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The CCRT: an inexpensive cosmic ray muon detector\*

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ABSTRACT

In this article the authors describe an inexpensive cosmic ray counter useful for physics demonstrations and experiments. Although many university departments use cosmic ray detectors as part of their upper division laboratory courses, these are often large and expensive devices requiring specialized equipment not usually accessible in high school and college programs. Our detector is very compact and can be constructed for about \$350 using commercially available materials and small scintillator panels that may be available (in limited supply) from Stanford Linear Accelerator Center (SLAC) and perhaps other accelerator laboratories. In the following, we provide detailed instructions for the construction of the detector as well as suggestions for its use in the classroom and laboratory.

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# 1. Introduction

## 1.1 HISTORY

The cosmic ray detector project described in this paper evolved during the annual Particles and Interactions workshop primarily for high-school physics teachers that is held at SLAC each summer. The original goal was to devise an experiment for the participants to illustrate the methods of high-energy experimentation and to demonstrate some high-energy phenomena. The first iteration of the project accomplished these goals with standard equipment that is in common use at accelerator laboratories, and it solicited the desire among workshop participants for a version of the experiment cheap and simple enough to be used in the classroom setting.

As a result, the authors redesigned the apparatus using more easily obtainable and cheaper components and materials, with special emphasis on manufacturing procedures that use only commonly available tools. Classroom safety was a consideration, resulting in the use of battery powered photo-multiplier tubes and electronics. Discarded scintillator panels, which can be obtained at SLAC in limited quantities, complete the system. A photograph of one of the completed setups is shown in figure 1.

## 1.2 COSMIC RAYS

The history of cosmic ray research can be traced to 1911 when researchers attempted to understand the mechanism responsible for discharging shielded electroscopes. Subsequent studies, at high altitude, demonstrated that the “discharging rays” causing the ionization responsible for the discharge were of extraterrestrial origin; hence the name “cosmic rays,” given by Milikan in the 1920’s. Cosmic rays reaching the Earth’s surface are now known to be secondary particles from “air showers” produced when high-energy, charged “primary” particles strike the upper atmosphere. These primary cosmic rays are protons and helium nuclei which range in energy up to  $10^{20}$  eV [1]. For comparison, the highest particle energy produced in accelerators on the Earth (such as the one at Fermi National Accelerator Laboratory) is a few TeV ( $10^{12}$  eV). There are also primary gamma rays and electrons, but in smaller numbers.

Collisions of cosmic rays with atoms in the upper atmosphere produce mostly neutral and charged pions. The neutral pions each decay into a pair of gamma rays in less than  $10^{-16}$  seconds. The charged pions each decay, within less than 30 nanoseconds, into a muon and a muon neutrino. The muons then decay in about 2 microseconds into an electron, a muon neutrino and an electron anti-neutrino. It is primarily these muons that are observed by the detector.

### 1.3 THE CCRT

Particles passing through our Compact Cosmic Ray Telescope (CCRT) are detected using scintillation counters.

A scintillator is a material that emits light when ionizing radiation passes through it. The light output is rather low and therefore it can only be measured electronically by using a light-amplification device such as a photo-multiplier tube.

The Compact Cosmic Ray Telescope (CCRT) hardware consists of two (or three) identical scintillation counters, each consisting of a scintillator panel, a light guide, a photo-multiplier tube and an attached voltage distribution network (a “base”), mounted on a stand that can rotate about a horizontal axis.

Each counter (see figure 2) of the telescope provides an output signal that can be connected directly to an oscilloscope. Cosmic ray events are then displayed as negative voltage “spikes”, distinguishable from “tube noise” by their much larger amplitudes. This simple demonstration provides direct evidence that “invisible” cosmic rays are a real, measurable quantity.

In its completed form, the CCRT acts as a directional “telescope” with the aid of a counting device. In our case, the counting device is a fairly simple electronics circuit, which is shown schematically in figure 3. Charged particles passing through both the upper and lower panels will generate electronic pulses at almost the same time. The electronics demands that these pulses occur within a small time window, and these “coincidences” are then counted as cosmic ray events. Since the cosmic rays must pass through both panels to be counted, one can obtain the angular distribution of the cosmic ray flux by measuring the rate of events with the telescope aimed at different angles  $\theta$  from the vertical direction.

There are several other experiments that can be performed with the device, such as the determination of the average energy of the cosmic rays, a demonstration of relativistic time dilation, and a crude determination of the muon lifetime.

### 1.4 OUTLINE

In chapter 2 we calculate the cosmic ray rate expected with our detector and discuss the cosmic ray angular distribution. We also elaborate on some of the other experiments that can be done with the setup.

The actual construction of the hardware, as well as testing and calibration, are described in great detail in chapter 3. The electronics and its assembly and theory of operation is described in chapter 4.

## 2. Cosmic rays

### 2.1 COSMIC RAY FLUXES

In the Particle Data Book [2] we find that the flux of cosmic rays per unit solid angle per unit horizontal area, about the vertical direction, is measured to be:

$$j(\theta = 0, \phi) = 110 \text{ m}^{-2}\text{sec}^{-1}\text{sterad}^{-1}$$

for  $0 < \theta < \pi/2$ . This is a “typical value”, and it depends, at the 10% level, on latitude, cosmic ray energy, and experimental conditions. The angle  $\theta$  is the zenith angle, measured with respect to the vertical direction, and  $\phi$  is the azimuth angle around the vertical direction. Because of the presence of the Earth, the flux for  $\theta > \pi/2$  is 0.

The angular distribution [2] of the cosmic rays varies as  $\cos^2 \theta$  for low energies (which comprises most of the cosmic rays; see also reference 3). There are various effects that lead to this angular distribution. Firstly, primary cosmic rays are extremely energetic. As a result, secondary particles produced in the same direction as the primary have considerable momenta and energy. Secondary particles produced at an angle, or in the “tail” of the of the air shower, have lower momentum than the primary particles. Consequently, the relativistic “boost” in the primary direction is much greater than at angles to the vertical. As a result, muons produced in the primary direction are much more likely to make it to the detector before decaying than particles coming in at an angle to that direction. Secondly, as the angle from the vertical increases, secondary muons must travel through more atmosphere before reaching the detector. The longer they travel through the atmosphere, the more energy they lose to ionization, and the more likely they are to decay before reaching the detector. For example, at an angle of  $45^\circ$ , a muon will have traveled at least 1.4 times farther than a muon traveling vertically. At  $85^\circ$ , the muon will travel eleven times farther.

We can combine the two measured facts into the following formula for the flux of cosmic rays:

$$j(\theta, \phi) = 110 \cos^2 \theta \text{ m}^{-2}\text{sec}^{-1}\text{sterad}^{-1} \quad (2.1)$$

In units of  $\text{cm}^2$  and minutes, this is:

$$j(\theta, \phi) = 0.66 \cos^2 \theta \text{ cm}^{-2}\text{min}^{-1}\text{sterad}^{-1} \quad (2.2)$$

One can now calculate the the total rate of cosmic rays from above and passing

through a horizontal unit area, per unit time:

$$\begin{aligned}
\int j(\theta, \phi) \cos \theta d\Omega &= 0.66 \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} \cos^3 \theta \sin \theta d\theta d\phi \\
&= -0.66 \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} \cos^3 \theta d \cos \theta d\phi \\
&= 0.66 \frac{\pi}{2} = 1.04 \text{ cm}^{-2} \text{min}^{-1}
\end{aligned} \tag{2.3}$$

The extra factor of  $\cos \theta$  is due to the fact that a cosmic ray that comes from an angle  $\theta$  sees the horizontal area of the detector foreshortened by just that factor of  $\cos \theta$ . Note, that we integrate only to  $\theta = \pi/2$ , to account for the fact that beyond  $\pi/2$  there are no cosmic rays.

In a setup where we require cosmic rays to pass through two surfaces, each of width  $w$  and length  $l$ , separated by a distance  $d$  and one located above the other, then the setup will see only those cosmic rays which come down almost vertically, if  $d$  is sufficiently large. In that case,  $\cos \theta$  is almost equal to 1 for those cosmic rays, and we can make the following approximation:

$$\begin{aligned}
j(\theta \approx 0, \phi) &\approx 0.66 \text{ cm}^{-2} \text{min}^{-1} \text{sterad}^{-1} \\
\int j(\theta, \phi) \cos \theta d\Omega &\approx 0.66 \Delta\Omega \text{ cm}^{-2} \text{min}^{-1}
\end{aligned} \tag{2.4}$$

Here,  $\Delta\Omega$  is the solid angle “covered” by the two panels.

One can approximate this solid angle if  $d \gg w, l$ :

$$\Delta\Omega \approx \frac{l w}{d^2} \tag{2.5}$$

To see this, imagine that cosmic rays come from all directions in equal amounts (we calculated the actual angular distribution earlier—now we’re just trying to find out how much our setup would see in principle—that is what “solid angle covered” means). Now, a lot of cosmic rays will miss both panels. But we know, from formula (2.3), that per  $\text{cm}^2$  roughly 1 cosmic ray will go through the top panel (or the bottom panel for that matter) per minute. So let us concentrate on those cosmic rays that do go through the top panel, and pick a particular cosmic ray. It sees the bottom panel as an area of  $l$  times  $w$  below it at a distance  $d$  through which it must go in order to be counted. Let us imagine further a sphere with radius  $d$

centered at the point where the cosmic ray hits the top panel. The bottom panel then forms, roughly, a part of the surface of that sphere. Clearly, the cosmic ray must go through the surface of the sphere somewhere, the area of which is of course  $4 \pi d^2$ . The bottom panel covers just a fraction of the surface of the sphere, and this fraction is approximately the ratio of the areas of the bottom panel and area of the sphere:  $(l w)/(4 \pi d^2)$ . So, in general, if cosmic rays come uniformly from all directions, then out of all cosmic rays hitting a certain area on the top panel, only this fraction would also go through the bottom panel. This then leads to the effective “solid angle subtended” by our setup: it is just  $4 \pi$  times that fraction, and this gives formula (2.5) above.

Except for one complication! We implicitly assumed that cosmic rays will only be counted if they go through the top panel **first**. What if a cosmic ray went through the bottom panel first and **then** hit the top panel? Clearly, it would now be heading **away** from the bottom panel, and the formula would not account for it. So the formula only holds if we **know** that the cosmic rays went through the top panel first. We could in principle measure which panel was hit first, but in practice, our setup is not capable of doing that, and any cosmic rays coming from the bottom going through both panels should be counted too! So why is formula (2.5) still the right formula for our case? The answer is the following: the flux in formula (2.1) and used in later formulas gives the measured cosmic ray flux impinging on an horizontal area **from above** (because there are no cosmic rays coming from below), and this **implies** that the top panel is always hit first, and formula therefore (2.5) is okay. There actually is a very small rate of muons coming from below. They are produced by neutrinos traveling through the Earth from the other side. The rate is so small that we don’t have to worry about it here. (There are a few other mechanisms for producing muons that come from below, but these occurrences are very rare).

This formula is an approximation in two ways. Firstly, the panel is flat, and the sphere of radius  $d$  is curved, and secondly, the distance of a point at one edge of the top panel to the other edge of the bottom panel is larger than  $d$ . At sufficiently large  $d$ , neither of these effects cause a very large error. However, we can do a more precise calculation using what is called a Monte Carlo Simulation.

## 2.2 MONTE CARLO SIMULATION

One can simulate an experiment using “Monte Carlo” techniques in a computer program. The listing for one such program written in C is given as appendix A, with an explanation of how it works.

Basically, it randomly computes a place on the top panel, and an angle for a cosmic ray, and then determines if the cosmic ray would also pass through the bottom panel. If it does, the event is called a “hit”, and if it doesn’t, it is called a “miss”. Of course, it really amounts to computing an integral numerically, and the method it uses is called the “Hit/Miss Monte Carlo” technique. On the other hand, it generates the cosmic ray angular distribution “exactly”, i.e. it generates cosmic rays such that their angular distribution is  $\cos^2 \theta$ . It does that using a bit of probability theory, which also amounts to doing an integral, but in this case exactly.

Program “cosmic” takes four arguments:  $w$ ,  $l$ ,  $d$ , and the number of cosmic rays to generate. In our case,  $w = 5.5'' = 14$  cm,  $l = 6.0'' = 15.2$  cm, and  $d = 24.25'' = 61.6$  cm. It gives the following output when asked to generate 10000 cosmic ray “events”:

```
disk5:cosmic> cosmic 14 15.2 61.6 10000
Width 14 cm
Length 15.2 cm
Distance 61.6 cm
Number of events 10000

Had 266 hits out of 10000 cosmics

Accepted cosmic ray fraction:      0.0266 +/- 0.00163
Cosmic ray rate through top panel: 221.312 /min
Cosmic ray rate through both panels: 5.8869 +/- 0.360949 /min
Simple estimate (wl/d^2 formula): 7.87636 /min
```

First, the output repeats what was given as its input values. It then tells us, that of the 10000 generated cosmic rays, only 266 actually passed through both panels. The fraction of accepted cosmic rays is just the ratio 266/10000. This is generally called the “acceptance” of a detector. The error is computed by taking the square root of 266, the number of “accepted” events.

