CONSTRUCTION AND USE OF A COSMIC RAY DETECTOR

By Josie Herman
McGill University

July 23, 2002

Contents

1 INTRODUCTION

The Berkeley Cosmic Ray Detector is a portable device that counts the number of cosmic rays passing through its scintillator paddles. Cosmic rays include any high energy particle that originates from outside the Earth's atmosphere. The source of cosmic rays is not yet known, and remains a curiosity of high energy physics today. There are two types of cosmic rays: primary and secondary cosmic rays. Primary cosmic rays are the original particles that entered from outside the Earth's atmosphere. When a primary cosmic ray enters the Earth's atmosphere it reacts with the atmosphere to produce a shower of particles called secondary cosmic rays. The Berkeley Cosmic Ray Detector, C.R.D., detects secondary cosmic rays.

At the Earth's surface secondary cosmic rays are usually muons. This is because of all of the particles created in the particle shower by a primary cosmic ray, only the muon has a long enough lifetime and sufficient penetrating power to travel as far as the Earth's surface. (Protons and electrons also have lifetimes long enough to travel to the Earth's surface, but are easily absorbed). A muon's mean lifetime is $2.20\,\mu s$, (because of relativity this gives the muons plenty of time to reach the surface of the Earth).[1] A muon is a charged lepton, and often referred to as the "heavy electron". Like electrons, there are positively and negatively charged muons. The mass ratio of muon to electrons (m_μ/m_e) is $\sim$206.8.

The expected rate of muons at sea level is roughly 1 muon/cm^2/min/steradian.[2] The Berkeley Cosmic Ray Detector allows the verification of this expected frequency.

2 PARTS OF THE COSMIC RAY DETECTOR

The C.R.D. is made up of four major parts: the scintillator, the photomultiplier tubes, the coincidence circuit and the aluminum box. The muons pass through the scintillator where they release a certain amount of energy as light. This light is detected by the photomultiplier tubes (PMTs) which then transmit an analog pulse to the circuit board. The circuit board checks to see if both detectors have seen this muon and, if so, outputs a count on the digital display. The aluminum box is for physical support of the scintillator, PMTs and the circuit (see Figures 1, 4).

2.1 THE SCINTILLATOR

The type of scintillator used in the C.R.D. is plastic scintillator. Plastic scintillator is usually made of polystyrene or polyvinyltoluene and looks much like Plexiglas. When any charged particle passes through scintillator it excites the atoms in its path. When these excited atoms return to their ground state they release some energy as light (photons), a process called scintillation.

Once the photons are produced in the scintillator, some of them are retained in the scintillator until they reach the window of the PMT. The photons are retained in the

---

[1]R.P.P., page 23
[2]R.P.P., page 151

Figure 1: The Berkeley Cosmic Ray Detector.

scintillator by total internal reflection. The index of refraction of most plastic scintillator is around 1.58, $(n_s = 1.58)$. Assume that the scintillator is surrounded by air, $(n_{air} \cong 1)$. The critical angle, ϑ_c, (the minimum angle of incidence for which total internal reflection is observed) can be found using Snell's Law as in equation 1.

$$n_1 sin\vartheta_1 = n_2 sin\vartheta_2 \tag{1}$$

Where the ϑ_1 is the incident angle, n_1 is the index of refraction of the first medium, ϑ_2 is the transmitted angle and n_2 is the index of refraction of the second medium. For the photons produced in the scintillator (in the scintillation process), the scintillator is the first medium and air is the second medium in equation 1. When $\vartheta_1 = \vartheta_c$, $\vartheta_2 = 90^o$ and $sin\vartheta_2$ is therefore equal to one. As ϑ_1 increases from the critical angle, total reflection is still observed. Therefore, to have total internal reflection inside the scintillator where $n_s = 1.58$,

$$sin\vartheta_1 \geq \frac{1}{n_s} = \frac{1}{1.58} = 0.63 \tag{2}$$

That is in order for the photons to stay inside the scintillator the incident angle must be at least 39.0^o.

