XI: Cosmic Rays

I. References

E. Fermi, *Nuclear Physics*, Notes compiled by Orear, Rosenfeld, and Schluter, Revised Edition, The University of Chicago Press, 1950, chapter on Cosmic Rays, pp. 215-224.

Review of Particle Properties: (http://pdg.lbl.gov/). See the review section on Cosmic Rays under Astrophysics and Cosmology.

II. Preparatory Questions

(must be answered in lab book before experiment is started and signed by instructor or TA)

Whenever a cosmic ray particle traverses the scintillator, a burst of light is produced which activates the PM tube to produce a pulse. The rate R of such pulses can be estimated from the value of $J_{\perp}$ and the area of one of the counters:

$$R = J \times (\text{Area}) = \left(1.14\,\text{x}\,10^{-2}\right) \times \left(2780\,\text{cm}^2\right) \approx 32/\text{sec} \qquad \text{XI-1}$$

The actual rate of pulses is several orders of magnitude greater than this and very steeply dependent upon the voltage. These "noise" pulses arise from electrons liberated from the photocathode by a combination of thermal emission and electric field emission. In the latter case electrons are pulled from the photocathode by the applied electric field. Thus, R(noise) >> R.

A. Show that the accidental coincidences involving noise pulses only from two counters A and B are given by the formula

$$R_{AB}^{(\text{accidental})} = 2 R_A^{\text{noise}} R_B^{\text{noise}} \tau \qquad \text{XI-2}$$

where τ is the maximum allowed time difference between pulses from A and B for which a coincidence will be recorded.

B. If counters A and B are set one on top of the other in close contact and the area of each is 2780 cm^2, what is the rate of true coincidences due to cosmic rays?

C. If $R_A^{noise} = R_B^{noise} = 1$ kHz and $\tau = 30$ nanoseconds, what is the accidental coincidence rate? Compare this with B.

D. What would be the effect on the accidental coincidence rate if we had three such counters A, B and C in 3-fold coincidence?

III. Introduction

The first indication of cosmic rays came from the observation of a residual current in ionization chambers after all known sources of radiation had been removed. These observations were reported by Elster and Geitel, and independently by Wilson, in 1900. Wilson speculated that here must be a species of radiation far more penetrating than x-rays, or radiation from radioactivity, and that this new radiation could come from extra-terrestial sources. Further verification came in 1911 in an experiment by Hess who used a balloon-borne pressurized ionization experiment. He found a slight decrease in the radiation at low altitudes, followed by a rapid increase up to 5 km, the highest altitude reached by the balloon.

The earth is under constant bombardment by energetic protons and heavier ions that are accelerated and trapped by galactic magnetic fields. This primary cosmic radiation produces secondary particles in collisions with atomic nuclei in the upper reaches of the atmosphere. It is this secondary cosmic radiation which penetrates the thick blanket of air and reaches us at sea-level.

The primary cosmic radiation is isotropic, that is, its intensity is the same for all possible directions. The radiation that reaches us at sea-level depends upon the zenith angle θ. The zenith is the direction perpendicular to the earth's surface. The angle θ measures the direction of the line of flight of an entering cosmic ray particle and the zenith.

As one would expect, the intensity of the radiation is maximum at $\theta = 0$ because the steeper rays correspond to traversals of greater distances in the earth's atmosphere. These steeper-going particles are subjected to a greater chance of absorption and decay than the particles that are produced directly overhead.

The angular dependence is well represented by the formula:

$$J(\theta) = J_{\perp} \cos^n \theta \qquad \text{XI-3}$$

The power of cos θ is observed to vary from n = 2 for the more energetic particles, to n = 3 for the so called 'soft' component which is more readily attenuated in the atmosphere.

The perpendicular component, $J_{\perp}$, depends somewhat on the latitude. It has been measured at our latitudes and its value is $J_{\perp} \sim 1.14 \cdot 10^{-2}$ cm^{-2} sec^{-1} steradian^{-1}.