Next the program prints out the total cosmic ray rate per minute for the top panel (which of course should be the same for the bottom panel). The calculation

uses formula (2.3) multiplied by the area of the top panel. The rate of cosmic rays going through both panels is then simply the product of the acceptance and the total rate.

Finally it prints out the result of the simple estimate obtained by using formula (2.5), which turns out to be larger than the simulated rate: clearly, the approximation is not extremely accurate.

By playing with the program, one finds that as one increases  $d$ , the two numbers start to agree. Of course, the acceptance also decreases, and, in order to maintain accuracy for the simulated result, one needs to generate more events.

### 2.3 OTHER ANGLES

In order to do these flux calculations for different angles, i.e. when the panels are oriented in such a way that primarily cosmic rays of a certain angle  $\theta \neq 0$  go through both panels, one can still use formula (2.5) for the solid angle seen by the setup, except for when the setup is approximately horizontal, i.e. with the top panel, say, on the left and the bottom panel on the right. In that particular configuration, cosmic rays can go through both panels when coming **either** from the left **or** from the right, and its accepted solid angle now is twice as big! But when the setup is just slightly tilted back towards the vertical direction, such that a precisely horizontal cosmic ray cannot go through both panels, then the problem goes away.

Of course, the flux of cosmic rays only passing through the “top” panel ought to be recomputed for this case. Formula (2.3) now has to be changed, because the foreshortening factor is no longer just  $\cos \theta$ . In fact, we now have to take the dot product of the direction of the cosmic ray  $\hat{\mathbf{p}}$ , and the direction of the normal to the surface of the panel  $\hat{\mathbf{A}}$ . If we tilt the panel around the x-axis, say, then  $\hat{\mathbf{p}}$  and  $\hat{\mathbf{A}}$  look like:

$$\begin{aligned}\hat{\mathbf{p}} &= (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \\ \hat{\mathbf{A}} &= (0, \sin \alpha, \cos \alpha)\end{aligned}\tag{2.6}$$

where  $\alpha$  is the angle of inclination of the panel. The dot product is:

$$\hat{\mathbf{p}} \cdot \hat{\mathbf{A}} = \sin \theta \sin \phi \sin \alpha + \cos \theta \cos \alpha\tag{2.7}$$

and we must take the absolute value of this, because cosmic rays coming from both sides of the inclined panel count. Note, that for  $\alpha = 0$  this reduces precisely to



$\cos \theta$ , as in equation (2.3). We now have to replace formula (2.3) by:

$$\int j(\theta, \phi) |\sin \theta \sin \phi \sin \alpha + \cos \theta \cos \alpha| d\Omega \quad (2.8)$$

Unfortunately, this integral cannot be done analytically, because of the absolute value in the integrand. Therefore, numerical methods are needed to compute the result. It is, in fact, not very hard to modify the attached computer program to allow the simulation of our setup when placed at an angle to the vertical, but this is left as an exercise.

We can of course derive another approximation. If we tilt the setup over an angle  $\alpha$  about the x axis, and  $d$  is sufficiently large compared to  $w$  and  $l$ , then only those cosmic rays that actually hit the top panel more or less perpendicularly will make it to the bottom panel. That is to say, they don't see the top panel foreshortened very much, and the factor  $\hat{\mathbf{p}} \cdot \hat{\mathbf{A}}$  is approximately equal to 1. Equation (2.4) now becomes:

$$\begin{aligned} j(\theta \approx \alpha, \phi) &\approx 0.66 \cos^2 \alpha \text{ cm}^{-2} \text{min}^{-1} \text{sterad}^{-1} \\ \int j(\theta, \phi) |\hat{\mathbf{p}} \cdot \hat{\mathbf{A}}| d\Omega &\approx 0.66 \cos^2 \alpha \Delta\Omega \text{ cm}^{-2} \text{min}^{-1} \end{aligned} \quad (2.9)$$

where  $\Delta\Omega$  is the same as in formula (2.5). In other words, as  $\alpha$  changes from 0 to  $\pi/2$ , the count rate goes as  $\cos^2 \alpha$ , as expected.

Note, that as  $\alpha$  increases, other effects may become a problem: the thickness of the panels may not be negligible, and air showers where two particles from the same hadron cascade each enter one of the panels may simulate a single cosmic ray going horizontally. And there is the already mentioned factor of two to be aware of when the setup is almost horizontal ( $\alpha \approx \pi/2$ ).

## 2.4 ADDITIONAL EXPERIMENTS

The cosmic ray telescope can also be used to explore and verify principles of special relativity. In particular, time dilation can be observed indirectly by measuring the muon flux through the CCRT at various altitudes. Another experiment can approximately measure the energy spectrum of the muons, and the combination of the two experiments lets students verify the predictions of relativity theory.

Since muons have a lifetime ( $\tau$ ) of 2.2 microseconds [2], muons produced in the upper atmosphere would decay long before their arrival at sea level without the effect of time dilation caused by their relativistic energies. At typical energies

in excess of 1 GeV [1], muons travel close to the speed of light ( $c$ ), and without relativistic effects the average distance  $c\tau$  before decaying would be:

$$c\tau = 3 \cdot 10^8 \times 2.2 \cdot 10^{-6} = 660 \text{ m} \quad (2.10)$$

Let us assume the muon lifetime in the Earth frame is  $t$ . The number of muons measured at an altitude  $y$  can then be compared to the number measured on, for example, a mountain top of elevation  $y_m$  and the following relation holds:

$$N(y) = N(y_m) \exp \frac{y - y_m}{v t} \approx N(y_m) \exp \frac{y - y_m}{c t} \quad (2.11)$$

with  $v \approx c$  the speed of the muons,  $N(y)$  the number of events measured at an elevation  $y$  and  $N(y_m)$  the number measured at the mountain top. Experimentally, muons are detected in significant numbers at sea level because of relativistic effects. Time dilation causes the clock in the muon's frame of reference to go slower, **as perceived by us on Earth**, and the **apparent** muon lifetime  $t$  is:

$$t = \gamma\tau = \frac{\tau}{\sqrt{1 - \beta^2}} \quad (2.12)$$

with  $\beta = v/c$  the velocity parameter. The correct decay formula can now be written as:

$$N(y) \approx N(y_m) \exp \frac{y - y_m}{c\gamma\tau} \quad (2.13)$$

The factor  $\gamma$  is about 7–10 for cosmic ray muons.

The measurement of  $N(y)$  and  $N(y_m)$  can give us, therefore, the value of  $\gamma\tau$ :

$$\gamma\tau = \frac{y - y_m}{c \ln \frac{N(y)}{N(y_m)}} \quad (2.14)$$

The effect of time dilation can be measured quantitatively if we can measure the factor  $\gamma$  independently. This can be accomplished by measuring the muon energy, and the value of  $\gamma$  then follows from the familiar relation:

$$E = \gamma m c^2 \quad (2.15)$$

where  $E$  is the muon energy, and  $m$  is the muon rest mass:

$$m \approx 106 \text{ MeV}/c^2 \approx 1.9 \cdot 10^{-25} \text{ grams} \quad (2.16)$$

Cosmic ray muons have widely ranging energies and an accurate experiment would require measurement of the energy for each muon separately, and using its  $\gamma$  value.

Our experiment is not capable of doing that, however. On the other hand, the cosmic ray energy spectrum can be determined, roughly, by placing lead shielding of varying thickness between the detector panels. One can compute the amount of lead needed to stop muons of a certain energy using data available in reference 2. According to the table of atomic and nuclear properties of materials, “minimum ionizing” particles, such as  $\approx 1$  GeV cosmic-ray muons, lose energy in lead at a rate of  $1.13 \text{ MeV}/(\text{g}/\text{cm}^2)$ . Multiplying by the density of lead,  $11.35 \text{ g}/\text{cm}^3$ , this becomes  $12.8 \text{ MeV}/\text{cm}$ . For a 1 GeV muon to lose all its energy, one would therefore need about  $1000/12.8 = 78 \text{ cm}$  of lead. One might also use iron, for example, where the energy loss is  $11.6 \text{ MeV}/\text{cm}$ , and the amount required to stop a muon of 1 GeV is about 86 cm.

This value is also called the “range” of the particle at this energy. In practice, the measured range is that amount of material that stops exactly half of the particles. As the amount of material is increased, not much seems to happen at first. When the amount of material starts to get close to the range, then the number of particles passing through decreases rapidly, and when the amount surpasses the range by a small amount, the number of remaining particles is almost zero. This phenomenon is called “range straggling” and it is caused by the essentially statistical nature of energy loss in matter.

The rather simple range calculation is not completely accurate, since the energy loss constant really depends on the energy: for small energies, the energy loss is much higher, and therefore the calculation above overestimates the amount of material needed. Reference 2 also has a range vs. energy graph for various materials, including lead. The curve for iron is not shown, but it is very close to that of copper. Note that the range is expressed in  $\text{g}/\text{cm}^2$ , so in order to obtain the range in cm, one must divide by the density of the material. From this table one can obtain the actual ranges of muons in lead and iron (copper) at 1 GeV: they are about 70 cm and 80 cm respectively. In other words, the simple calculation was wrong by about 10%, which is not significant for the precision that we are likely to obtain.

As stated before, cosmic ray muons come in a variety of energies. Therefore, when we try to measure the “range curve” by increasing the amount of material between the two panels from, say, about 55–80 cm of lead, we will find a much more gradual drop-off in the number of surviving particles. Yet, the 50% point will give us a reasonable estimate of the average energy of the muon spectrum, and this gives us an average value for  $\gamma$ .

The fact that muons also lose energy in the atmosphere leads to a small correction which must be made. On the mountain top, the average energy of the muons is a little higher, and in fact some very-low-energy muons never make it down to

sea level at all. Also, as they lose energy, the factor  $\gamma$  becomes smaller as does the apparent lifetime, and even fewer muons make it all the way down. It is therefore best to “preselect” muons of a somewhat higher energy, by using lead shielding for the measurements from the start. To select only muons above about 250 MeV, one would use 20 cm of lead. It is also necessary to compensate for the additional amount of air through which the muons have to travel when the measurement is done at sea level. Again using reference 2, we can compute that 1 cm of lead is equivalent to about 60 m of air at standard temperature and pressure. Therefore, for each 100 meters of elevation difference, we should add 1.7 cm of lead for the measurement at higher elevation (about 1 “brick-height” per 300 m), so that the muons we count at the higher elevation are comparable to the ones measured at the lower elevation. Of course, on the mountain top the pressure and temperature are somewhat lower, so one ought to take that into account too, but for our level of accuracy this doesn’t make much difference.

In the above, an effort has been made to keep all calculations very simple, termed “back-of-the-envelope” in the jargon. One can go into much more detail if one wants, as was done in e.g. reference 4, which describes a somewhat different method of measuring the muon lifetime and time dilation.

### 3. Construction of the CCRT hardware

The detector can be constructed using common hand tools, or somewhat more rapidly using machine or power tools. This report emphasizes the use of construction techniques involving commonly available materials and parts, such that it can be built without the need for an elaborate mechanical and electrical workshop.

#### 3.1 PARTS

The following is a list of the parts needed.

- Scintillators: Rough cut panels (approximately six by eight inches) may be obtained by contacting the SLAC education department (see appendix C).
- Light Guides: Lucite can be obtained commercially (TAP Plastics serves the Bay Area), either cut to specifications, or cut and polished by hand.
- Photo-tube holders: Lucite cylinders can be obtained commercially and cut to specifications.
- Glue: “Five minute epoxy” or equivalent.
- Light shielding: Electrical tape, aluminum foil, black plastic or paper.

- Photo-tubes: 2 Hamamatsu 931A side-on tubes (manufacturer cost about \$30/each).
- Bases with built-in high voltage converters: 2 Hamamatsu HC 122-01 (manufacturer cost about \$100/each).
- Base power supply: 2 nine volt radio batteries (or DC power supply).
- Adjustable resistors: 2 potentiometers (1000 Ohm, 2 Watts).
- Electronics: A list of components is given in appendix B. The Printed Circuit Board is available through SLAC, see appendix C.
- Electronics power supply: 2 six-volt lantern batteries, or 2 six-volt DC power supplies.

### 3.2 CUTTING AND POLISHING

The cutting and polishing of the scintillator panels and light guides requires the following materials:

- Hacksaw, clearance at least 4".
- One regular metal file, medium grade.
- Emory cloth in grades: 80, 120, 180, 240, 600 wet.
- Wood or aluminum block, roughly 3" x 4" x 1" around which to wrap the emory cloth.
- Coarse paper towels.
- Vise.
- Soft cloth gloves.
- Scissors.