Not all of the photons will be incident on the surface of the scintillator at an angle larger than 39.0^o. In an effort to recover some of the light that does escape, the scintillator was wrapped in a reflective material called TYVEK. TYVEK has a highly reflective surface that is intended to reflect (at random angles) the escaped photons back into the scintillator. Further investigation can show that in order for the TYVEK to effectively reflect the photons back into the scintillator, the index of refraction of the scintillator

must be larger than $\sqrt{2}$, (see Appendix: Total Internal Reflection). The index of refraction of the plastic scintillator used in the CRD was $1.58 > \sqrt{2}$, thus satisfying this condition.

The only exit for the photons is a section in the scintillator large enough for the PMT window. The reason that the photons can exit here is that the material making contact with the scintillator is no longer air, it is optical grease. The index of refraction of optical grease is such that the critical angle has been changed dramatically. The index of refraction of the optical grease is 1.465 (Bicron product BC 630), where the critical angle is 68.0^o. (Note that $1.58 > 1.465$, a necessary condition for total internal reflection.) The photons incident on the PMT window must then be at an angle smaller than 68.0^o in order to be transmitted through the optical grease and onto the PMT window.

One can quickly see that a lot of the photons produced inside the scintillator will never reach the window of the PMT. It turns out that this does not matter for the C.R.D. The number of photons produced by the passing of a muon through 1 cm of scintillator is estimated to be 2×10^4.[3] Most of the muons detected are travelling almost completely vertically, and therefore travel through approximately 2.5 cm of scintillator in the C.R.D.[4] Though many photons are lost before ever reaching the window of the PMT, the PMT is capable of detecting as few as several photons. Despite the inefficiencies of the scintillator, the PMTs are sensitive enough that there is no significant effect on the efficiency of the C.R.D. (A way to test the efficiency of the C.R.D. is explained in Section 5.4.)

2.2 THE PHOTOMULTIPLIER TUBES

Photomultiplier tubes are devices that can convert very small amounts light into a pulse of current. When photons strike the cathode, (also called the photocathode), of the PMT photoelectrons are produced by the photoelectric effect. The PMT is designed to multiply the number of photoelectrons until they produce an electrical signal that is large enough (of the order pC) to be detected by simple electronics. PMTs were used in this C.R.D. to detect the small amount of light produced by the muons when they passed through the scintillator. The PMT outputs a small pulse of negative current after the passing of a charged particle through the scintillator. This small current can be seen on a oscilloscope as a negative analog pulse of voltage, with an amplitude of several hundred mV and a width of about 40 ns (see Figure 2).

PMTs have three main components. There is a photocathode, several dynodes, and an anode (see Figure 3). The photocathode is the location at which the photoelectrons are produced and is always at negative high voltage with respect to the anode. The dynodes are semi-conductor coated conductors located between the photocathode and the anode. The dynodes are arranged in a ladder type fashion and are kept at voltages that increase as you move from the photocathode to the anode. The photoelectrons travel from one dynode to another by following the electric field produced by the voltage gradient between the dynodes. Upon striking a dynode several secondary electrons are

---

[3]R.P.P. , page 174

[4]This is due to the fact that the angular distribution of cosmic rays is proportional to $\cos^2\theta$.
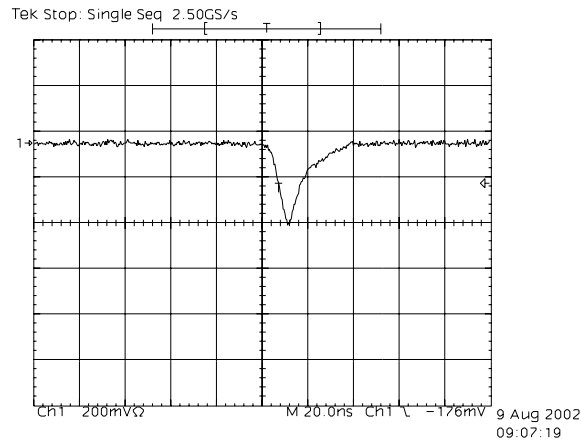
Figure 2: A sample pulse output by one of the PMTs in the C.R.D. The pulse's width is approximately 40 ns, and its height is 400 mV. This pulse was recorded using a Tektronix digital scope.