In this experiment you will measure $J_{\perp}$. You will also identify two components of cosmic radiation and measure their relative abundance. There is a soft component consisting mainly of electrons and heavier particles of low energy. There is also a hard component consisting of energetic muons. Muons are charged particles that are about 200 times more massive than electrons. They are in every other respect like electrons. Like electrons, they do not undergo nuclear interactions, and are therefore far more penetrating in matter than protons or neutrons. Electrons by contrast are readily absorbed in matter. The principal mechanism for energy loss by electrons is the production of electro-magnetic radiation whenever an electron is accelerated in the electric field of an atomic nucleus. The frequent encounters with atomic nuclei cause an average energy loss rate for an electron of energy E given by the following formula.

$$\left(\frac{dE}{dx}\right)_{\text{radiation}} = -\frac{E}{X_0} \qquad \text{XI-4}$$

In this expression, dE is the average energy loss when an electron traverses a distance dx of some material. The parameter X_0 is the so-called radiation length, which depends upon the atomic number of the material. High Z materials, such as lead, have a short radiation length. Some typical radiation lengths are listed in the following table

Material	**Z**	**X_0 (g/cm^2)**	**X_0 (cm)**
C	6	43.3	18.8
Al	13	24.3	8.9
Fe	26	13.9	1.77
Pb	82	6.4	0.56

The radiation lengths are given in two units: the familiar centimeter, and the density adjusted unit of grams/(centimeters)^2 (length × density).

The above differential equation can be integrated to give the average energy of an electron after penetrating a finite distance x.

$$E(x) = E(0)\exp\left[-\frac{x}{X_0}\right] \qquad \text{XI-5}$$

This mechanism for energy loss is far less effective for heavy particles like the muon for which the acceleration in the nuclear Coulomb field is reduced by a factor 1/200. It must be pointed out that the electric charges of the muon, μ^- and its anti-particle, μ^+ are the same as for those of the electron e^- and positron e^+ (1.6×10^{-19} Coulombs).

The principal mechanism for energy loss of energetic heavy charged particles in matter is the energy lost to atomic ionization and excitation. At high energies, this loss rate is nearly constant over a large range of energy.

For lead, for example:

$$\left(\frac{dE}{dx}\right)_{\text{ionization}} = 12.8\ \frac{\text{MeV}}{\text{cm}} \qquad \text{XI-6}$$

(1 MeV = 10^6 eV = 1.6×10^{-13} Joules)

Thus, we can compare the energy losses of an electron and a muon, each with an initial energy 10^3 MeV in traversing 5 centimeters of lead.

Energy loss of the electron $= 10^3\ \text{MeV}\left(1 - \exp\left[-\frac{5\,\text{cm}}{0.56}\right]\right) \approx 10^3\ \text{MeV}$

Energy loss of the muon $= \left(\frac{12.8\ \text{MeV}}{\text{cm}}\right)(5\,\text{cm}) \approx 64\,\text{MeV}$

The electron is seen to lose essentially all of its energy whereas the muon loses only 6.4% of its energy. In fact the electron will lose almost all of its energy irrespective of how much energy it started with. Therefore, an electron of any energy will be effectively attenuated in 5 cm of lead.

The actual process of absorption also involves the absorption of the radiation produced by the electrons. There are two processes to consider for very energetic electrons in matter:

A. radiation produced in the Coulomb field of atomic nuclei:

$$e^- \rightarrow e^- + \gamma \quad \text{and} \quad e^+ \rightarrow e^+ + \gamma$$

B. production of an electron and a positron in the Coulomb field of atomic nuclei:

$$\gamma \rightarrow e^- + e^+$$

Energy and momentum conservation prohibit both processes in vacuum. The processes can, however, occur in the Coulomb field of an atomic nucleus where some of the initial energy and momentum can be transferred to the atomic nucleus.