Testing for light leaks requires in addition:

- Light source (e.g. a flashlight).
- Black paper or plastic.
- Dark cloth.

After obtaining rough cut pieces of scintillator (we have used setups with panel sizes ranging from  $5.5 \times 6$ " to  $6 \times 8$ " ), use the hacksaw to cut them to the same size if they are not sized properly already. Keep the cut wet with water, making the cut as smooth as possible. Try not to cut off any existing polished edges that are already there, as this will save work. The larger the pieces, the higher the count rate will be, but as always, bigger is not necessarily better.

At all times, try to keep objects away from the flat surfaces of the scintillator. This includes fingers and finger prints. Also try to keep scintillator material from being subject to temperature extremes. When scintillator material is heated, and then cooled, tiny cracks will appear on the surface, often a few days later, that tend to reduce the light output of the final device. This phenomenon is known as “crazing.” If you are using a power tool or grinding wheel to polish the scintillator, be sure to minimize the heat generated.

Next, you will need to polish the edges of the scintillator so that internal reflection will occur: this is so light that initially does not travel in the direction of the photo-tube may be reflected towards the tube and be captured. Mount the scintillator in a vise, first wrapping the clamped part in paper towels so it won't get damaged. Note that a rule of thumb is that if you don't do an operation properly, the next phase will take longer. Unless mentioned otherwise, all operations are done wet. Be careful not to abrade your finger tips too much while sanding!

If the edges of the scintillator are really rough, use a regular metal file to file down the sides. Continue filing until the side is straight and has no more saw-blade marks. Keep file and surface wet with water. Occasionally, wipe the surface with a paper towel and clean the file (holding it under running water and wiping with a paper towel works well). Estimated time: 5 minutes per side, depending on how well the side was cut. Note that a power sander will greatly shorten your workload, but it will also cause crazing to some degree. If you do use a sander, work slowly and use a lot of water to avoid excess heating. At SLAC, making smooth edges is usually done using a milling machine with a fly-cutter.

After filing, turn to grade eighty emory cloth wrapped around a block of wood or aluminum. Wet both the emory cloth and the surface. Use slow strokes applying some pressure, stroking away from you and back again in the direction of the length of the side. Occasionally, wipe the surface and check. Eventually you should see length-wise scratches consistent with the coarseness of the emory cloth, but no sideways scratches, or other gouges. Note: Don't use regular sandpaper. Emory cloth lasts a lot longer. Estimated time: 5 minutes per side. These steps are usually not needed after a fly-cut.

Repeat the above with 120, 180, 240, and 400 grade emory cloth. Keep things wet (this will not only keep the material cool, it will also keep dust out of the air). Whenever changing to a finer grade of cloth, clean the surface and the cloth carefully so you won't make gouges with left over coarser material. Each time, especially when wetting the surface, the scintillator will look a little less opaque. Note that when you get to the 400 grade emory cloth, you will have to clean it often with water. Estimated time: 2-3 minutes/grade and side. These steps are usually not needed after a fly cut.

Repeat once more with grade 600 emory cloth. This fills up easily with material, so clean it often. Also slow down the strokes, to reduce the heat build-up by friction (Don't let it squeak!). It should start to become semi-transparent now. If you have access to a buffing wheel and "rouge" (cerium oxide), buff the edges until they are transparent. As always, go slowly to reduce excess heat. Make sure the buffing wheel is either new, or very clean. Estimated time: 5 minutes/side.

Now clean the scintillator under running water and dry it carefully with a paper towel. If you are buffing by hand, clean the vise and remount the scintillator. Use a coarse paper towel, or newspaper without ink, and polish the sides by hand. This time, don't use a block or water. Don't buff too hard or too fast. Within a minute or two, you should get a reasonable gloss. If not, experiment with different types of paper. When finished, you should be able to see the opposite side of the plastic pretty well. Note that if you are using a buffing wheel, you can skip this step. Estimated time: 1-2 minutes/side.

### 3.3 FIXING CRAZED SCINTILLATOR

Scintillator material is called crazed when it has tiny hair-line cracks on the surface that are easily visible when holding it up to a light and looking inside through a side. It will probably work fine, though its light output is reduced because the light is absorbed in the cracks or scattered out of the scintillator instead of being internally reflected. One can use a hot air gun or a "pistol"-style hair drier to fix the crazing to some extent, usually only temporarily.

Put the scintillator on a paper towel on the workbench and apply hot air without letting the scintillator get too hot. Check often to see if the crazing is diminishing.

### 3.4 CUTTING AND POLISHING LIGHT GUIDES

The light guides we need are trapezoidal pieces of Lucite, the same thickness as the scintillator panels (in our case 0.5"), and with a baseline that is the same size as the shorter of the sides of a scintillator panel (in our case about 6"). The pieces should be 6-8" tall, and the side opposite the baseline should be about 1 1/8" wide (see photo).

Cutting and polishing Lucite proceeds in a manner very similar to cutting and polishing scintillator material, though usually scintillator material is a lot softer and more delicate. Because Lucite is tougher, it may take longer to cut and polish, but on the other hand, one has to be more careful with scintillator in order to avoid crazing, so on the whole the time involved is about the same.

With Lucite light guides, however, there is a different option available. One can buy Lucite sheets in various thicknesses at local plastics shops (in the San Francisco Bay Area, for example, TAP plastics). For a modest additional fee, they can cut the sheets into the shape needed, and even polish the edges. As an order of magnitude estimate, one should expect to pay about \$10 for each light guide (you need one for each scintillator panel). Most often they need a few days to complete your order. If you decide to polish the Lucite yourself, it pays to have the plastics shops do the cutting for you.

### 3.5 THE TUBE MOUNT

The 931A type photo-multiplier tube is a “side-window” or “side-on” tube. This means that the cathode is part of the dynode structure itself, and faces the side of the tube, rather than the front. This type of tube is one of the earliest types that were used in nuclear physics. Most modern tubes have a cathode that is evaporated onto the inside of the glass at the front of the tube. Side-window tubes, however, have the distinct advantage of being inexpensive, and are still used quite a bit.

Unfortunately, one has to do a bit of work in order to attach such tubes to our scintillator/light-guide. The solution we came up with is the following. Acquire two pieces of cylindrical Lucite tubing with outer diameter  $1\frac{3}{8}$ ”, and a wall thickness of  $\frac{1}{8}$ ”, with a length of  $1\frac{7}{8}$ ”. The inner diameter is then just about  $1\frac{1}{8}$ ”, which is just a bit less than the glass part of the Hamamatsu tubes listed above. In order to allow the tube to fit inside, make a saw cut length-wise on what will become the “back side”.

With some emory cloth, remove any rough edges on both ends of the Lucite cylinders and also on the inside and outside edges of the length-wise cut. The tube should now slide onto the cylinder with just enough pressure to keep it firmly seated.

With the tube removed, mount each cylinder in the vise, with the “front” side up (i.e. the cut side down). With a file and emory cloth, flatten the top, until the flat surface is about as wide as the light guide ( $\frac{1}{2}$ ”). Then polish this surface using the same procedure as for the light guide.

If the proper diameter tubing cannot be obtained, one can use tubing with a smaller inner diameter at the expense of some more work. Instead of just one cut in the back side, make two cuts, such that about two-thirds to three-quarters of the tubing remains. Now, take a heat gun and warm up the tube mount, and when it is hot, bend it out a little. Let it cool before seeing if the tube fits. If the tube still doesn't fit, repeat this procedure and bend the tube mount until it does.



Make sure the tube fit is not too loose, although if it is a little loose, one can use tape to hold the tube in place.

### 3.6 GLUING THE COUNTER TOGETHER

In order to glue everything together, we use a clear two- component fast-drying viscous epoxy glue such as 5-Minute Epoxy. Note that in the lab setting, all pieces would have been machined flat, and in that case, a special bonding agent such as “Weld-On” is commonly used. Basically, this liquid dissolves the surfaces of the two pieces to be glued together, and when the two pieces are pressed together and the liquid dries, a very nice welded joint results (Epotek 301, a non-viscous highly ultra-violet transmitting epoxy, is sometimes used when high-performance counters are made).

When doing the cutting and polishing by hand, perfectly flat surfaces are unlikely, and therefore a glue with “body” is needed. While 5-Minute Epoxy is not ideal for this purpose, it works well enough.

Now mount the piece of scintillator in a vise, with the “best” polished side at the bottom. Use some paper towels to keep the surface from being scratched by the vise. The reason the best side is at the bottom is that the glue will fix most of the defects of the side that is to be glued.

Make sure that the top side of the scintillator is clean, and also the side of the light-guide that will be glued to it.

Mix up enough of the two components of the glue such that the area to be glued can be covered liberally—where the pieces don’t quite touch, we want the glue to fill the gap. Try to avoid bubbles when mixing the two components: the clearer the glue the better the light transmission. The best thing to mix the glue on is a piece of aluminum or plastic. One can get small disposable aluminum dishes, for example. Use a lollipop stick (or tongue depressor) to mix the two components.

Now apply the glue liberally to the top of the scintillator, and spread it out with the lollipop stick. One can use the same lollipop stick as the one used to mix the glue with, but first clean it with a paper towel: it often has more of one component than the other near its surface. Try not to spill too much glue on the surfaces that are not to be glued, but it doesn’t cause much harm if you do.

Now take the light guide and place it with the wide side down on the scintillator. With some jiggling and pressure, try to eliminate all air bubbles and make sure that the glue reaches everywhere, on both surfaces. If you mounted the scintillator piece vertically, and both surfaces are reasonably flat, then you don’t have to hold the light guide in place. Put the lollipop stick back in the remaining glue. Let the glue cure for at least 10 minutes. If the light-guide does slide off because things

are not mounted horizontally or because the surfaces are not flat, just hold it in place by hand for a few minutes until the glue is sticky enough. After about 10 minutes, check the lollipop stick where it sits in the remaining glue—it should be pretty solid by now.

Next, repeat the procedure for the tube mount. It should be glued with its flat side down onto the narrow part of the light guide, just about centered length-wise (see picture). In order to prevent the tube mount from changing its position, you may want to fix it in place by using some tape. If the tape comes in contact with the glue it will be hard to remove it later, but this is usually not serious, and it can make the gluing process a lot easier.

After 10 more minutes, you should be able to take the assembled counter out of the vise. Look through the back end—you should be able to see pretty clearly all the way through to the tube- mount.

Repeat the entire procedure for the other counter. Remember that while the epoxy hardens in a few minutes, it takes a few hours to cure completely. So handle the counters with care.

### 3.7 WRAPPING THE COUNTER

Before wrapping a counter and making it light-tight, you will have to insert the photo-tube into the tube mount. Make sure the photo-cathode is oriented in the right direction. The side with the grid made up of thin wire mesh is the photo-cathode side. For the Hamamatsu tubes, this side also lines up with the notch in the middle stem of the socket of the tube.

Now carefully wrap the entire counter in aluminum foil. The plan is to cover as much surface as possible with a single stretch of it, while causing as little as possible in the way of folds, wrinkles, creases or rips. One strategy is to take a piece of about twice the size of the counter in either direction, and fold it around the counter so the two ends meet just in back of the tube mount. Tape it right there, and then proceed to fold and tuck the aluminum foil, occasionally using some tape to hold it in place, until it looks like a very pretty Christmas present. Avoid applying tape directly to the plastic parts. At the end, peel back the aluminum foil until the plastic socket of the tube protrudes about half an inch.

Now use black electrical tape to cover the entire counter. The idea is to provide a protective layer, but more importantly, a light-tight layer. In order to achieve the latter, it may be helpful to cut pieces of black paper or plastic in roughly the shape of the counter and put those in front and back before the taping process. This step will prevent pinhole-sized light leaks from appearing later.

Tape the perimeter of the counter first. Then wrap the entire counter, starting from the “bottom”, and working your way up to the tube mount, in a slow spiral. Don’t pull the tape too tight, and leave sufficient overlap between windings of the spiral. When pulled too tight, the tape will creep later and perhaps uncover some sections. Things get tricky near the tube mount. Be inventive, think about where the light would go, and use tape to prevent it. Examine your work, and use more tape. Remember, electrical tape is your friend. Pay special attention to where the aluminum foil reaches the socket of the tube, and try to tape that part especially well. All that needs to protrude from the tube is the very bottom of the socket.

During the taping, try not to rip the aluminum foil. If you do, use a piece of aluminum foil to fix the rips and tape over them.

In the end, there should be no visible holes in the black tape, and no visible aluminum foil. The entire counter, with the exception of a small part of the socket of the tube, should be covered.

