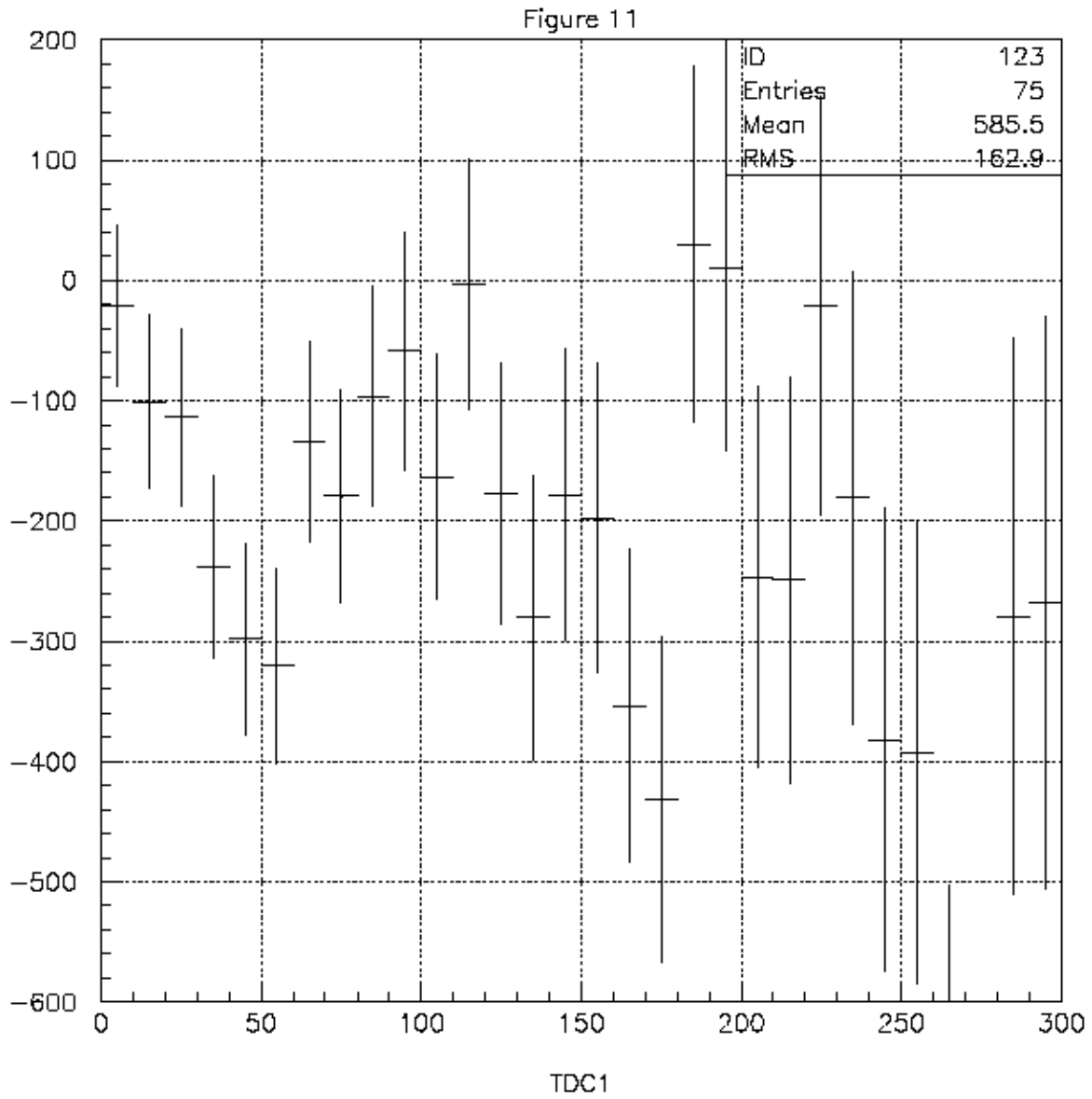


Figure 11

B. μ^- Capture

The apparatus is shown in Figure 12. Following the usual stopping muon telescope (PMTs C1, C2, C3 and C4), there is a large block of scintillator to detect low energy neutrons emitted from μ^- - capture in the target. The neutrons are detected in either of two ways: (1) quasi-elastic scattering on hydrogen in the plastic,; (2) radiative capture on a proton to make a deuteron. This process is slightly exothermic and can give a signal even for zero KE neutrons: $n + p \rightarrow d + \gamma$.

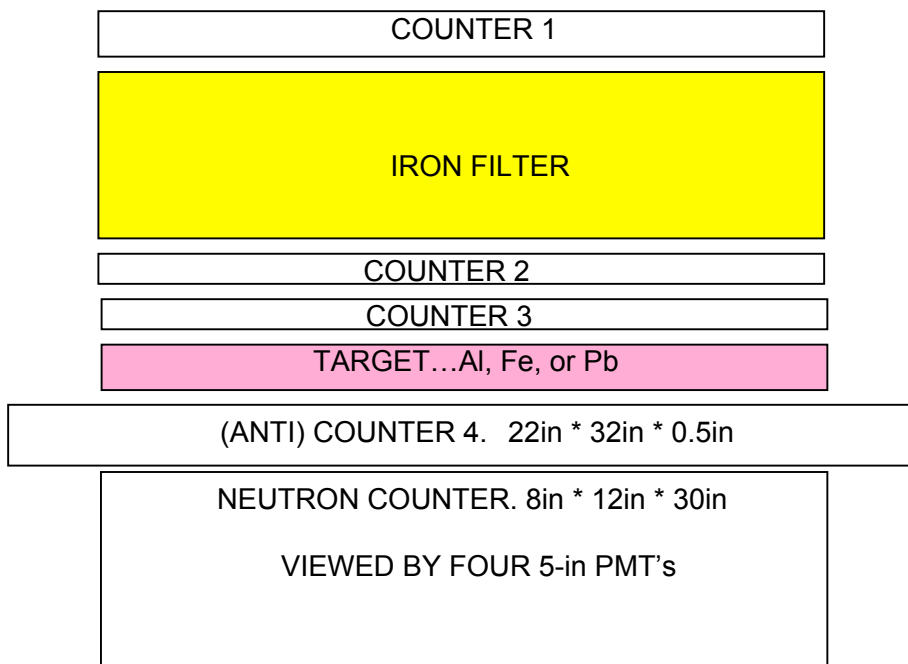


Figure 12. μ^- Telescope

The scintillator block in the neutron counter is instrumented with four large (5 inch diameter) PMTs, C5, C6, C7 and C8, to be able to detect the small signals from the two types of neutron interactions (for example, the low energy proton recoils from quasi-elastic scattering yield at most 5 MeV), as well as the large signals (up to 55 MeV) due to electrons or positrons from muon decay. This counter is 8 inches (20 cm) thick, so even a minimum ionizing muon with dE/dx of about 2 MeV/cm will deposit at least 40 MeV, and electrons will lose more than that if they make an electromagnetic shower.