The probability for an energetic $e^\pm$ to produce a γ in traversing dx is simply dx/X_0. The corresponding probability for an energetic γ to produce an e^+e^- pair is $(7dx/9X_0)$.

The actual absorption of the initial electron involves a sequence of these processes. The electron produces a gamma that in turn produces a pair. Each of the three electrons ($2e^+,e^-$) will produce gammas which produce yet more electrons. The numbers of electrons and gammas increase rapidly with increasing penetration. However, as their numbers increase, the average energy of these particles decreases until they can no longer produce new electrons or gammas. The process thereby terminates and the initial energy is fully dissipated in the absorber in the form of atomic excitation and eventually as thermal energy. This process, in which large numbers of secondary particles are produced, is called shower production. The initial electron and all of the secondary electrons, positrons and gammas constitute a shower.

The following simple model can be used to calculate some of the main features of showers. Replace the factor 9/7 with 1 in the expression for the pair production probability and represent the penetration distance in units $X_0 \ln(2)$.

The number of shower particles (electrons, positrons and gammas) at distance $t=x/(X_0 \ln(2))$ is simply $n = 2^t$. The average energy per shower particle at t for a shower initiated by an electron of energy E is simply

$$E_t = \frac{E}{n} = E\,2^{-t} \qquad \text{XI-7}$$

Let ε be the energy below which processes 1) and 2) can no longer take place. The maximum penetration X_{max}, of the shower is then given by

$$\ln(\varepsilon / E) = -t_{\max} \ln(2) = -\frac{X_{\max}}{X_0} \qquad \text{XI-8}$$

so $X_{max} = X_0 \ln[(E)/\varepsilon]$.

The critical energy ε in lead is about 7 MeV. For an energetic electron with E = 100 GeV (1 GeV = 10^3 MeV) the maximum penetration of a shower produced in lead is (0.56 cm) $ln(10^5/7)$ = 5.36 cm.

In the experiment, cosmic rays will be detected in a telescope consisting of four scintillation counters so arranged that downward-going cosmic ray particles will traverse all four counters. These counters respond to the passage of even a single particle by the generation of a brief pulse of electric current. The passage of a particle through all four counters causes the production of four such current pulses all at the same instant of time. The receipt of four pulses in time coincidence is the signature of a passing cosmic ray. One measures the rate of 4-fold coincidences.

The counters are arranged in two levels. S_1 and S_2 are paired to form the top level and S_3 and S_4 form the bottom level. Check the distance between the two pairs of counters. The attenuation of the cosmic rays can be studied by introducing lead between the top and bottom pairs of counters. The cosmic ray rate is measured for each thickness of lead starting with zero thickness and increasing in steps up to twenty centimeters. The lead will attenuate the soft component, but will have little effect upon the muons. One can expect, therefore, a rapid initial drop in the cosmic ray rate as the thickness of the lead layer is increased until the entire electron component is stopped. Thereafter the rate should be nearly constant as the thickness of lead is further increased. Any further attenuation of the muon component can be attributed to the 'ranging out' of the lowest energy muons, which in losing energy through atomic excitation in the lead, eventually comes to rest.

The data will be used to determine the quantity $J_\perp$, the cosmic ray flux at $\theta = 0$, which was discussed earlier. This quantity can be represented as a sum of contributions

$$J_\perp = J_\perp^{\text{hard}} + J_\perp^{\text{soft}} \qquad \text{XI-9}$$

You must determine both $J_\perp^{\text{hard}}$ and $J_\perp^{\text{soft}}$.

You will need to calculate the acceptance of the telescope, and to measure the actual rates for hard and soft components in the telescope. Since the soft component rate is significantly diminished by the overburden of concrete in the building, a correction will have to be made in order to extrapolate the soft component rate to ground level without overburden. The procedures for data taking and analysis will be described in section V.

IV. Apparatus

A side view of the apparatus is shown in Fig. XI-1. There is a top pair of scintillation counters, S_1 and S_2; and a bottom pair, S_3 and S_4. Lead plates and bricks are provided and these can be conveniently stacked on the table top between the two pairs of counters.