Even so, more likely than not, you’ll still have light leaks, especially near the corners of the scintillator and near the tube mount. We will return to this problem later.

### 3.8 TUBE POWER SUPPLY

In order to operate the counter, we need to supply high voltage to the tubes. The Hamamatsu bases we use have a built-in low-voltage DC to high-voltage DC converter (called a Cockroft-Walton voltage multiplier).

There are three leads coming from the base. The thicker black lead is a coaxial cable, which carries the signal from the anode. Since the anode is at ground potential, the signal can be connected directly to an oscilloscope or to our electronics (see later). The thin black and red leads are for the low-voltage power supply. The red lead should be connected to positive voltage and the black lead to ground. For a given positive input voltage  $V_{in}$ , the base will generate a photo-cathode voltage of about  $V_c = -140 V_{in}$ . The maximum rated input voltage is 8V, which translates to about  $-1100V$  on the photo-cathode. Note, that the voltage on the photo-cathode is negative, even though the input voltage is positive.

The tubes require only a modest amount of power, so they can actually be run from a 9V radio battery. In order to regulate the input voltage, we use a  $1000\Omega$  variable resistor and a  $100\Omega$  fixed resistor in series with the 9V battery. The fixed resistor is there to limit the voltage going into the base to about 8V. The reason this works is that the “impedance” of the base, as seen by the battery, is about  $800 - 1000\Omega$ , so the adjustable range is from about 4–8V. The bases, as shipped from the factory, vary a little, so it is always a good idea to measure the exact

voltage to the base, and one may have to play a little bit with the resistor values. The normal operating voltage of the Hamamatsu tubes is 1000–1100V (negative), so the input voltages will eventually be set to 7–8V. But for now, we set the voltage to the minimum value of about 4V, until the counter has been tested.

A schematic of this circuit is shown in figure 4. In our case the 9V battery and the potentiometer/resistor assembly were mounted on a small vector-board which was then taped to the frame on which the panels were eventually mounted, using electrical tape.

### 3.9 TESTING THE COUNTER

Now that we have assembled the counter and its power supply we are ready to try it out. Make sure the voltage adjustment for the base supply is set to the maximum resistance, i.e. the voltage across the base supply should measure about 4 volts.

Wrap the counter in a black cloth, to protect it from light in case there are light leaks (it is possible to burn out the tube if it sees too much light when powered). Now try to see small signals on an oscilloscope. If you have a reasonably high-bandwidth and sensitive oscilloscope available, use the  $50\Omega$ -terminated input, and set the scale to about 50–100 mV/cm. If you only have an old low-bandwidth scope that is not very sensitive, use a high-impedance ( $1\text{ M}\Omega$ ) input, but connect a  $1000\Omega$  resistor between signal and ground. This will cause the signal amplitude to be much larger, but also the pulse shape will be somewhat distorted.

Now raise the voltage until you see something happening. When things “go wild”, back off on the voltage a bit. You should be able to see what is called tube noise: little negative signals generated by thermal electrons boiling off the photo-cathode.

If you have a radioactive source of reasonably high-energy beta-rays, such as Strontium  $^{90}\text{Sr}$  or Ruthenium  $^{106}\text{Ru}$ , you can try to see if you get more signals when the source is held near the counter. The signals should decrease when you move the source away. Note that you can also have electronic pick-up noise, which may be caused by your hands being near the counter, so also try holding your hand near the counter without the source.

Next remove the black cloth. If the signal gets a lot stronger, then you have light leaks.

### 3.10 LIGHT-TIGHTENING THE COUNTER

In order to make the counters light-tight, shine a flashlight onto the counter (at somewhat reduced voltage) from all possible directions. When you find a particular area that causes extra signal, apply more black tape to that area. Re-check with the flashlight that you have indeed fixed it. This procedure is best applied in a dark room or under a large piece of black cloth.

Repeat the procedure until you have no more light leaks.

### 3.11 COUNTER SUPPORT STRUCTURE

In order to turn the two panels into a telescope, they must be attached to a support structure. In order to measure an angular distribution, the support structure must be such that the telescope can be aimed in various directions, yet the distance and relative orientation of the two panels do not change. In case lead shielding is required between the two panels, the support structure must be strong enough to hold about 600 pounds of lead. Clearly, the two requirements are hard to meet simultaneously, and therefore it is probably best to make one light-weight rotating structure, and another, more sturdy contraption pointing in the vertical direction that can hold stacked bricks of lead.

In our case, we used a discarded stand plus some Unistrut<sup>TM</sup> for the rotatable telescope. We actually used the lead bricks themselves to build a pile of lead, with a space at the bottom to hold one panel and the other panel taped to the top of the pile.

## 4. Electronics

The electronics for the cosmic ray telescope are shown schematically in figure 3. Electrical signals from the photo-multiplier tubes are received, amplified and transformed into digital signals. The digital signals are displayed visually using LEDs for each channel separately, and if they are coincident, they are counted and displayed in binary form using another set of LEDs.

In the following, we will first discuss the operation of photo-tubes, and then estimate the signal size that can be expected. The actual subsystems of the circuit are then described in subsequent sections.

## 4.1 PHOTO-MULTIPLIERS TUBES

A photo-multiplier tube is a vacuum tube which converts light into a large number of electrons. It does this by employing light sensitive material. When a photon strikes a surface (the photo-cathode) that is covered with this substance, some of the time a single electron is released and it enters the vacuum. The photo-cathode is held at a negative high voltage, and these photo-electrons will find themselves attracted to the nearest point of higher (i.e. less negative) voltage. By design, that point is the first of a set of electrodes within the tube, called dynodes. Each electron striking the first dynode has a large enough energy that it frees more electrons from the dynode. This is called secondary emission. The secondary electrons then will look for the nearest higher voltage and strike the second dynode, and so on. Each subsequent dynode is held at a voltage more positive than its preceding neighbor, attracting the electrons to it. At each dynode more electrons are freed and the current of electrons therefore increases at each dynode.

Voltages are usually provided to the separate dynodes (and the cathode) by the use of a resistor divider network that is external to the tube. The device containing the resistor network is called a “base”.

Details about photo-multiplier tubes are provided on demand by their manufacturers. Well-known are companies such as Hamamatsu, RCA, Thorn-EMI and Philips. For the CCRT project, we have chosen a Hamamatsu 931A photo-tube, and a Hamamatsu HC122-01 base. The 931A tube is a “side-on” tube with a circular cage dynode structure having 9 dynodes. It has a photo-cathode covered with Sb-Cs material, with a peak sensitivity to light with a wavelength of 400 nm. The base includes a high voltage power supply, so that it can be operated from a 9V battery, as described previously. At a power supply setting of 1000 Volts, the tube has a gain of about two million. The rise time of the signal is about 2 ns.

Figure 5 shows what the tube looks like and the dynode structure of a circular cage multiplier. The figure also shows a typical voltage divider chain and the relationship between the anode pulse shape and the light pulse at the photo-cathode, and finally, the typical response of a bi-alkali photo-cathode.

## 4.2 SIGNAL SIZE

A charged particle traversing a scintillator causes electrons within the molecular structure of the scintillator to occupy higher energy levels. These electrons then return to their ground states later, emitting visible photons. Particles passing through a plastic scintillator typically lose 2 MeV of energy for each  $\text{g/cm}^2$  of material through which they pass. Plastic has a density of about  $1 \text{ g/cm}^3$ , so a 1 cm thick counter will have received about 2 MeV of energy.

In general, it takes about 200 eV of deposited energy to create a scintillation photon (note that the scintillation photon energy is much less—it is in the visible range). If the tube has a “quantum efficiency” of 10%, then it takes about 10 photons, or 2 keV of deposited energy, before the tube generates a single electron off the cathode (a “photo-electron”). Therefore, for a 1 cm thick plastic scintillator, we expect about 1000 photo-electrons to be produced if all the photons actually hit the photo-cathode. In our geometry, only about twenty percent do, however, so our signal will be the result of about 200 photo-electrons.

The tube has a gain of about  $2 \times 10^6$  so the output current will be about  $4 \times 10^8$  electrons arriving over a time period of about three times the risetime of the photomultiplier tube, or about 6ns. The electronics described here are a bit slower than this, so it is as if the electrons arrive in a time period of about 10 ns. Thus, the peak voltage we would see across a 50 ohm resistor is about:

$$\begin{aligned} V &= IR \approx \frac{Q}{T} R \\ &\approx \frac{4 \cdot 10^8 \times 1.6 \cdot 10^{-19} \text{ C/e}}{10 \times 10^{-9} \text{ s}} \times 50 \Omega \\ &= 320 \text{ mV} \end{aligned} \tag{4.1}$$

This is only a ball park estimate, depending on many additional factors. It does, however, tell us that we need an amplifier to deal with the signals.

## 4.3 AMPLIFIER/COMPARATOR

The amplifier necessary to receive these signals therefore has to be one which has a noise figure, at 100 MHz, on the order of the noise of the photo-multiplier tube, i.e. a few photo-electrons or a few mV. There are a number of inexpensive operational amplifiers which easily fulfill this requirement.

The circuit, drawn schematically in figure 6 is based on the choice of the uA733 Differential Video Amplifier which offers a fixed gain of 10 with no external components, high common mode rejection, low noise and wide bandwidth.

We now need to turn the analog signals into digital ones, and we also need to reject very small signals, mostly caused by tube and amplifier noise. Both goals are accomplished using a comparator, which compares the amplified photo-multiplier signal to an adjustable threshold voltage. The circuit therefore feeds the signal, through a capacitor, into an LM360 High-Speed Differential Comparator, which provides TTL compatible outputs. The threshold voltage ( $V_t$ ) can be adjusted using built-in potentiometers from 0V to about +0.8V.

#### 4.4 DIGITAL CIRCUITS

As it is, the pulses from the comparator are very short, of the order of 10 nsec in duration. To make life easier, the TTL output of the LM360 is stretched in time by a 74123 one-shot to 1 microsecond by the selection of components external to the 74123.

The printed circuit board designed for the CCRT can be loaded with a number of identical analog channels. Figure 6 shows three, however, two have been used in the demonstration model of the cosmic ray detector. The outputs of the 74123 are now input to a multi-input NAND Gate (7420 in the circuit). This four-input device allows the formation of a coincidence signal from the two (or three) analog channels, and it supports the additional feature of a run/stop switch connected to a third input.

The output of the coincidence circuit is input to a 74HC4040 Twelve Stage Binary Ripple Counter which counts the coincidences. The output of this counter drives 7406 Inverter/Drivers, which in turn drive LEDs mounted on the chassis of the device. The counter can be reset by use of a RESET push button also mounted on the chassis.

Figure 7 is a component side drawing of the CCRT electronics. It shows the placement of the major components on the board for ease of recognition. The demonstration model has been fabricated using the wire wrap technique on vector-board. It is enclosed in an aluminum chassis of dimensions 5"  $\times$  6"  $\times$  9". There are connectors on the chassis for a 6V power source, but the electronics will also operate on two 6 Volt lantern batteries. A photograph of the completed circuit is shown in figure 8.

The printed circuit (PC) board has been developed at SLAC specifically for the CCRT. The PC board has three analog channels and can display three-fold or two-fold coincidences. Additionally, it allows one of the channels to be displaced in time, providing for a delayed coincidence capability. A list of components is given in appendix B.



It is anticipated that the circuit board will be available for a nominal fee by contacting the Department of Education at SLAC, see appendix C.

#### 4.5 OPERATING THE CCRT

In order to experiment with the CCRT it is necessary to calibrate the counter, so that only cosmic ray events are being counted, rather than background events (tube noise). In practice, this means adjusting the threshold voltage levels of the discriminator circuits to a value somewhat lower than the signals generated by the muons, and higher than the background signals. The following describes one procedure to do this.

After you are convinced that the counter is light-tight, connect the base output to an oscilloscope with a  $50\Omega$  termination. This allows the scope to see the same signal as is seen by the electronics. Connect 9V batteries, or a 9V power supply, to the red and black leads of both bases, as described earlier and shown in figure 4. Next set the tube voltage to about 7.5 V and adjust the oscilloscope until you see signals. You will need to set the scope sensitivity such that one can see the small signals. See also section 3.9. Trigger the scope properly on these signals, and turn the tube voltage down from 7.5 V to 6.5 V to see how the signal size varies. Choose a reasonable operating voltage. Most of the signals you see are due to tube noise. You can read off the amplitude of the noise signals from the scope.

To provide power to the electronics circuit, it is most convenient to use a DC power supply that has a common terminal and separate positive and negative 6V DC outputs. One can also use two 6 V DC lantern batteries, in the following way. Connect the two batteries in series, i.e. connect the plus terminal of one of them to the minus terminal of the other. Use this point as the “ground” for the electronics. Now use the “free” plus terminal for plus 6V and the free minus terminal for minus 6V DC.