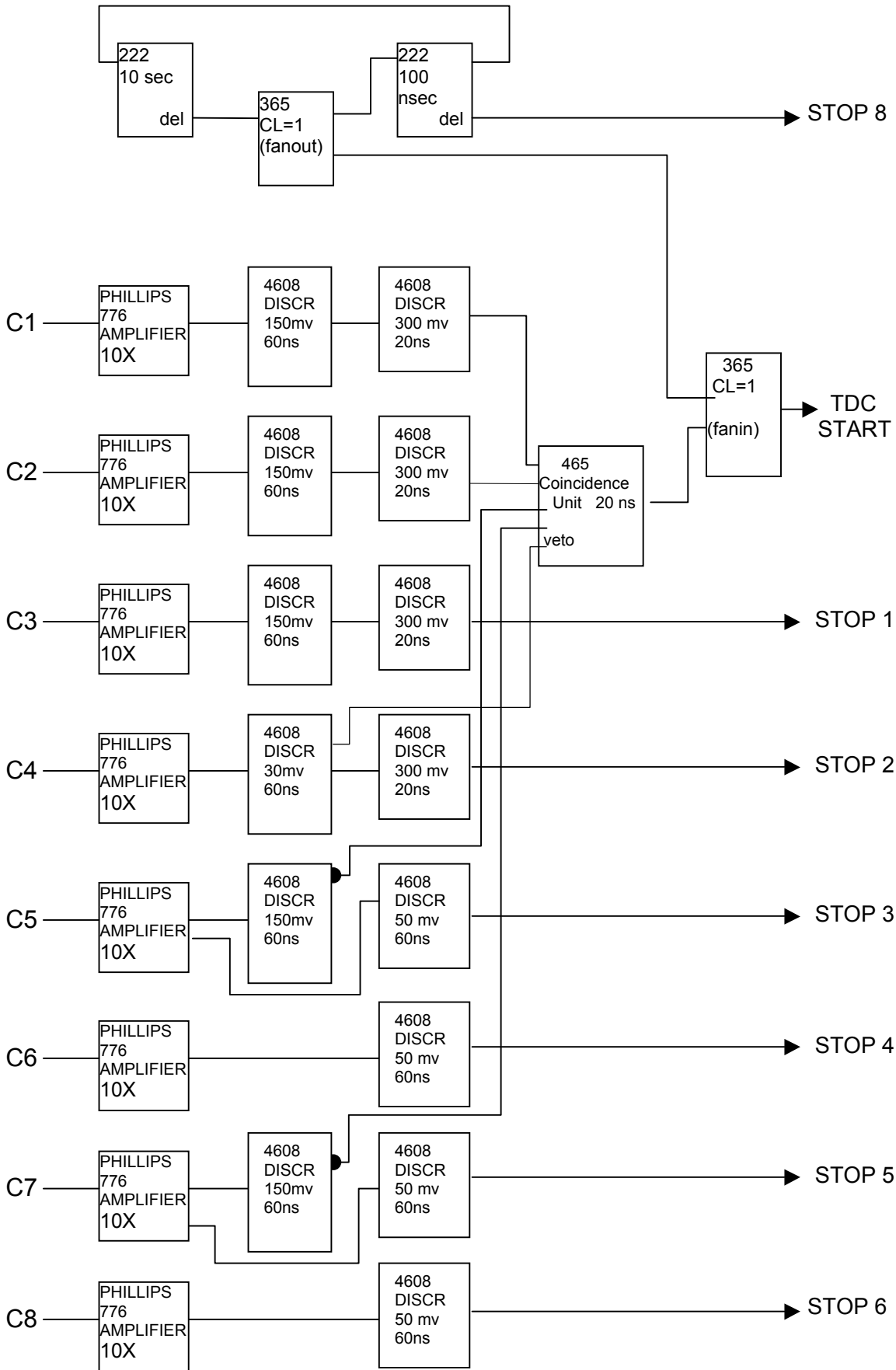
All eight PMTs must be plateaued and timed before you try to set up any logic. The anticounter, C4, and the four neutron-counter PMTs require more care than the others since they must be sensitive to weak signals (and hence operate closer to the noise level). To achieve this quality performance you must exercise more care than usual in setting the operating points, i.e., HV and discriminator threshold. The following plateau process is described for counter C4; with suitable modifications you should also use it for C5, C6, C7, and C8.

Use C3 for the normalizing counter because (a) it follows several inches of iron that removes nearly any particle other than a muon, (b) it is physically close to C4 so there is optimal overlap, and (c) there is no material between C4 and C3. To do an ordinary plateau you would fix HV3 first. Having previously chosen discriminator thresholds, you would then make a coincidence $C3 \cdot C4$ and scale both C3 and $C3 \cdot C4$. To make the nomenclature unambiguous let's call S3 and S34 the two scaler counts. You would start with HV4 low enough to have the count $S34/S3$ well below unity. Then you would raise HV4 in suitable steps, say 25 or 50 volts and plot $S34/S3$ versus HV4. Ideally you would find a HV4 range where the ratio is constant at unity. However, as you raise HV4, you not only increase the tube gain and therefore its probability to respond to a single photoelectron signal but you also increase the noise level, i.e., the emission of thermal electrons from the photocathode.