Each counter is connected via coaxial cables to the fast logic system in which the signal pulses will be processed and 4-fold coincidences will be detected and recorded.

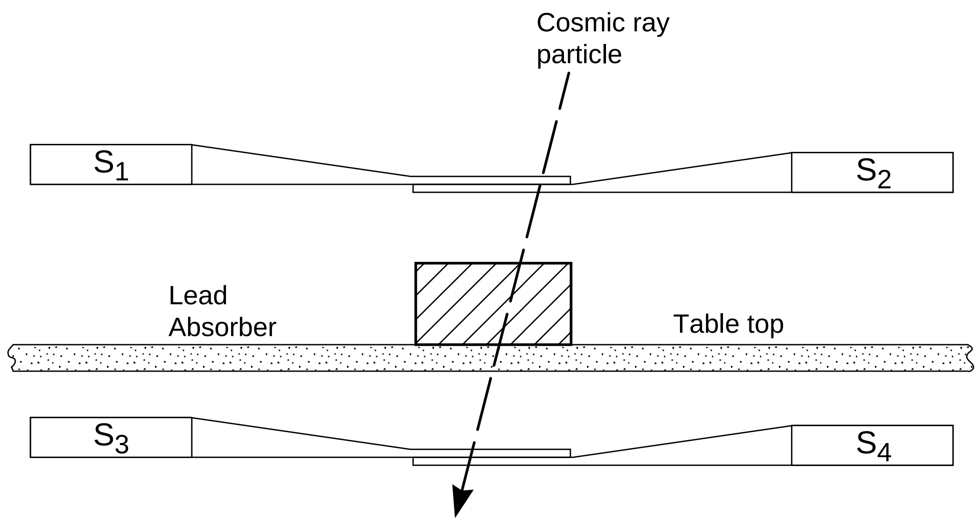

Figure XI-1

Each part of the apparatus will be described in the following paragraphs:

A. Scintillation Counter: The counter consists of a slab of scintillation plastic (12” × 36” ×1”) in which some of the energy deposited by a traversing charged particle is converted into light via thermal excitation, and subsequent de-excitation of phosphorescent materials in the scintillation plastic. The typical de-excitation times are about 10^{-8} seconds, and about 1300 photons are produced whenever an energetic muon or electron passes through the counter. The scintillator is optically connected to a lucite light-guide which conducts some of this light to the entrance window of a photomultiplier tube (PMT). The photomultiplier is described in Experiment VII. The particular tube used in this experiment is the high-gain Hamamatsu R329-02, which operates at a voltage of about −1800V. **DO NOT EXCEED 2300 V**, and be sure the HV supply is set to negative. The typical light collection efficiency of a counter of this design is about one percent. The quantum efficiency of converting photons into photoelectrons at the photocathode of the tube is ten percent. The average number of photoelectrons is therefore $(1300)\times(0.01)\times(0.10) = 1.3$. When the voltage on the tube is high enough so that even single photoelectrons are detected, the efficiency for detecting cosmic particles becomes nearly 100%.