produced for every incident electron. PMTs usually have between 10 and 14 stages of dynodes leading to gains up to 10^7![5]

PMTs are not 100% efficient at converting all of the photons that strike the photocathode into photoelectrons. The quantum efficiency, $n(\lambda)$, is a measure of the photocathode's ability to convert incident photons into photoelectrons.

$$n(\lambda) = \frac{number\ of\ photoelectrons\ produced}{number\ of\ incident\ photons} \tag{3}$$

The PMTs used in the C.R.D. were from Electron Tubes, model number 9125B. The quantum efficiency for these PMTs is around 20% for wavelengths between 380 nm and 630 nm, which includes the wavelengths of the light output by the scintillator. With a quantum efficiency of 20%, one would expect that for every five photons that strike the photocathode's surface, one photoelectron is produced.

The PMTs used in the C.R.D. were a photodetector package from Electron Tubes (model P30CW5). The photodetector package included the PMT and a negative high voltage power supply. The PMTs have 11 dynodes. The maximum voltage that the PMTs can withstand is 2000 volts. The PMTs are equipped with their own negative high voltage power supply and require only 5 volts DC to operate. The HV of each PMT is adjustable using a small screw at the back of the PMT. The HV on the PMT can also be monitored using a voltmeter to read the voltage on the white and yellow wires which is 1/1000 of the actual voltage on the PMT. The PMTs were wired up to the PC board, which itself required 12 volts DC to operate. The C.R.D. was wired up so that it could be operated using two 6 volt (RadioShack) batteries wired in series or using a DC adapter (Recoton) that can be plugged into a wall socket (see Figure 4).
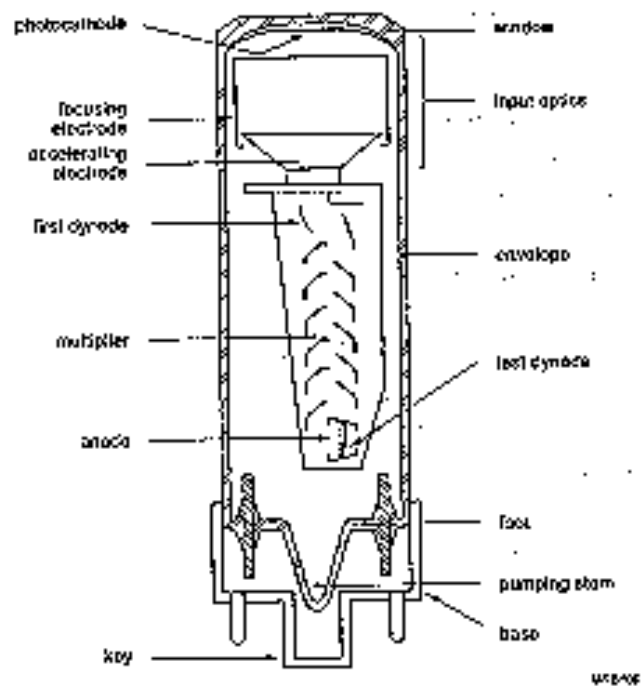
[5]Leo page 181

6

Figure 3: A schematic of the inside of a PMT. Note that in the C.R.D. the high voltage is supplied by the PMT's base, the PMT itself only requires 5 volts to operate.

Figure 4: Above all of the components of the C.R.D. have been removed from the aluminum box for better viewing. The batteries and DC adapter are the power supply options.

The PC board split the input voltage (12 volts) so that each PMT was supplied with 5 volts DC.