Therefore to get the best signal to noise adjustment you must detect both signal and noise. You can detect noise by generating an out-of-time C3 signal as well as the in-time C3. Run one of the discriminator outputs for C3 to a gate generator and call the DEL (delayed) output C3d. Set the gate width to, say, 200 nanoseconds. With three scaler channels you can simultaneously record C3, $C3 \cdot C4$, and $C3d \cdot C4$. Adjust HV4 so that $S34/S3$ approaches unity as closely as possible while keeping $S3d4/S3$ from rising significantly. Always plot the error bars so you can see how much data is needed. In this context, you should be able to reach $S34/S3$ above 99.5% and still have $S3d4/S3$ below about 5%.

With appropriate modifications you should follow this same procedure for C5, C6, C7, C8. Here you should plateau one of these tubes against another that views the neutron detector rather than C1, C2, C3, or C4.

Figure 13 is the logic for this experiment.



Unless otherwise marked in my logic diagrams, the left side of a module shows the inputs and the right side shows outputs. The stopping muon trigger is $C1 * C2 * (C4 \text{ veto}) * (-C5) * (-C7)$, where $-C5$ and $-C7$ are "out-bar" signals from their respective discriminators. If there are no $C5$ or $C7$ signals, the "out-bar" signals are constant at -0.7 V for NIM electronics. This acts as a "True" signal into the "stopping muon trigger" coincidence. If there are $C5$ or $C7$ signals, the "out-bar" line goes to 0 V and this acts like a "False" signal, and hence a veto into the "stopping muon trigger coincidence". $C4$ is the main logical negative here, while $-C5$ and $-C7$ are somewhat redundant. A "stopping muon trigger" signal starts the 8-channel TDC. Signals from $C3$, $C4$, $C5$, $C6$, $C7$, $C8$ each stops one channel of the TDC. The TDC ignores any stop signal unless it occurs within 2047 counts (40 microseconds) of a start. Thus there is no contradiction between requiring a $C5$ that follows a mu-stop, even though the earlier mu-stop requires $-C5$.

Since $C1$ and $C2$ are above the target slab while $C4$, $C5$, $C7$ all lie below, the logic in the last paragraph characterizes an incident muon that stops in the target. There is also some background from slanting incident particles that miss the counters below the target. In the great majority of these events there will be no TDC stop signal and the data acquisition program (mudaq.exe) will ignore them.

Electron or positron secondaries from mu decay may travel either up or down when they leave the target. If the anticounter $C4$ is not efficient enough, the downward-going electrons or positrons will not be vetoed by $C4$ and may be detected in $C5$ - $C8$. If you set up $C4$ carefully enough, much of this background can be eliminated. The up-going secondaries enter the close-lying $C3$ and allow a good measurement of the superposition of the decay time distributions of both positive and negative muons. Since negative muons have a disappearance rate equal to the sum of the decay and capture rates, while positive muons can only decay, the resulting time distribution will be poorly fit by a single exponential. On the other hand it is very free from accidentals. In fact, you will not realize how clean your data is until you fit it.

The TDC has 8 channels. You should use six of them to record times for $C3$, $C4$, $C5$, $C6$, $C7$, and $C8$. The TDC channels overflow at $2047 * 20\text{ns}$. An overflow is indicated by " -1 ". If all 8 channels overflow, the event is not recorded. TDC channel 8, shown in Figure 13, samples background in the neutron detector.

The large neutron counter is sensitive to several backgrounds. In addition to particles entering from outside there is background that appears to come from within the scintillator itself. There are substantial coincidences among PMT's 5,6,7,8 that occur more or less randomly within the 40 microseconds following a muon stop. To assess the background level relative to the signal, I introduced a minimum bias trigger. The purpose is to generate events that are not correlated with muon stops. These triggers give the "STOP 8" shown in Figure 13; the logic is shown at the top of the figure. One section of a LRS222 is set to a long time so its rate is much less than the real data rate; ten seconds is reasonable. The delayed pulse starts the second gate which is set to an arbitrary value that ends up as the TDC channel 8 datum. The PMT data easily reveal coincidences among PMTs 5,6,7,8 but show no correlation with the other PMT's.

The data acquisition program is called "MUDAQ". It runs on a 486 vintage PC. When you have accumulated a data file you must transfer it (via FTP and the local Ethernet) to one of the two 180F UNIX machines, hepsun6 or hepsun7.

The analysis program is called histominus.f and runs on a Sun UNIX workstation. You will have a copy of the source file along with a script file fl-histominus to carry out compilation and linking to produce the executable file, histomunus.exe. You may change the program if you wish, but you will need to know something about the Fortran language. It is pretty straightforward, though not up to modern software engineering style. The plots to study before you try to change the program to be more sophisticated are histograms

C. Multiple Coulomb Scattering with Spark Chambers

The multiple scattering experiment looks like Figure 15. This is a two-dimensional picture in the x-y plane. In reality scattering is 3-dimensional, but the distribution of projected angles can be calculated (See Ticho's notes, chapter 6) for comparison with experiment. Muons that go through the apparatus ionize the helium gas in the chambers. They are also detected in the trigger counters at the top, middle, and bottom of the chamber stack. The trigger signal is sent to the high voltage switch which pulses the chambers with about 5 kilovolts to produce the sparks that are seen by the video camera. The x-coordinates of the sparks are measured at at four y-positions, i.e., the chamber planes. From these two separate track-segments are identified the angle between them is calculated. For genuine events where the scattering occurs in the lead sheet in

the middle of the apparatus, the two segments intersect in the lead. This is a valuable constraint in removing spurious events from your data.

Events are recorded by the PC with the program **spark.exe**. The event files are copied (FTP) to a unix workstation. There are 3 programs that you can run on the raw data. First you may wish to see what some events look like. A display-preparation program "**scan.exe**" can read consecutive event files and write 2-dimensional histogram files that you can display with the physics analysis workstation (**PAW**). When you have collected a few hours worth of events you will find it instructive to see what they look like. It is then possible to select clean events. By being selective with your data sample you have a better chance to get a good fit to the scattering angle distribution. SCAN.exe writes two files for each input event, a .dsh file with the 2-dim histogram and a .kumac file that tells PAW what to do on each event. Input event (123.evt) to scan produces 123.dsh and 123.kumac. When PAW is running, the command "exe 123" will display event number 123.