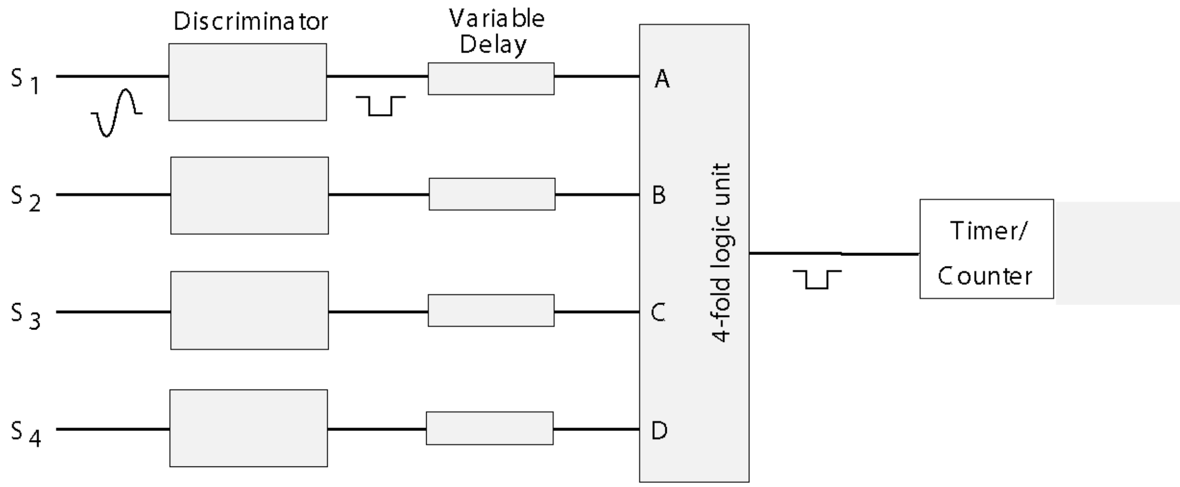

Figure XI-2

B. Coaxial Cables: The short duration signal pulses (< 10^{-8} seconds) must be conducted in coaxial cable transmission lines. These cables have an excellent high frequency response. The signal speed is about 9 inches per nanosecond, as compared with the speed of light, which is 12 inches per nanosecond. The cable impedance is 51 **Ω**. Care has been taken to use the same cable lengths to each counter.

C. Discriminator: The raw PMT pulse must be shaped to produce a standard logic signal of about -0.7 Volts. The discriminator generates a logic pulse of adjustable width whenever the input PMT pulse exceeds a pre-set threshold value. This value is set by the threshold potentiometer (labeled T). The threshold level can be read with a voltmeter where the meter reads 10 times the actual value. The width of the logic pulse is determined by the potentiometer labelled W. The relationship between the input PMT pulse, and the resulting logic pulse is represented schematically in Fig. XI-3.

D. Coincidence Circuit: The output from each of the four discriminators is connected to an input channel of the 4-fold coincidence unit through an adjustable delay. The delay can be adjusted in steps of 0.5 ns up to 32.5 ns by the switch selection, which introduces corresponding cable lengths to the total delay. The coincidence circuit generates a logic output pulse (-0.7 V) whenever there is an overlap of the logic signals in all of the four input channels.