Next, use a digital multimeter to measure the threshold voltage directly on the circuit board. The wiring diagram in figure 6 will help you find this point. Be sure to use a suitable ground for the “common” terminal of the multimeter. Now (remembering that the comparator stage comes **after** the amplifier stage, which amplifies the signal by a factor 10) adjust the threshold voltage until it is between 1.5 and 2 times the noise amplitude times 10. That is, if the noise amplitude is 10 mV, then the threshold voltage should be between 150 and 200 mV. Repeat these steps for the second photo-tube.

The final step is to connect the two photo-tube outputs to channel 1 and 2 of the coincidence circuit. If everything works properly, then the LED’s at the inputs of the two channels should flash once every few seconds in random fashion. Place

the panels side by side and set the counter to “run”. Since the same muon cannot pass through both counters this way (or at least it is very unlikely), this test should fail to count anything at all, or at most one count every few minutes. The rate at which the counter counts in this configuration can be used as an indication of how many “fake” counts one gets.

Next, place the two panels one above the other, with a small separation, say 25 cm. Again, set the counter to “run”, and verify that your results are not too far from the prediction of formulas (2.9) and (2.5). In other words, the rate you measure should be about:

$$N \approx 0.66 \frac{(l w)^2}{d^2} \quad (4.2)$$

with  $N$  the number of muons per minute, if  $l$ ,  $w$ , and  $d$  are in cm. For example, with  $l = 20$  cm,  $w = 15$  cm and  $d = 80$  cm, the cosmic ray rate would be approximately 9 counts per minute.

Another test is to double the distance  $d$  and verify that the rate decreases by approximately a factor of 4. Note, however, that at the relatively small distances  $d$  we are using here, formula (4.2) is not completely accurate.

If the count rate is much too low or too high, try adjusting the threshold values. During experiments, make sure that the 6 Volt supply for the electronics remains constant, and that the tube supply voltages are also unchanged. When you are using batteries, these can change significantly, especially during lengthy measurements.

Once you are satisfied that the CCRT is operating as expected, you may want to try the experiments outlined here, or invent your own. Note, that all experiments involve the variation of some external parameter, such as the angle of the setup, the amount of shielding material, the altitude, or the panel separation. For any of these experiments to have a chance of success, you must avoid the temptation to adjust the internal parameters such as the tube voltages or the threshold settings once the experiment is underway.

The following are a few recommendations based on the above. Use regulated power supplies for the electronics whenever possible for long duration experiments. Otherwise, monitor the lantern battery voltages carefully using a voltmeter. If the battery voltage falls below 5.9 V, the batteries should be replaced. As for the tube power supply, Duracel 9V batteries seem to hold their charge long enough to run an experiment stably over the course of a few hours. However, they also run down slowly, so a voltmeter should be used to monitor the tube voltage during the experiment. This value (about 7.5 V) should be held constant by adjusting the potentiometer.

## 5. Summary

In the previous chapters we have described the design and construction of a simple inexpensive cosmic ray telescope, that can be used in a high-school (or college) physics class. Construction requires no specialized tools, and takes only a modest amount of time. Since both the photo-tubes and the electronics can be battery-operated, classroom safety is assured.

We have also presented several suggestions for measurements that can be performed with the device, and the necessary background information to evaluate the results. At all times, the complexity of the formulas has been kept to a minimum, so that only a calculator is needed to analyze the data. For those interested, an example of a simulation program was also supplied, but its use is not required.

We would like to emphasize that the CCRT is not a toy, but a tool for scientific research that is very similar to particle detectors that are currently used at the frontiers of physics. It is hoped that the CCRT and its applications will help bring modern-day physics to the classroom.

## 6. Acknowledgments

We are very grateful to Hamamatsu Photonics K.K. for providing SLAC with tubes and bases for this effort at their cost price. We also thank W. Ralph Nelson for discussions about the range of muons in metals, and Helen Quinn and P.A. Moore for their efforts in organizing the workshop in Particles and Interactions.

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## FIGURE CAPTIONS

- 1) Photograph of a complete CCRT setup. Some of the components prior to assembly are shown in the foreground.
- 2) Schematic representation of the CCRT, illustrating its functionality.
- 3) Schematic representation of the electronics, demonstrating the conversion of a passing cosmic ray into a coincidence count in the counter.
- 4) Schematic of the photo-multiplier tube and a connection diagram of the 9V power source to the base.
- 5) Photo-multiplier tube characteristics. Displayed are: a side-on tube; the arrangement of dynodes inside it and a representation of the multiplication chain; a schematic of a typical pulse shape demonstrating the important timing parameters of a photo-tube; a diagram of the typical spectral response of bi-alkali photo-cathodes and the relationship between quantum-efficiency and the wave length of the incident light; a schematic of a typical base resistor chain.
- 6) A schematic diagram of the CCRT electronics.
- 7) Component side and trace side drawings of the CCRT printed-circuit board showing component placement and interconnections.
- 8) Photograph of a completed CCRT printed-circuit board.

## APPENDIX A

### COSMIC.C

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*
```

Program to calculate the cosmic ray rate through a set of two rectangular scintillation panels of width  $w$ , length  $l$  and with a distance of  $d$  between them.

The program uses a “Monte Carlo” method, i.e. it generates “cosmic ray events” and tracks them through the panels. If the cosmic goes through both panels, a hit is recorded. The total fraction of hits/tries is the fraction of the solid angle seen by the setup. A “guess” is also calculated, based on the formula:

$$\text{fraction} = \frac{lw}{4\pi d^2}$$

This formula is only a good approximation for fairly large separation  $d$ .

The cosmic ray rate is then calculated as number of counts per minute for the vertical orientation of the setup, where the nominal cosmic ray rate is 1 /min/cm<sup>2</sup>.

```
*  
**/  
#include <stdlib.h>  
#include <stdio.h>  
#include <string.h>  
#include <ctype.h>  
#include <math.h>  
  
void main(int argc, char **argv)  
{  
    double cost, sint, phi, cosp, sinp;  
    double w, l, d, tant, tantx, tanty, xtop, ytop, xbot, ybot;
```

```

long i, n, hit;
double frac, dfrac;

if (argc < 5) {
    printf("Usage: %s <width> <length> <distance> <nevents>\n"
           "Where:\n"
           "<width>    - width of paddles (cm)\n"
           "<length>   - length of paddles (cm)\n"
           "<distance> - distance between paddles (cm)\n"
           "<nevents>  - number of events\n", argv[0]);
    exit(0);
}

w = atof(argv[1]);
l = atof(argv[2]);
d = atof(argv[3]);
n = atol(argv[4]);

printf("Width %g cm\nLength %g cm\nDistance %g cm\n"
       "Number of events %d\n\n",
       w, l, d, n);

/*

    Main event loop
*/
hit = 0;
for (i = 0; i < n; i++) {
    if ((i % 5000) == 0) {
        printf("Event %6d out of %d\r", i, n);
        fflush(stdout);
    }
}
/*

```

We're interested in the accepted number of cosmic rays. Therefore generate  $\cos\theta$  such that it is distributed as  $\cos^2\theta$ . Note that we're interested in  $\cos^2\theta d\Omega$ , which is  $\cos^2\theta d\cos\theta d\phi$ . When one generates  $x = \cos\theta$  as  $\mathcal{R}^{\frac{1}{3}}$ , one actually gets an  $x^2$  distribution:  $P(x) dx = 3x^2 dx = d(x^3) = d\mathcal{R}$  ( $\mathcal{R}$  a random number). Therefore,  $x = \mathcal{R}^{\frac{1}{3}}$ . The factor 3 in  $P(x) dx$  is so the

distribution is normalized, i.e. the integral  $\int P(x) dx = 1$  for  $x$  between 0 and 1 ( $\theta$  between  $\pi/2$  and 0).

```
*/  
    cost = pow(drand48(), 0.333333);
```

```
/*
```

The phi distribution is thrown “flat”.

```
*/  
    phi = drand48() * 2.0 * PI;
```

```
/*
```

Determine a place on the top counter where this one is going to hit. Assume “translation invariance”, i.e. any place on the counter is equally likely to get hit by the cosmic ray.

```
*/  
    xtop = drand48() * w;  
    ytop = drand48() * l;
```

```
/*
```

We “know” that this one hits the top scintillator. Now see if it hits the bottom one. Coordinate system: Z is up,  $\theta$  is wrt. Z-axis,  $\phi$  around it. X is in the “width” direction, Y in the “length” direction. Given  $\cos \theta$  and  $\phi$ , see if the cosmic hits the panel at the bottom. For this to be true, first calculate the direction tangents in x and y.

```
*/  
    sinp = sin(phi);  
    cosp = cos(phi);  
  
    sint = sqrt(1.0 - cost*cost);  
    tant = sint/cost;  
  
    tantx = tant * sinp;  
    tany = tant * cosp;
```

```
/*
```

Extrapolate to the bottom counter

```
*/  
    xbot = xtop - tantx * d;  
    ybot = ytop - tany * d;
```



```

/*
    See if it hits
*/
    if ((xbot < 0.0) || (xbot > w)) continue;
    if ((ybot < 0.0) || (ybot > 1)) continue;

    hit++;
}
/*

    Print out results
*/
printf("Had %d hits out of %d cosemics\n\n", hit, n);

frac = ((double) hit)/((double) n);
dfrac = sqrt((double) hit) / ((double) n);

printf("Accepted cosmic ray fraction:      %g +/- %g\n",
       frac, dfrac);
/*

    Total flux of cosemics through a horizontal area, per unit horizontal area per
    minute, is 1.04 /min/cm2.
*/
printf("Cosmic ray rate through top panel:  %g /min\n",
       1.04 * l * w);

printf("Cosmic ray rate through both panels: %g +/- %g /min\n",
       1.04 * frac * l * w, 1.04 * dfrac * l * w);