There are two steps in the subsequent analysis: (1) **find-y-bands.exe** to locate the chamber positions in pixel space. Once the y-coordinates are known they must be copied to the program **bends.f**. After bends.f is compiled and linked, **bends.exe** is produced and run on the event files. The program listing is included in an appendix.

This process sounds complicated but there are "script files" to do the compilation and linking. To run an executable file you just have to enter its name on the command line.

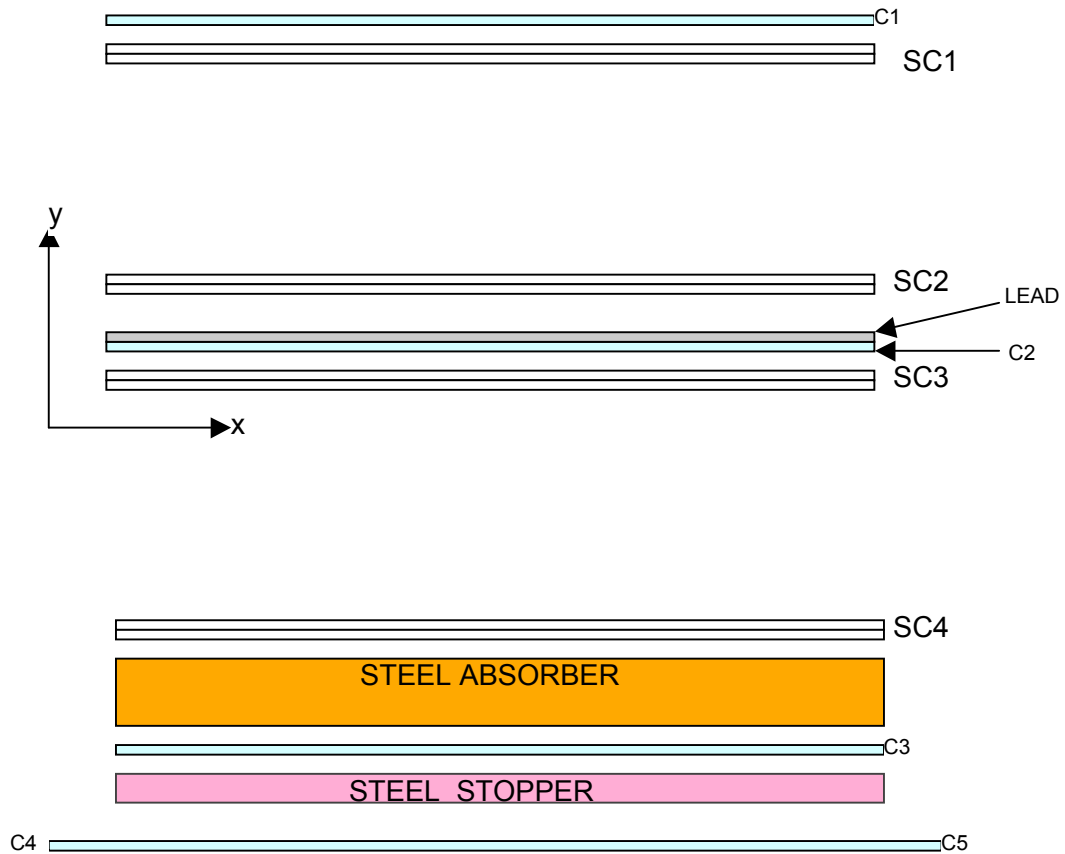


FIGURE 15. MCS EXPERIMENT

The trigger logic is shown in Figure 16. After adjusting the cable lengths of all the counters with straight-through tracks to synchronize their signals you must then arrange the veto counters to come early. Make sure the counter 4.or.5 veto generated by a LeCroy 365AL is wide enough and starts early enough to kill a muon that does not stop in the last iron slab. This is the NIMBAR signal from the 365AL [CL=1] to the second LRS465 coincidence module in Figure 16.

Note that you can switch between "LOW" and "HIGH" momentum muons without changing any cable lengths: take the NIM signal from the 365AL and set CL=2 to make an AND instead of an OR. This requires the presence rather than the absence of a muon following the lower iron filter.