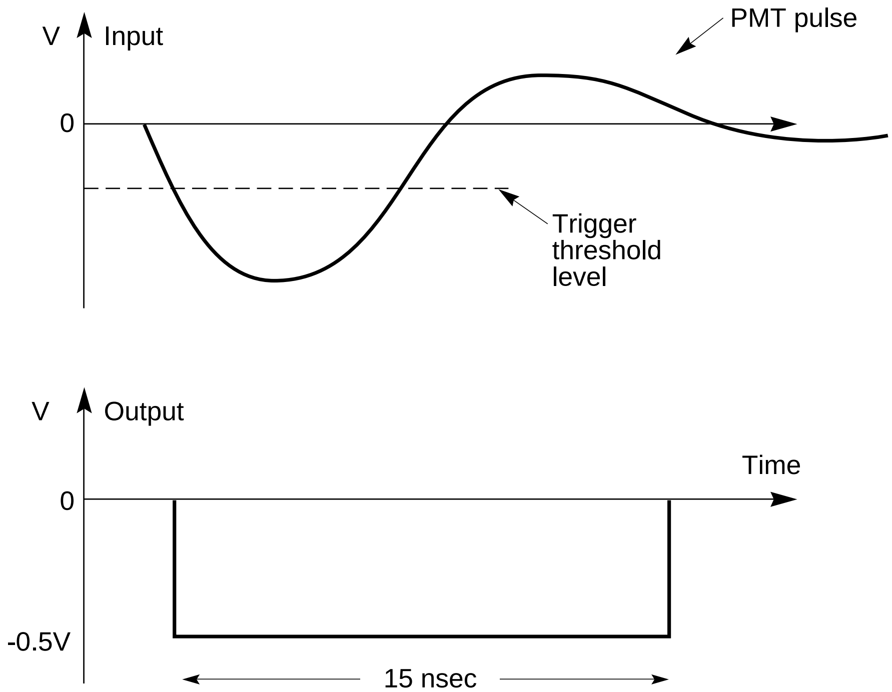

Figure XI-3

E. Timer and Counter: This unit consists of a counter and an adjustable timer. The timer controls the time interval during which pulses will be counted and is set by the INC M and INC N push buttons and the LED display. The selected interval is = $M \cdot 10^N \cdot$ TIMEBASE. The TIMEBASE SELECT gives the choices of 0.1 second and/or 1 minute increments providing the capability of time intervals from 0.1 seconds to 9×10^7 minutes. The input signal going into the timer/counter is negative.

V. Procedure

You should examine the entire apparatus to make sure that the fast logic is connected according to the schematic in Fig. XI-2, and that the PM takes are connected to the H.V. power supply through the four-fold fanout located just above the power supply at the back of the electronics rack. The signal cables are all RG58A/U; the H.V. cables are RG59/U.

1. The signal cable must be connected to the anode connection at the back of each counter.
2. Set the discriminator-trigger thresholds to approximately 70 mV. Reset the timer/counter. Note: each photomultiplier tube has different gain and noise characteristics, so setting all four discriminators to the same value may not be optimum. It is wise to look at the counting rates (with no coincidence) of the individual detectors and adjust the discriminators so that each detector counts at approximately the same rate before proceeding (you will likely find that detector #1 counts at a lower rate than the rest for the same high voltage, so you may need to reduce its threshold). You may also want to adjust the widths of the discriminators to optimize the coincidence timing.

3. Set the HV selection dial to 0, and turn on the power supply. Wait about 30 second and then turn up the HV to −1700 Volts. Switch the power to ON in the two other power supplies.
4. Set the S_3 and S_4 variable delay to O (i.e. all switches UP), and S_1 and S_2 delay to 2 ns in order to correct the lag between the arrival times at the top and bottom counters of a cosmic ray particle moving with the speed of light.

The entire system should be "in time"; that is, pulses produced by a cosmic ray particle traversing the four counters should reach the coincidence unit at the same time. You should be registering coincidences on the scaler at the rate of a few per second.

Trace signals through the entire system using the oscilloscope. Make sure that PMT pulses are present at the inputs of each discriminator, that these units are producing outputs, and that these outputs are present at the coincidence unit. It is very instructive to examine both the PMT pulses and the logic level pulses.

You must now set the HV so that all counters are fully efficient. Measure the coincidence rate for voltage settings from 1700 to 2300 in steps of 50 to 100 Volts. You should not exceed a setting of 2300 Volts. Use the Timer/Counter watch to count for fixed intervals of 1 to 2 minutes. Your data should look qualitatively like the following plot.