if ((d > 2 * w) && (d > 2 * l)) {
    printf("Simple estimate (wl/d^2 formula):  %g /min\n",
           0.66 * (w * l) * (w * l) / (d * d));
}
else {
    printf("Simple estimate not reliable\n");
}
exit(0);

```

}

## APPENDIX B

### ELECTRONICS PARTS LIST

The following is a list of parts needed for the printed circuit board that holds the CCRT electronics. In addition, a cabinet to hold the PC board and various lengths of wire are needed, but these are not listed.

#	PC board designation	Quantity	Description
1		1	PC Board
2	U1, U3, U5	3	$\mu$ A733CN Differential Video Amplifier
3	U2, U4, U6	3	LM360N High Speed Differential Comparator
4	U7, U8, U9, U16	4	74123N Retriggerable Mono-stable Multi-vibrator
5	U10	1	7420N Dual 4-input Nand Gate
6	U11, U13, U14	3	7406N Hex Inverter Buffer/Driver
7	U12	1	74HC4040 12-Stage Binary Ripple Counter
8	U15	1	PPG 38F-10 "Data-Delay" Programmable Pulse Generator
9		5	Excel 500B-PC-16 16-pin DIL Socket PC Pin
10		3	Excel 500B-PC-8 8-pin DIL Socket PC Pin
11		1	Excel 500B-PC-40 40-pin DIL Socket PC Pin
12		8	Excel 500B-PC-14 14-pin DIL Socket PC Pin
13	LED1-LED17	17	GI-MV5753 Light Emitting Diode-Red T 1 3/4 pkg
14	D1-D6	6	1N3064 General Purpose Diode
15	ZD5	1	1N3866 5V Zener Diode
16	SW-1	1	Grayhill #78BR08 8-SPST Switch
17	RP1, RP2	2	Beckman 4300R Series 7-470 $\Omega$ resistors with one common
18	RP3	1	Dale CSOXA Series 8-10k $\Omega$ resistors with one common
19	POT 1-3	3	Bournes 3262W-1K 10-turn Cermet potentiometer 1/4 Watt PC-mount
20	R1, 2, 5, 6, 9, 10	6	51 $\Omega$ resistor 1/4W 5%
21	13, 35	2	1k $\Omega$ resistor 1/4W 5%
22	R15, 17, 19, 20, 21, 22, 31, 33	7	10k $\Omega$ resistor 1/4W 5%
23	R3, 4, 7, 8, 11, 12, 23, 24, 25, 26, 27	11	510 $\Omega$ resistor 1/4W 5%
24	R14, 16, 18, 28, 29, 30, 34	7	5.1k $\Omega$ resistor 1/4W 5%