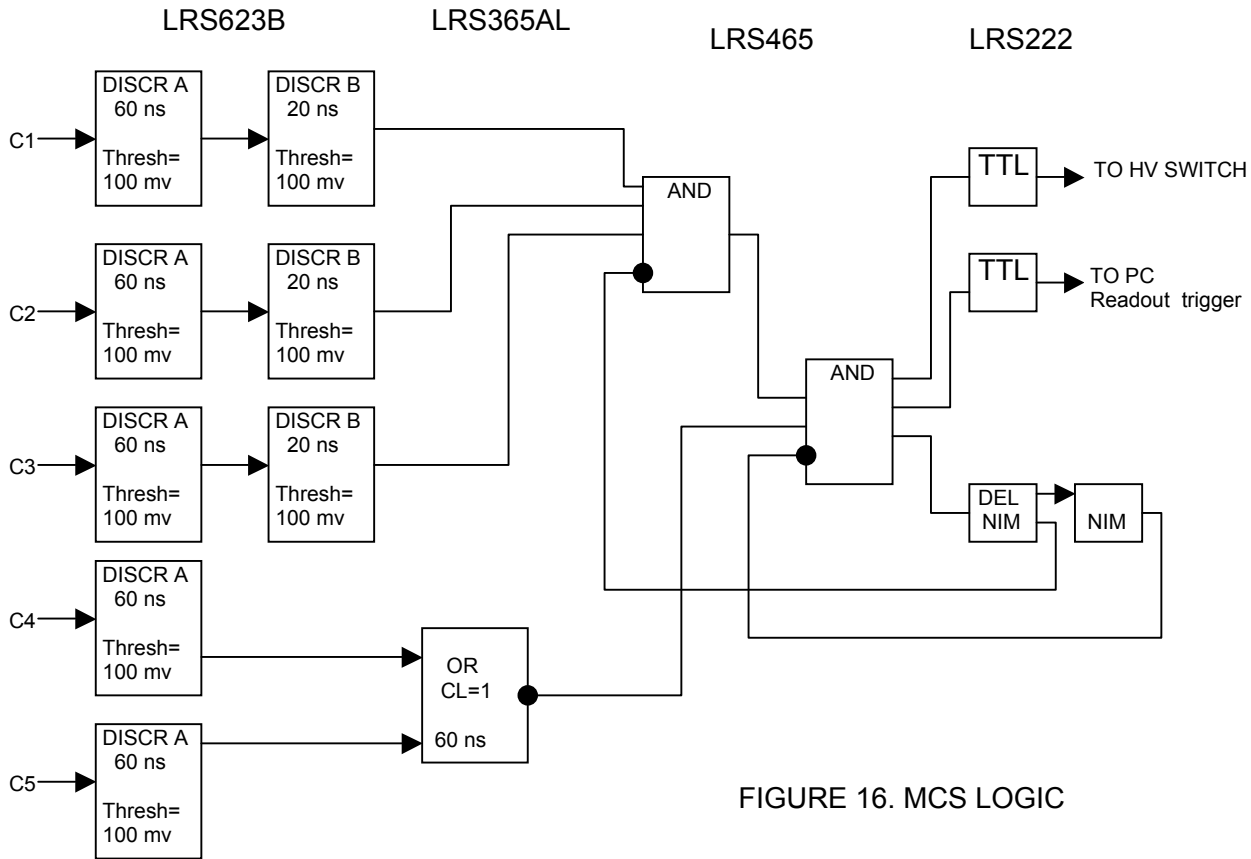


FIGURE 16. MCS LOGIC

To provide enough time between events for the PC to read the digitizer and write its output, dead-time is generated by another Lecroy 222 module. The requirement can be as much as 30 seconds which is more than you can do with a single gate generator. The DEL output at the end of the first gate starts the second gate. Two other LecCroy 222 channels (one dual module) are used for TTL signals to (a) actuate the HTS150 HV switch and (b) signal the video digitizer in the PC to grab a frame. The lengths of these TTL signals are not critical; 50 nanoseconds is a good setting.

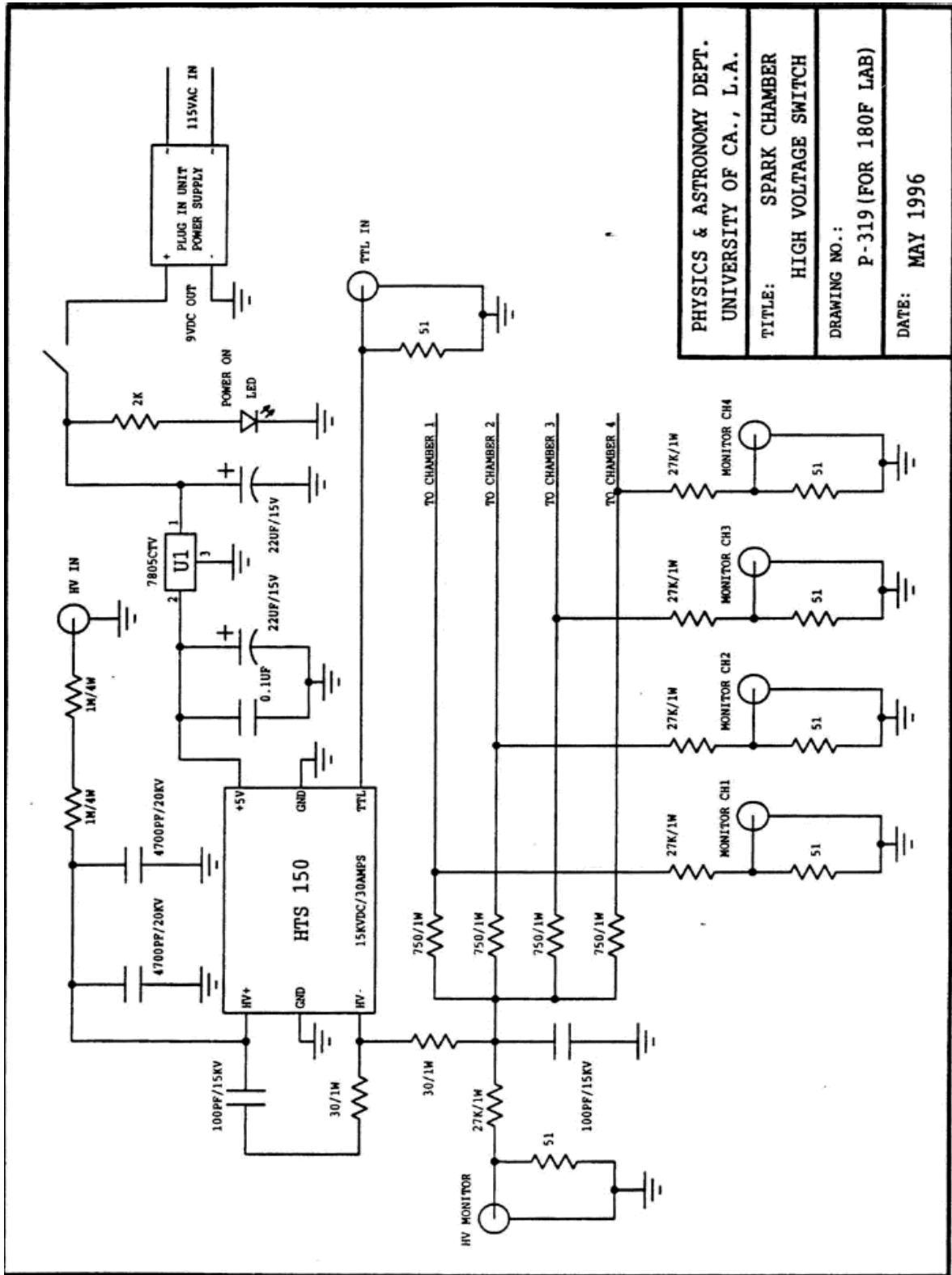
The optical spark chamber is a very direct though antiquated way to observe tracks. A charged particle leaves an ion trail in the chamber gas, and if a strong enough electric field is applied a spark will form along the ionized path. To avoid continuous discharge, the electric field must be pulsed as the result of a trigger signal. In the days when these chambers were used in research, a thyratron tube or a sparkgap functioned as a HV switch to dump the charge on a capacitor across the parallel-connected chambers. In the 180F experiment, we use a mosfet high voltage switch manufactured by BehlkeElectronic GmbH and marketed in the US by Eurotek, Inc., USA in

Morganville NJ. The designation is HTS150 with option of fixed pulse length of 3 microseconds. The switch is rated for 30 amperes at 15kVolts.