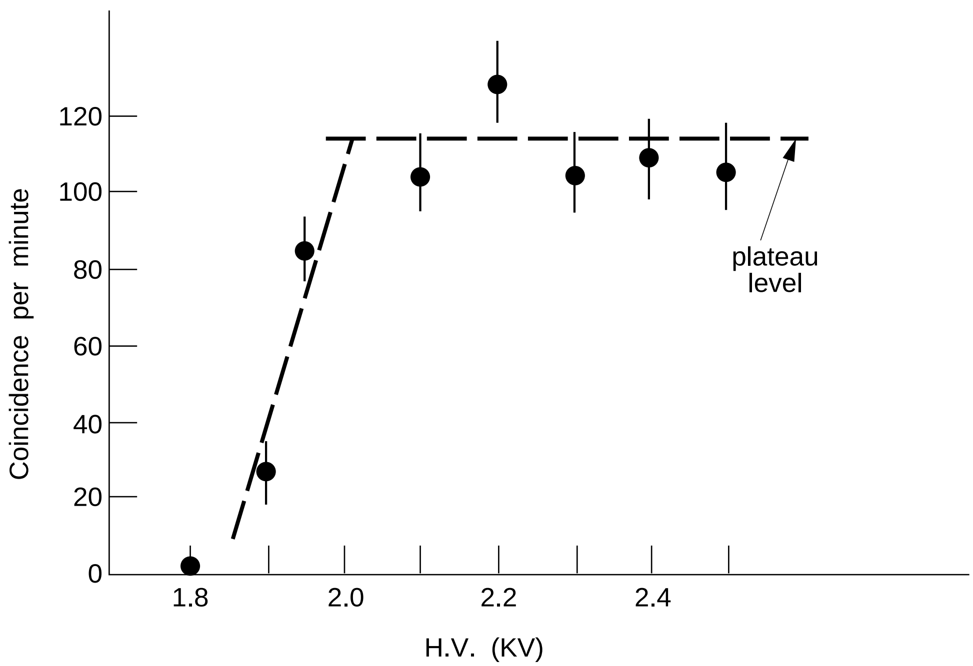

Figure XI-4

The data are plotted with uncertainties σ = sqrt(*N*), where *N* = the number of counts (see Bevington, p. 38 ff.).

One sees that the counting rate increases rapidly with voltage until it attains a fixed level. Any further increase of voltage does not produce more counts. In this plateau condition, the counters are maximally efficient: the corresponding rate is the actual rate of cosmic rays in the telescope. One sets the HV conventionally about 200 volts above the "knee" of the curve. With the voltage set to about 2000 the detection efficiency will be about 100% even if the voltage drifts by ± 100 Volts (Note: the curve in figure XI-4 is only for illustration, as it corresponds to a different detection system than the one you are presently using.)

You must convince yourself that the system is indeed in time. This can be done by shifting in fixed steps the time of arrival of one of the signals in the coincidence, and recording the counting rate. An example is plotted in Fig. XI-5.

In tracing out this plot, the delay of S_4 was increased in steps of 4 ns while the delays of S_1, S_2, S_3 remained at their original settings. Then the delay of S_4 was set to 0, and an additional delay was added to each of S_1, S_2, S_3 in steps of 4 ns. One can see that the count rate goes to zero when S_4 is out of time at ± 20 ns.