25	R32	1	100k $\Omega$ resistor 1/4W 5%
26	C1, 4, 5, 9, 12, 13, 17, 20, 21	9	2.2 $\mu$ F capacitor monoblock ceramic subminiature 20% 50V

27	C2, 3, 6, 10, 11, 14, 18, 19, 7, 8, 15, 16, 22, 23, 24, 25, 28, 31, 34, 35, 36, 37, 38, 45, 48	25	0.1 $\mu$ F capacitor monoblock ceramic subminiature 20% 50V
28	C26, 29, 32, 47	4	33 pF Silver Mica dipped 5% 500VDC
29	C27, 30, 33, 34, 39 40, 41, 46	8	10 $\mu$ F electrolytic tantalum, dipped encap. 20 %, 25V
30	C42, 43, 44	3	100pF Silver Mica dipped 5% 100VDC
31	S1	1	C+K 7101 Toggle Switch (miniature) SPDT on-on
32	S2	1	C+K 8121SHCBE miniature SPDT push button
33	S3	1	Cutlerhammer 7563-K4 Toggle switch (not on PC board) DPDT on-off-on

## APPENDIX C

### ORDERING INFORMATION

While the phototubes and bases can be ordered directly from Hamamatsu, SLAC is currently able to buy them at a discount for this particular purpose. For information about ordering phototubes and bases as well as the PC boards and plastic scintillator panels, contact Dr. Helen Quinn, head of the education department at SLAC.

Lucite can be bought from most dealers in plastics.

The analog circuits, viz. the  $\mu$ A733CN (LM733DC) differential video amplifiers in a 14-pin plastic DIP package and the LM360N high-speed differential comparators, are available from the manufacturer, National Semiconductor, or from its licenced distributors (e.g. Hamilton Avnet, see below).

The TTL digital circuits, viz. 74123, 7406, 7420 and 74HC4040 are available from electronics distributors.

The PPG 38F10 Data Delay programmable pulse generator is available directly from the manufacturer:

Data Delay Devices  
3 Mt. Prospect Ave.  
Clifton NJ 07013  
tel. (201) 773-2299

All of the remaining parts (resistors, capacitors, diodes, switches etc.) can be purchased from local electronics distributors, e.g.:

Hamilton Avnet Electronics  
1175 Bordeaux Dr.  
Sunnyvale CA 94089  
tel. (408) 743-3300

Newark Electronics  
1155A Chess Dr. #107  
Foster City CA 94404  
tel. (415) 572-8300

All other materials mentioned in this document can be obtained from most hardware and/or stationary stores.

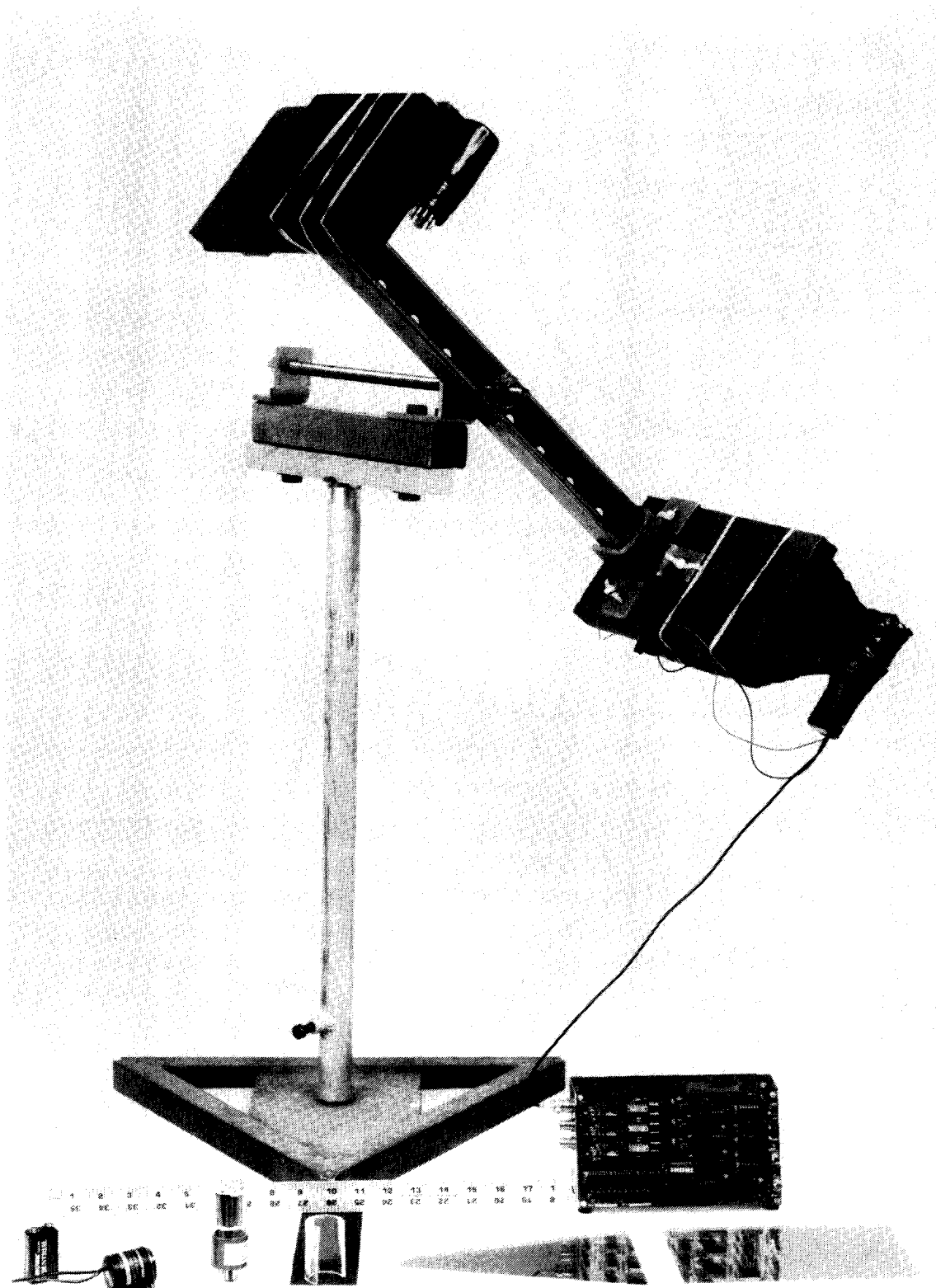
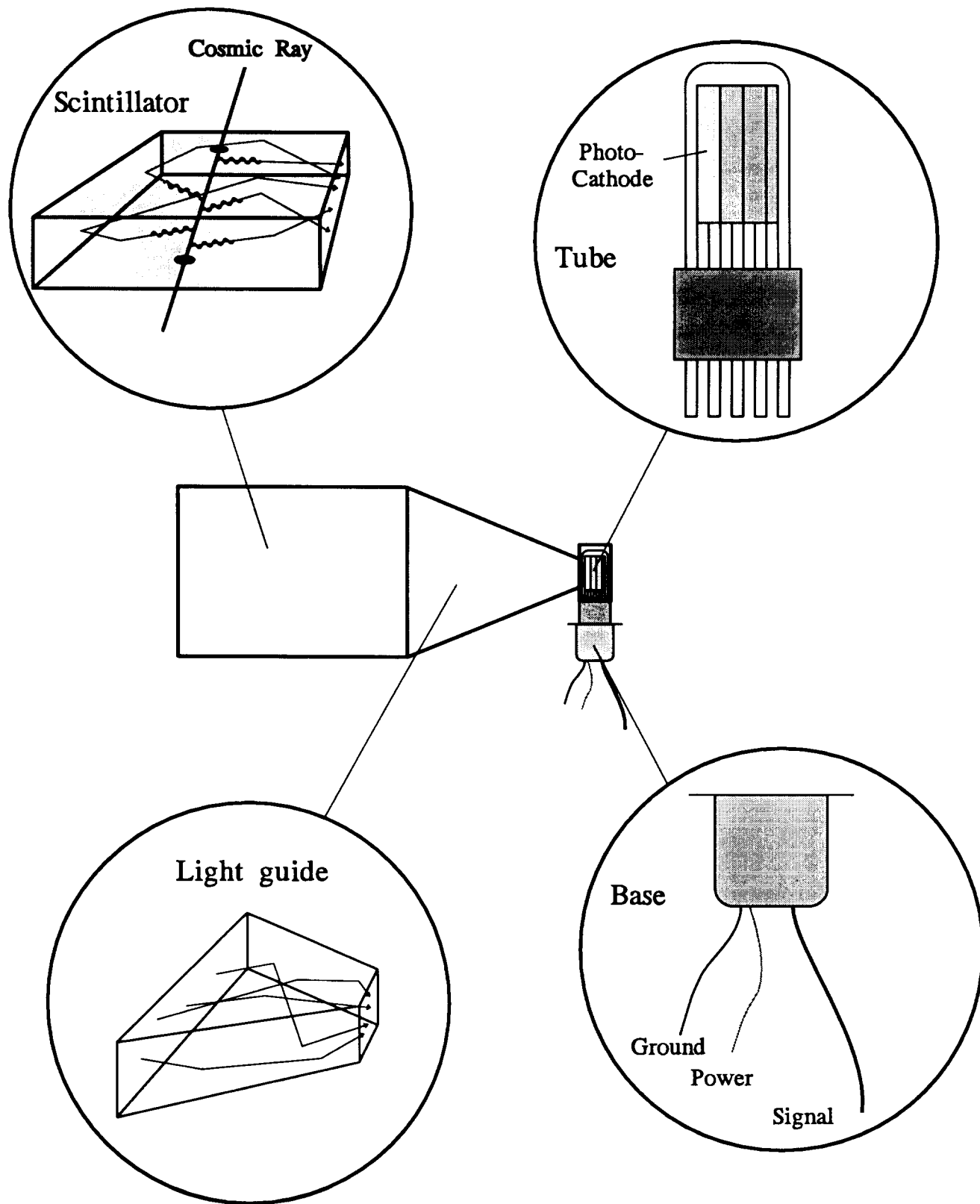
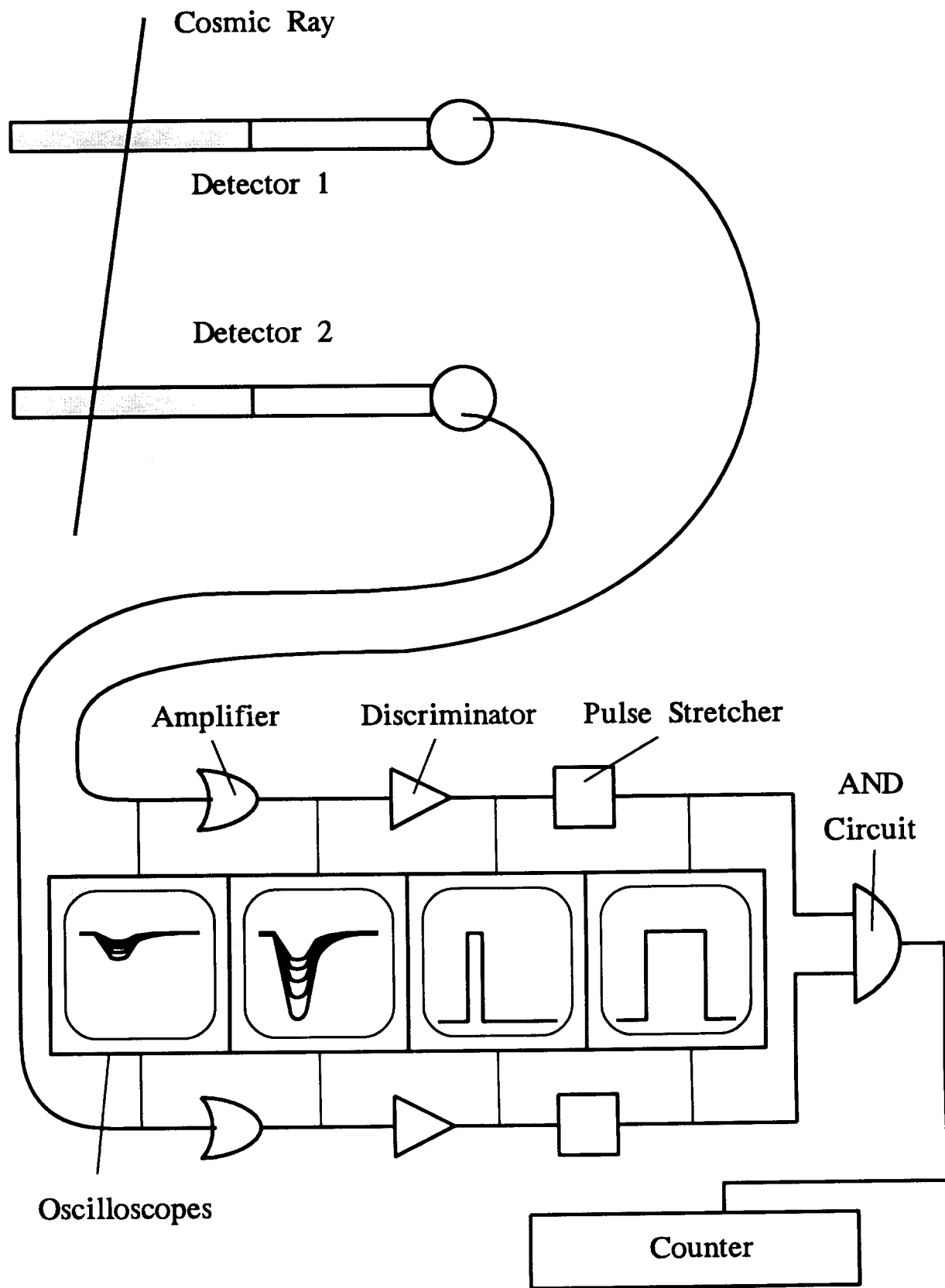


Figure 1



## Cosmic Ray Detector

Figure 2



Cosmic Ray Detector Electronics (Schematic)

Figure 3



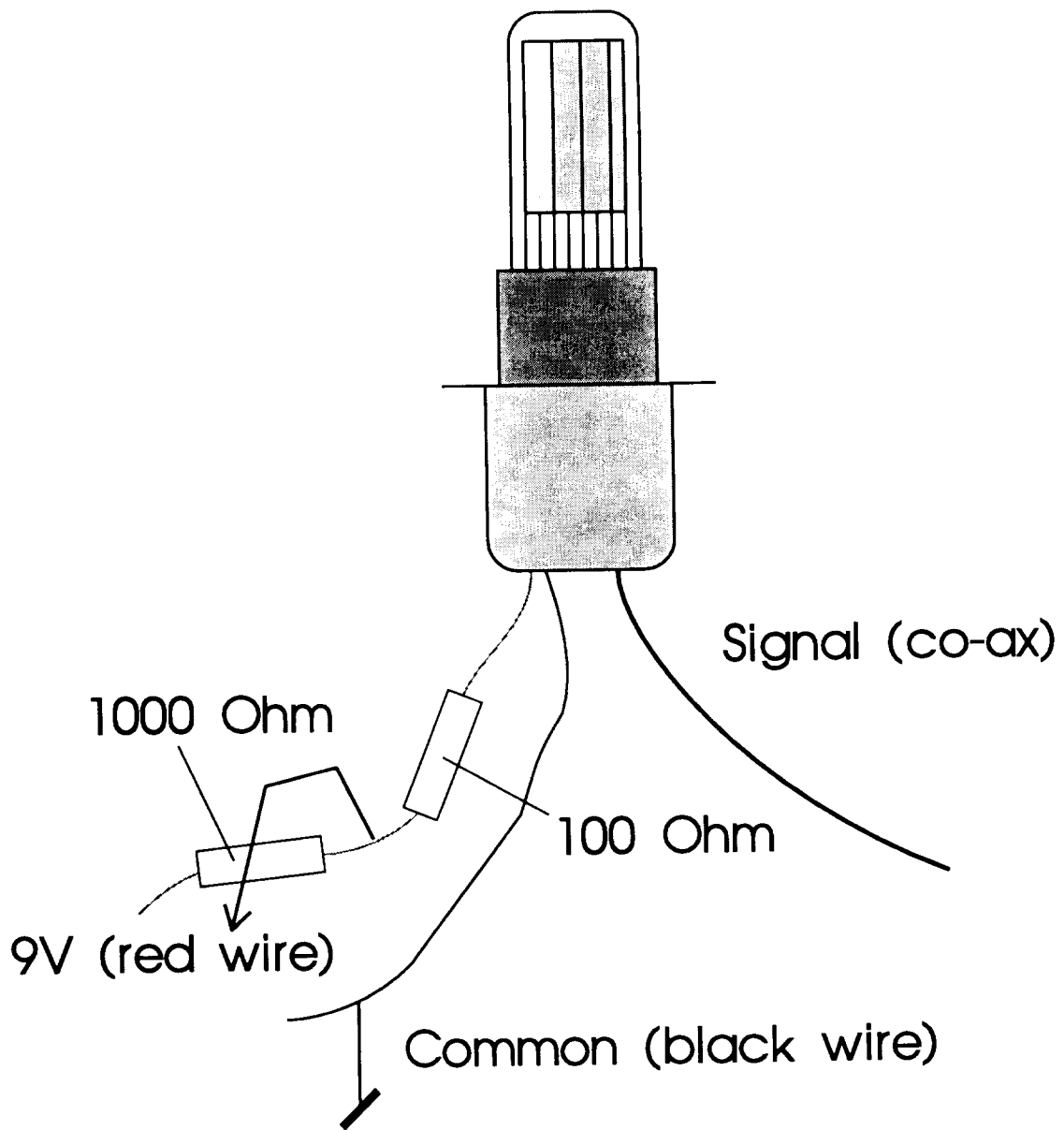
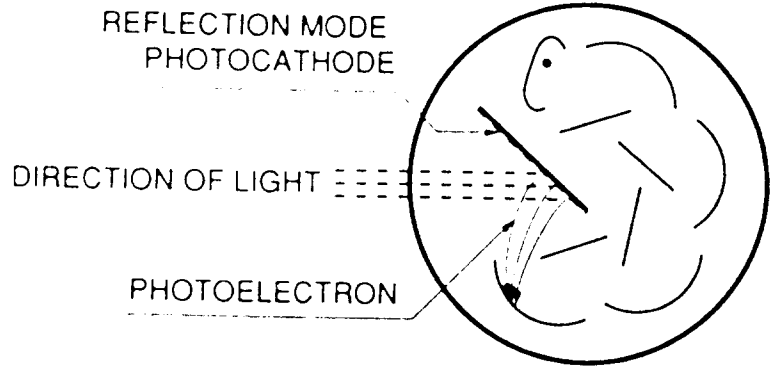
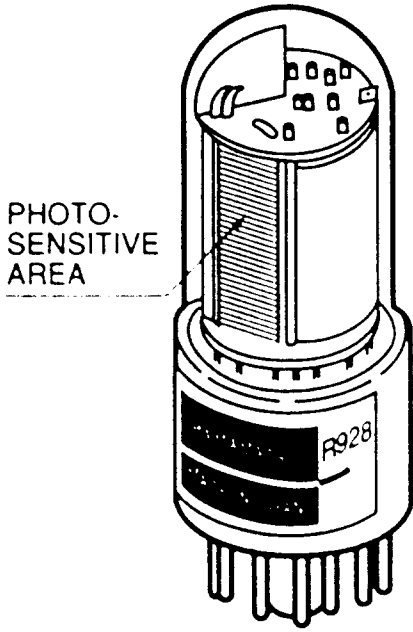
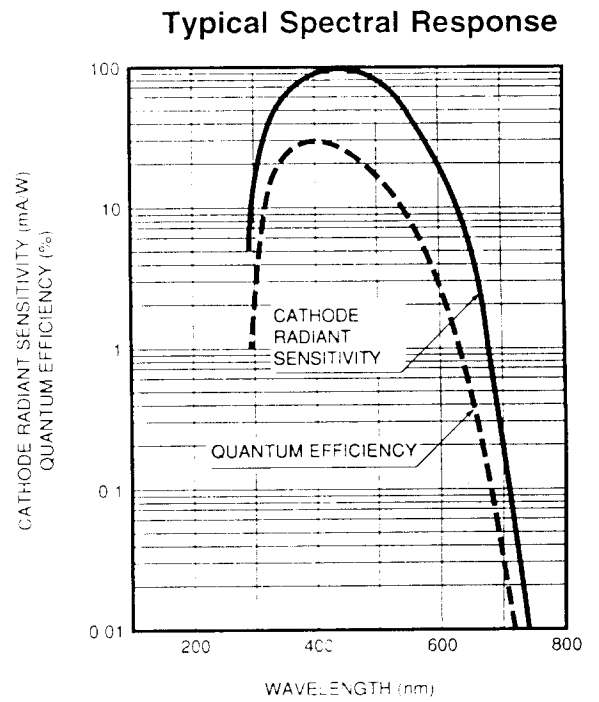
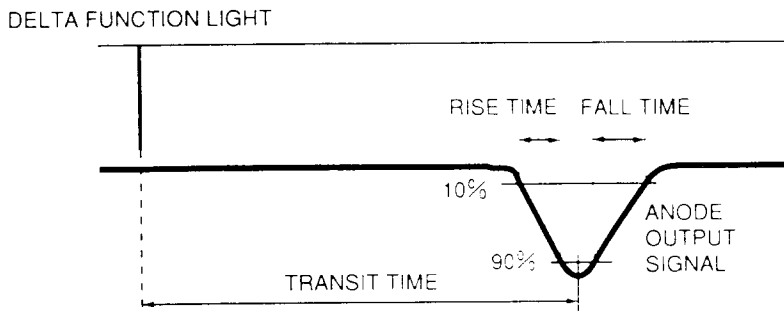


Figure 4

# Side-On Type



## Anode Pulse Rise Time and Electron Transit Time



## Schematic Diagrams of Voltage-Divider Circuits

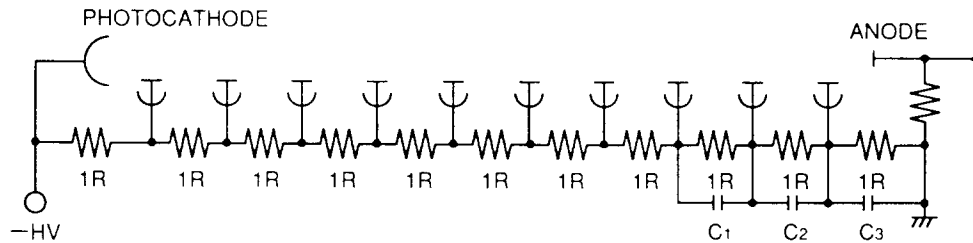


Figure 5

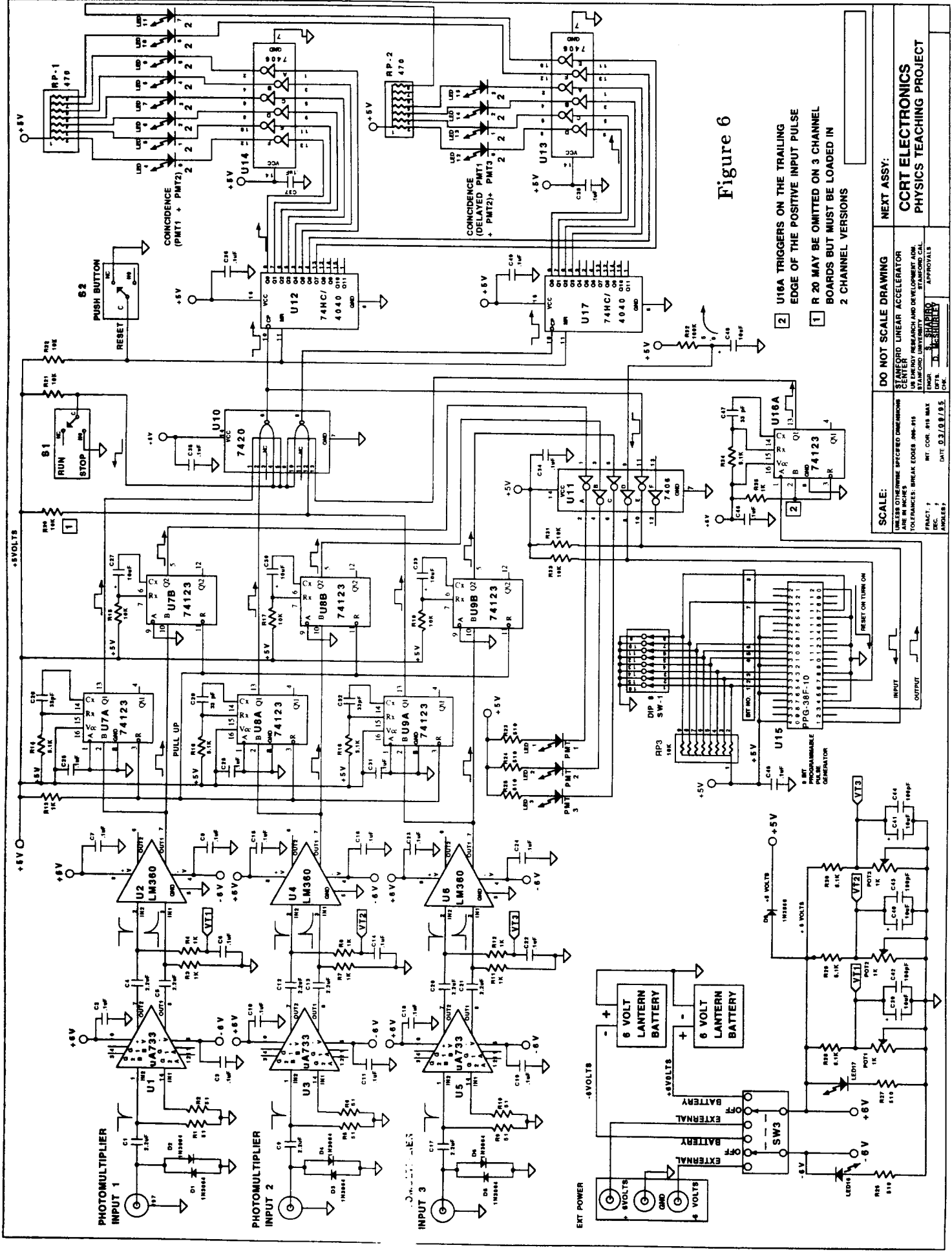
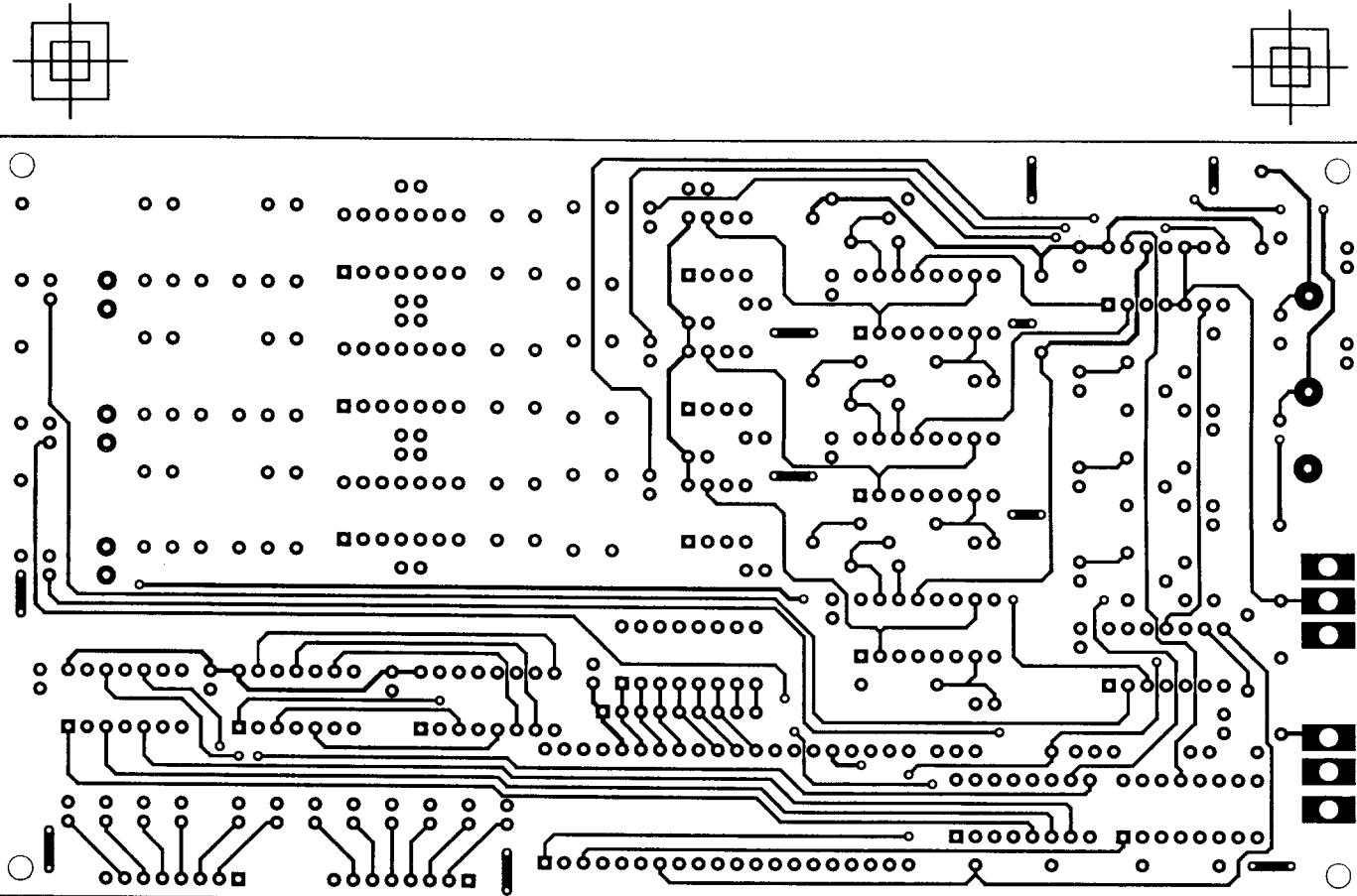


Figure 6

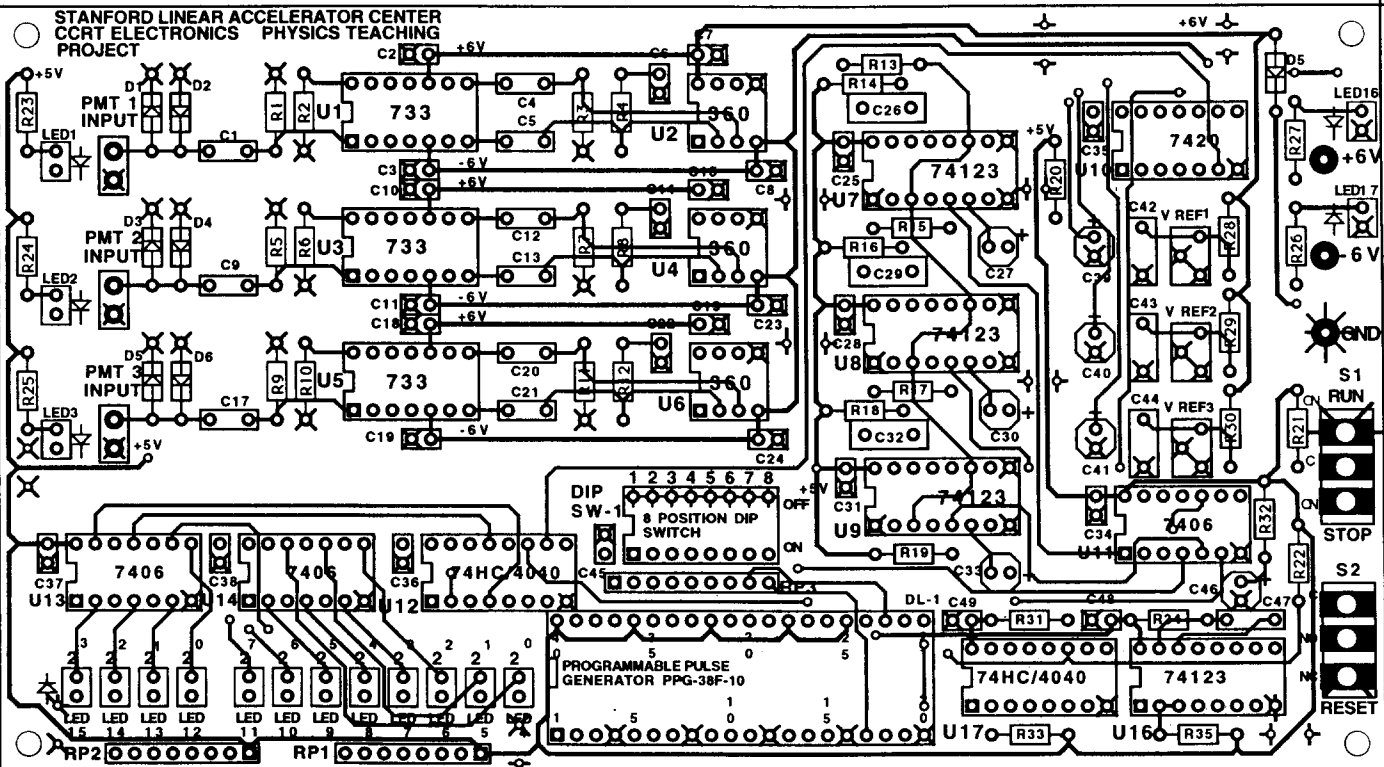
- 1 U16A TRIGGERS ON THE TRAILING EDGE OF THE POSITIVE INPUT PULSE
- 2 R 20 MAY BE OMITTED ON 3 CHANNEL BOARDS BUT MUST BE LOADED IN 2 CHANNEL VERSIONS

SCALE:	DO NOT SCALE DRAWING	NEXT ASSY:
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES	STANFORD LINEAR ACCELERATOR CENTER	STANFORD UNIVERSITY
TOLERANCES: BREAK EDGES: ANG: R15	UNIVERSITY OF CALIFORNIA	STANFORD CALIF.
FRAC. 1/2	INT. COR. R15 MAX	APPROVALS
DEC. 1	DATE: 03/08/95	CHK.



BOTTOM LAYER

STANFORD LINEAR ACCELERATOR	SCHOOL TEACHING PROJECT
McSHURLEY	03/10/95



STOP SCREEN

STANFORD LINEAR ACCELERATOR	SCHOOL TEACHING PROJECT
McSHURLEY	03/10/95

Figure 7

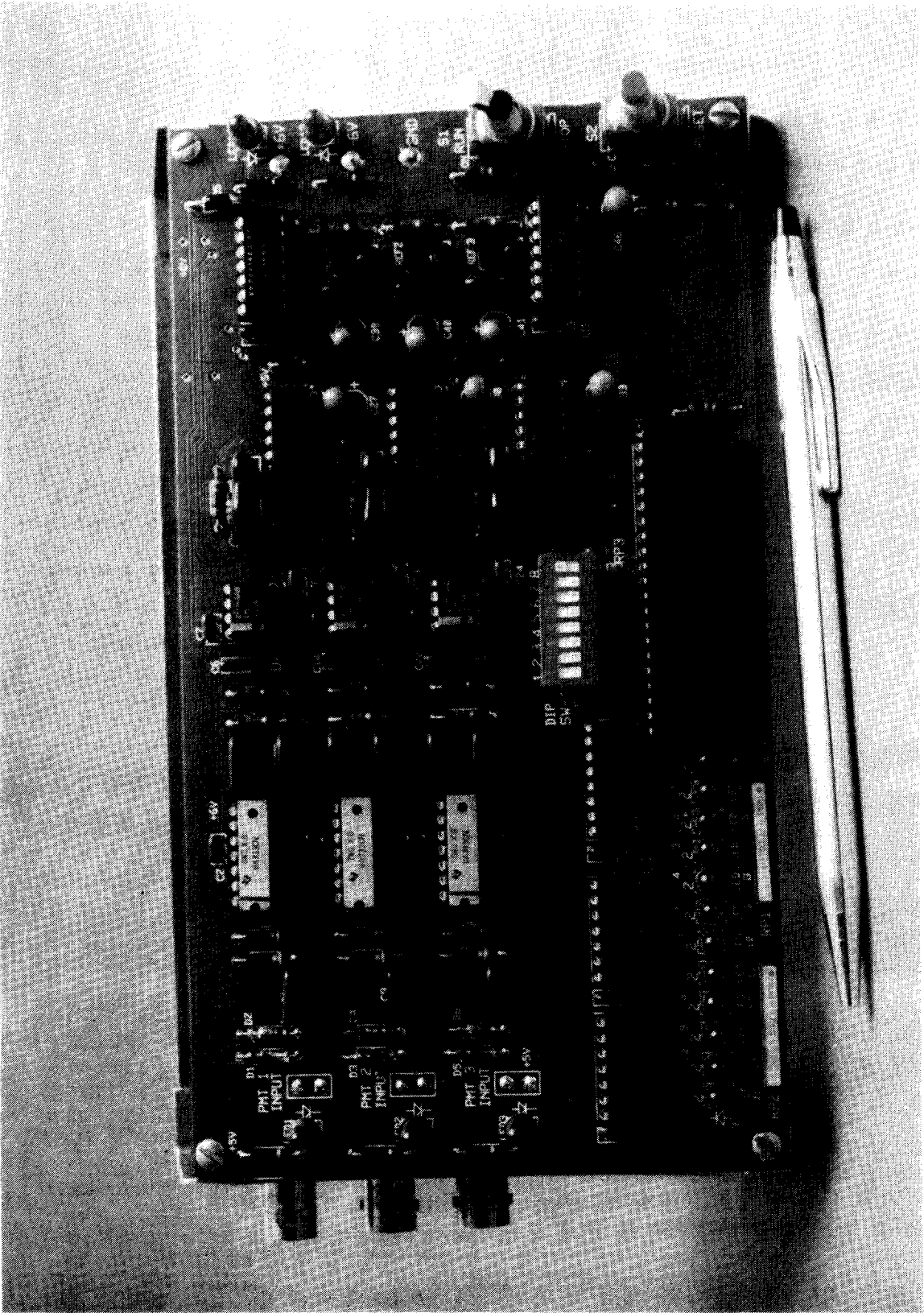


Figure 8