A HV pulse distribution and isolation circuit (Figure 17) designed and built by Y. Shi is mounted in a panel on the experiment frame near the 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 discharge at somewhat different times; the first spark usually occurs about 1 microsecond into the pulse. Rise time is a few hundred nanoseconds. The purpose of the isolation circuitry is to prevent the first-firing chamber from taking all the stored charge. A spark in the first chamber effectively short-circuits its electrodes. Its isolation resistor prevents this short being connected across the switch output. Thus the HV pulse is maintained on the remaining chambers so that they also will spark. The chambers work very reliably at about 5 kV. This corresponds to a reading of about 16 volts on the meter.

Spark quality is greatly affected by chamber gas purity. Bottles may fluctuate in quality. With air in the chambers, you will see no sparks at 6 kV. As helium flushes the chambers, sparks will appear in one chamber at a time. It may take an hour or two for the chambers to stabilize.

Although you can easily see the sparks, you must measure their coordinates and therefore need to record a picture, either photographically or electronically. We use a Panasonic WV-BP504 camera with sensitivity rated at 0.08 lux. With good quality gas, the fully open lens aperture gives images that spread more than necessary. However, it is wise to start with the lens open and only after observing some recorded data to adjust the aperture down. Because the sensitive CCD array can be damaged by excess exposure to light, the lens should be capped or else its aperture should be reduced when the room lights are on. You can connect the camera to a large video monitor and verify that it points toward the array of chambers. During data taking the apparatus is operated in the dark inside a Faraday shield. The sparks are the source of light. They also make electrical noise that is isolated by the Faraday cage from the other experiments and from your data acquisition computer.



PHYSICS & ASTRONOMY DEPT.
 UNIVERSITY OF CA., L.A.
 TITLE: SPARK CHAMBER
 HIGH VOLTAGE SWITCH
 DRAWING NO.: P-319 (FOR 180F LAB)
 DATE: MAY 1996

Figure 17. Spark Chamber high voltage switch control. (Designed by Y. Shi)

The video camera is interfaced to a digitizer card on the AT bus of a PC. A simple BASIC software program imports each picture into the PC and writes pixel data to a file. The program has two modes: SCAN and RUN. The SCAN mode is intended to be used during setup and troubleshooting; you see events displayed on the PC monitor, but they will not be recorded.

The SCAN mode should not be confused with the data quality monitor program discussed in the following section IV.

III. Fast Electronics

A. Signal Transmission

All the logic circuits in the 180F experiments are 50Ω systems. The output and input impedances of the logic modules are 50Ω and the cables, both LEMO and BNC, have a characteristic impedance of 50Ω . To see why this is important, I will derive the wave equation for a typical *lossless* transmission line; it does not quite confront 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. I 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 I lump the inductance and capacitance into discrete components and I build up the long cable 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!

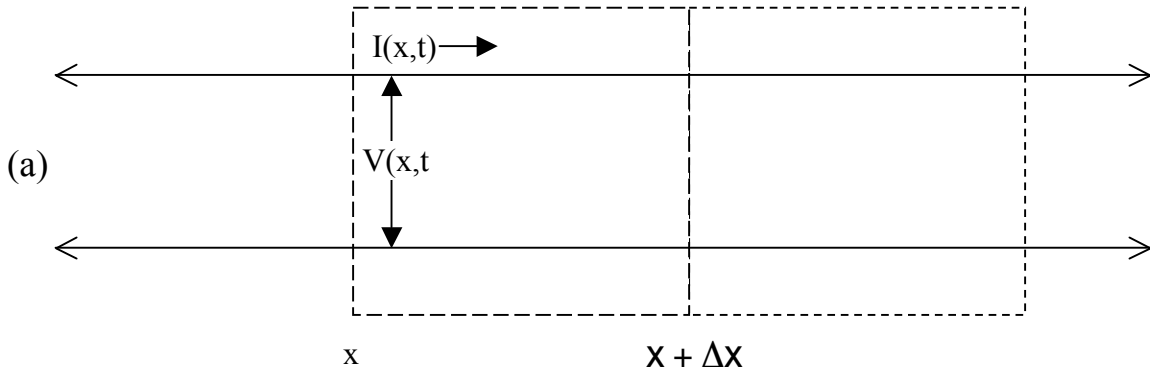
The cable is characterized by its capacitance per unit length C_ℓ , and its inductance per unit length L_ℓ . The discrete components of the T are the capacitor $C = C_\ell \times \Delta x$ and the inductor $L = L_\ell \times \Delta x$. The current $I(x,t)$ and potential $V(x,t)$ change by small amounts 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 $I(x,t)$, for the moment I need the

charge on the capacitor, so I will introduce the charge per unit length, λ , and write