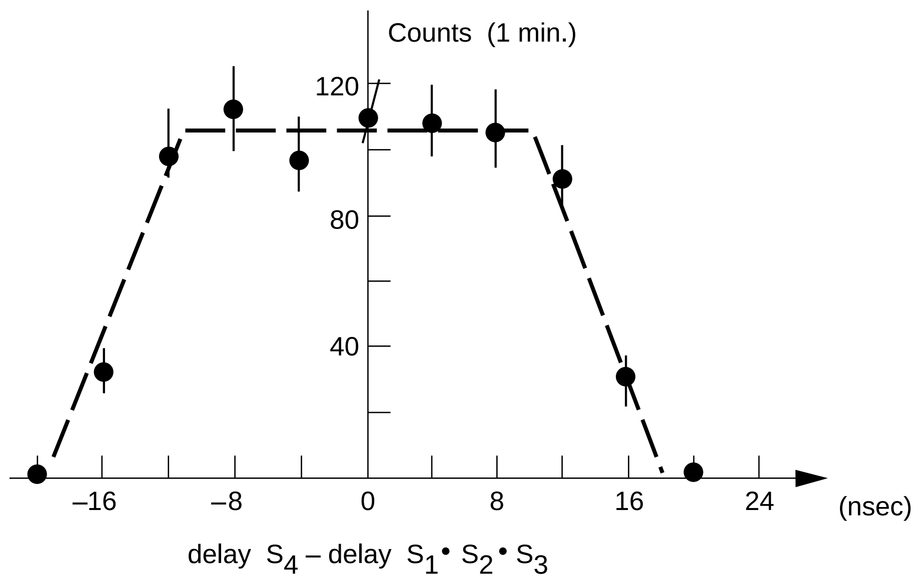

Figure XI-5

Restore the timing to the normal settings. You are now ready to do the experiment. Measure the counting rate for a fixed time interval sufficiently long to collect around 10,000 counts. This may take up to 30 minutes per data point. The corresponding statistical error for N = 2000 is sqrt(N) = 44.7. This should be good enough to see the small effects (10-20%) we expect to see in the counting rate as we increase the absorber thickness from 0 to 10 cm.

After collecting data with no absorber, stack the maximum thickness of lead on the table. Make sure you see a decrease in counting rate. Take data at various thicknesses by removing bricks and plates. Then take data at intermediate values by adding lead. This will help you isolate any temporal drifts in the electronics. Make 4-5 measurements in small steps up to 2.5 cm of lead, and take 3-4 measurements with at least 1 layer of bricks up to the maximum available (you can use 2 layers of bricks). You need enough data to fit two lines to the your results.

Compute the natural logarithms of these data, and make a plot vs. absorber thickness. Be sure to calculate the errors on the logarithm appropriately. Fit a straight line to the data for thickness greater than about 3 cm using a least squares fit. These are all muons. Fit the data below about 3 cm to a straight line and extrapolate to −3 cm of lead. This extrapolation is intended to correct for the loss of electrons in the concrete overburden of the building. The intercepts of both lines are respectively the logarithms of the total rate and the muon (hard component) rate. In order to determine $J_\perp$ you must compute the acceptance of the telescope in units of (cm^2-steradians).

The counting rate in a telescope consisting of two square detecting planes, each of area W, and separated by a distance h is given by the following formula:

$$R = J_\perp \int_0^{x1} dx \int_0^{y1} dy \int_0^{x2} dx' \int_0^{y2} dy' \frac{\cos^{n+2}\theta}{r^2}$$

$$\cos\theta = \frac{h}{r} \qquad \text{XI-10}$$

$$r^2 = (x - x')^2 + (y - y')^2 + (z - z')^2$$

Carry out the calculation for n = 1, 2, 3.

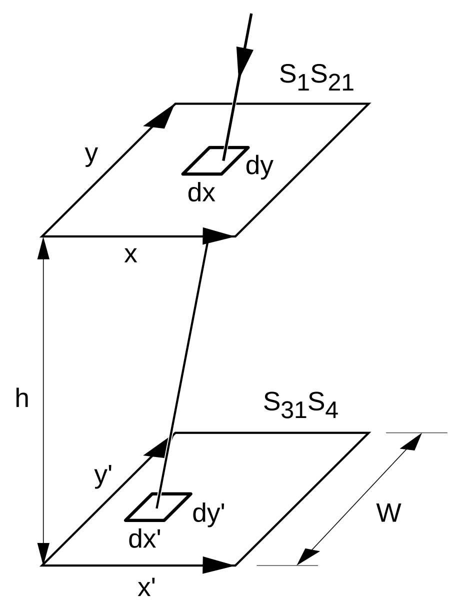

Figure XI-6

The calculation is done most conveniently computationally rather than analytically. See a numerical methods book. Or, you can use the Mathematica notebook Integral.nb available on the laboratory computers (written by Prof. C. C. Chang.) Use the resulting acceptances and the measured rate R to determine $J_\perp$. Propagate the dominant uncertainties. You should also estimate the statistical error in the extrapolation to −1 inch of lead and the uncertainty in the index n (±1) etc. Report a value, with errors for $J_\perp$ and for the ratio $J_\perp^{\text{hard}} / J_\perp^{\text{soft}}$.