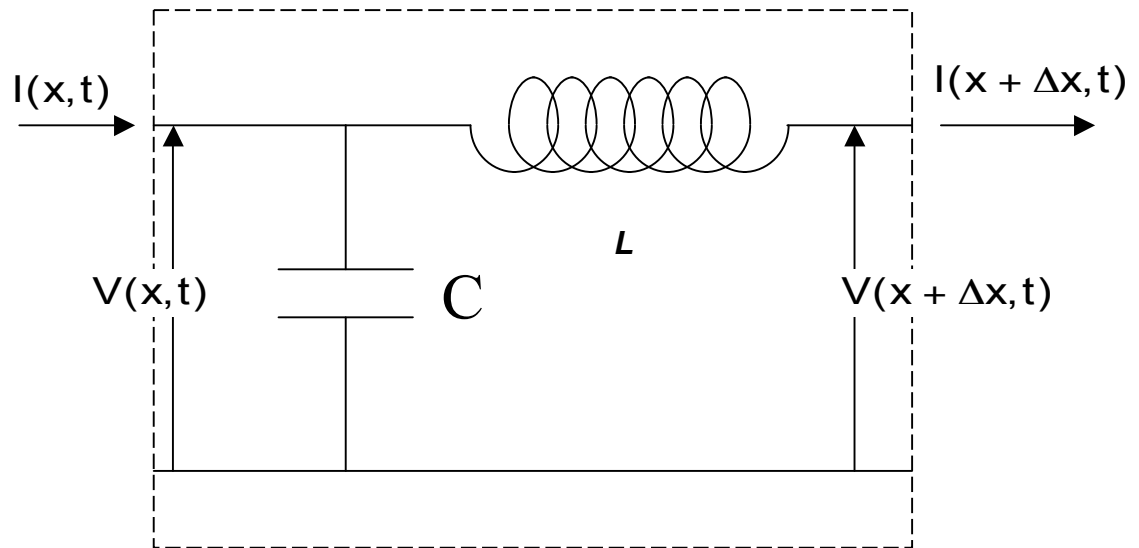
$Q(x,t) = \lambda(x,t)\Delta x$. In a short time interval, Δt , the charge that flows into the little T input side is $I(x,t)\Delta t$ and it can go to only two places, to charge C or to the output of the T.

Figure 18

Transmission line, lumped parameters



(b)



To put this in the language of 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 :

$$I(x + \Delta x, t) \approx I(x, t) + \frac{\partial I}{\partial x} \Delta x \text{ and you get } \frac{\partial\lambda}{\partial t} + \frac{\partial I}{\partial x} = 0. \text{ Take } \frac{\partial}{\partial t} \text{ of Eq. 2: } \frac{\partial\lambda}{\partial t} = C_\ell \frac{\partial V}{\partial t}$$

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:

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

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.

End effects are not too difficult to understand. Let's look at the case where $V(x,t) = f(x-ut)$. From

$$\text{Eq.(4): } \frac{1}{C_\ell} \frac{\partial I}{\partial x} = -\frac{\partial V}{\partial t} = uf'(x-ut); \text{ f' denotes differentiation of f(y) with respect to its argument}$$

$$y=x-ut. \text{ Thus we have for the current: } \frac{\partial I}{\partial x} = uC_\ell f'(x-ut)$$

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

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 I set it to zero for pulses.

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

This looks like Ohm's law for simple direct currents. More importantly, now we know 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 another 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 can always be replaced by its equivalent circuit to study the remainder of the circuit. Suppose 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: $V(x = x_0, t) = 0$. I 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 that $I(x = X_0, t) = 0$. 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.

B. Logic Modules

B.1 Discriminators

These modules convert the analog signals from the phototubes 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 discriminator (eight channels) 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 a signal out when many 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 vitiate the 50Ω termination and produce reflections at the minimum.

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-volt reading means the threshold is set to 100 millivolts. The LRS 4608C is direct reading; what you see is what you get.

Discriminator speed has two somewhat different accepted definitions: (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. (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. In experiments with cosmic rays, a too high event rate is not a problem.

“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 slew 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 phototubes that because the transit time through the dynode chain obviously 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.

B.2 Coincidence Units

We use two kinds of modules labeled coincidence unit. The model 465 which has three sections, 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. A second type of coincidence unit is used for pairs of signals. Each of the four channels of the model 622 coincidence unit can produce either the AND or the OR of two inputs, depending on a switch setting. Each channel of both module types has its own output width adjustment.

B.3 Majority Logic Unit

The LeCroy model 365 modules are more flexible than the coincidence units, but have only two channels. The coincidence level defines how many inputs must be true to make an output, while the “OFF” selection allows any channel or combination to be “pinned off”. There is also an old model 165 unit that can handle five inputs.

Both majority logic units and coincidence units are used in constructing the boolean logic of your triggers. What makes the trigger logic more difficult than implementing simple logical expressions is that the input signals must be in time, and must have the appropriate durations.

B.4 Jorway Scaler

A scaler is used to count pulses. The Jorway nnnn is a dual unit which is used for making high voltage plateau plots for the phototubes and for cable delay curves to adjust relative timing of the counters. The sections operate independently but there are inputs for external start/stop and reset. These signals can be chained so you can control both sections simultaneously, as is obviously necessary for these two applications.

IV. Computer Programs

Data acquisition is done with 486-class PC's acquired in the Fall quarter 1996. The DA programs run from a DOS command line. The PC's all run Windows 3.11, are on subnet 64 of the Physics/Astronomy department, and can communicate via TCP/IP. You can TELNET or FTP outbound anywhere from the DOS command line. The PC's do not respond to TELNET or FTP incoming requests. The data analysis programs are stored on the hepsun workstations, two of which (hepsun6, hepsun7) are in the 180f lab. There you can make histograms and run the physics analysis workstation (PAW) software.

A. μ^+ experiment

The program PCPLUS is the data acquisition routine; it runs on the PC, and is written in BASIC. FTP is used to transfer data to one of the unix workstations. To transfer data, you type (not case

sensitive): ftp 169.232.152.21 or ftp 169.232.152.22. There is no name server for the PC's so you have to use the numerical domain name.

Within a few seconds you will see a Username: prompt. Log in with the response p180f. Respond to the password with fall03, which does not echo. Once logged in, you will be in the p180f directory. Change your directory to ~p180f/muplus. The language is an awkward mix of DOS and unix, but you do not need very many commands. In the sample dialog below **boldface** is what you type on the keyboard. Comments are given in [square brackets].

It might go as follows::

ftp> pwd	[This command will show your current directory]
ftp> "/usr/hep0/p180f" is current directory	[This is the home directory; same as ~p180f]
ftp> cd muplus	[Change to the subdirectory ~p180f/muplus]
250 CWD command successful.	
ftp> !dir	[List the files in the current path on the PC]
ftp> dir	[List the files on the Sun station you logged into]
ftp> put 10jan00.dat	[Transfer data from PC to Sun]
ftp> quit	[Stop ftp and log off the Sun]

A program called HISTO is also listed below, along with some sample data. HISTO makes the distribution of TDC1 and TDC2 data. In the μ^+ experiment TDC1 designates the up and TDC2 the down decays. These histograms can then be fit by signal plus backgrounds using PAW.

In HISTO the raw data are plotted in histograms 100 and 200, for the two TDC's. The bins are single TDC counts of 20 nanoseconds. Usually this resolution is not needed and is actually too fine. The μ^+ mean-life is 2.2 microseconds, and to measure it, bins of 200 nanoseconds are small enough. To detect the spin precession, 200 nanoseconds is also appropriate, giving about ten data points per mean-life which allows one complete period in about 10 bins. The magnet current was chosen with this precession rate in mind. The reason to choose bins as large as possible is to reduce statistical uncertainty. Histograms 101 and 201 are coarser. In addition, if you choose, you can arbitrarily rebin an existing histogram in PAW.

HISTO also makes background plots based on the events beyond ten meanlifetimes where one would expect only accidentals. These accidental events are prorated and plotted in histograms 300,301, 400,401 so they can be subtracted in PAW if you want to step through the analysis. Histograms 1,2,3,4 are culled from the first 40 bins of histograms 101,201,301,401. Histogram 3 is a background-subtracted difference between up and down decays. In addition the ordinate is corrected for the muon exponential decay in order to make the precession oscillation more visible. Histogram 4 contains the statistical errors on the bins of histogram 3. For presentation, you can use PAW as follows on the output of HISTO:

```
PAW>}h/fil 1 magnet.dsh      [Read histograms from HISTO output file]
PAW>}hi/pl 1                 [ plot ``up" decays]
PAW>}hi/pl 2                 [ plot ``down" decays]
PAW>}ve/cre h4(40)           [ Define a vector array with 40 elements]
PAW>}hi/get/co 4 h4          [ Fill vector h4 with histo 4 contents]
PAW>}hi/put/er 3 h4          [ Fill error array for histogram 3]
PAW>}hi/pl 3                 [ Plot histo 3}
PAW>
```

In a normal run there are more "up" than "down" decays. A source of these extra events is from muons that stop and decay in counter 3. Down decays of this kind will either be vetoed because the positron is vetoed by C3 and because the target is thick enough to stop the maximum energy positron from ever getting to C4. Up decays in C3 are only suppressed because C3 is much less efficient for stopping muons than is the target. To correct for this background you must to a run with the target out. To make a meaningful correction you must know the running time of both data and target-out. The stop and start time of each run is recorded on the data file.

It will take several weeks of running to get good enough statistics for the precession measurement. You can use the **cat** command to combine small data files.

B. μ^-

In the μ^- experiment the TDC has 8 channels. The recommended assignment of channels is shown in Figure 13. C3 goes to TDC1 and provides a clean source of up-decays. C4 has more background but is mainly down-decays. C5,C6,C7, and C8 can be either decay or capture events depending on your use of C4. If C4 detects a particle the event is a decay and if it does not the event is a capture. Use **MUDAQ** for data acquisition. This program reads all channels of the 8-channel TDC. It has both a test mode and a run mode. Transfer data files to the unix cluster with

FTP just like the μ^+ experiment. Use **histominus.exe** to make a histogram file from the data file. Read that file with **PAW** and make plots and analyze them.

Analysis of the neutron counter data is complicated by the background, especially that which appears to be generated internally. The large, nearly flat tails obvious in histograms 117, 217, 317, and 320 can be corrected by subtracting (after normalization) the ones taken with the minimum bias trigger. While this does not completely clean up the neutron detector TDC plots, the process does demonstrate an absence of correlation with incident muons.

C. Spark Chamber

The spark chamber programs are listed below. The first one, going by the name **SPARK**, runs on the PC. It cycles in a short program loop until it receives a signal to read out the memory of the video digitizer card. The digitizer is on the PC's internal bus. It has two inputs from the experiment: (1) a TTL trigger line and (2) the composite video signal from the camera which continuously transmits vertical and horizontal synchronization pulses along with the analog video. This is converted to addresses of illuminated pixels plus ADC data for each pixel. **SPARK** writes a list of pixel addresses with ADC values to a file on the PC's hard disk. Each scattering event is contained in a separate numbered file.

Event files are transferred to hepsun6 or hepsun7 with FTP, the standard file transfer program using the TCP/IP protocol. Use of FTP was described in section A. Three programs digest the raw data files. The first is called **FIND_Y_BANDS**. Its purpose is to plot the y-coordinates of raw pixel data which (except for noise) obviously concentrate in narrow horizontal bands around the chambers. It also makes four plots of ADC output. You can display these plots with PAW to see where to set cuts to remove background.

The analysis program is called **bends**. The source code is in the file **bends.f**. If the camera or any chambers have moved since the program was most recently compiled and linked, the numbers must be updated. There is a short "script" that you have to run to produce a new **bends.exe**. This program produces a histogram of projected scattering angles that you can compare with the theoretical prediction.

There is also a data quality monitor program called **scan.exe**. The input to **scan.exe** is a collection of **.evt** files that are read and plotted to look as much like raw data as possible so that you can select clean events for analysis with **bends.exe**. **scan.exe** writes two files for each event. One is a **PAW**-readable scatterplot and the other is a **.kumac** file that **PAW** can execute to plot the event on the computer screen. Thus, when **scan.exe** reads the event file **1201.evt** it writes **1201.dsh** and **1201.kumac**. Your procedure is to put the event files into a directory. Then run **scan.exe** where you have to enter the filename of the first event. **scan.exe** will read the events in order and write it out. After that you launch **PAW** and do “exe 1201” at the command line; the next display you see plots all the pixels for event 1201. You then have the opportunity (in a separate window) to copy the file 1201.evt to another directory where you collect good events on which to run **bends.exe**. Following is an example of the **PAW** display of the output file from a **scan.exe** run:

The line segments approximately intersect the clusters of pixels as recorded from the camera output. This event is reasonably clean and the lines intersect between the two inner chambers as they must to be associated with a real scattering in the Pb plate. This event is a suitable candidate to be passed to **bends.exe**.