In order not to confuse the passing of a muon with photons from the light in the room the detectors were made light-tight. If the detectors were not made light-tight then photons could either directly hit the photocathode of the PMT or enter the scintillator and get bounced around by total internal reflection until they hit the photocathode. In either case, these photons do not represent the passing of a muon and need to be eliminated (also too much light can destroy the PMT).

2.3   TWO SCINTILLATOR PADDLES AND TWO PMTS

The passing of penetrating particles, charged particles, radioactivity, light leaks and dark current will all cause the PMT to fire. The pulses caused by the passing of penetrating particles (usually muons) can be distinguished from the other signals by using a coincidence circuit. Penetrating particles can pass through large amounts of material before stopping. The less penetrating particles, (protons, electrons), will stop just after or during their travel through a piece of scintillator. Muons have such a large amount of energy that they continue with only small changes in their momentum after passing through a piece of scintillator. It is because muons can pass through a piece of scintillator with only very small changes in their momentum that two scintillator paddles are used with two PMTs in the C.R.D. If a particle is detected that has passed through both scintillator paddles within a specified amount of time, called a coincidence, then that
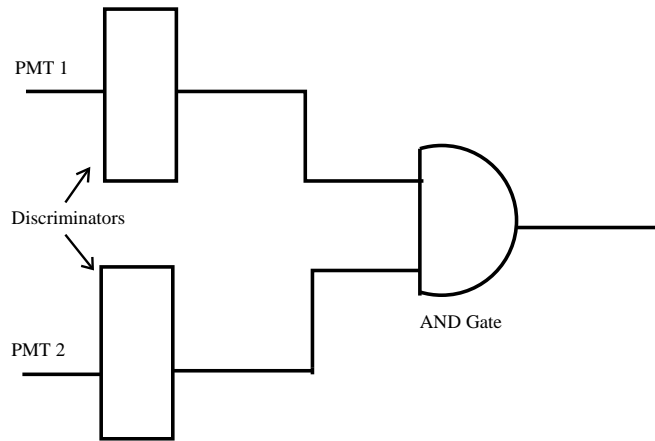
Figure 5: A schematic of the electric circuit used for the coincidence counting in the C.R.D.

AND Truth Table		
Top PMT	Bottom PMT	Output
0	0	0
0	1	0
1	0	0
1	1	1

Table 1: The truth table for AND logic.

charged particle must have been a penetrating particle (most likely a muon).

The electric circuit is the device that enables proper comparison between the events in the two scintillator paddles. The electric circuit has separate inputs for each PMT (See Figure 5). When an analog pulse is received at the PMT input of the circuit that is larger (more negative) than the threshold, -50 mV, the circuit produces a digital pulse that is 800 ns wide. This 800 ns wide digital pulse is then carried through the rest of the circuit. If the PMT inputs a pulse that is smaller (less negative) than the threshold of -50 mV or inputs nothing at all, the digital signal remains a "zero", and the zero is carried through the rest of the circuit. The inputs from the top PMT and the bottom PMT are compared using AND logic. The output after the AND gate is true (or a non-zero digital pulse) if and only if both PMTs are true (or have a non-zero digital pulse that overlaps). The truth table for AND logic is as in Table 1.

Where a "1" represents a non-zero digital pulse and a "0" represents no digital pulse.

The really important part about this circuit is to understand that any overlap of two non-zero digital pulses causes a digital pulse (or a "1") to be output from the AND gate. This means that the two pulses can be separated in time by up to 800 ns and still be counted as the passing of a muon. This type of counting is often referred to as

coincidence counting, since a count only occurs when the event has been seen by both counters at the "same" time.

Muons travel very close to the speed of light, that is,

$$\beta = \frac{v}{c} \cong 1 \tag{4}$$

The maximum time required for a muon to travel from one scintillator to the other would be along the diagonal separating the two opposite corners of the scintillator paddles. The scintillator paddles are separated by 12 cm and each is $20.3\,cm \times 30.5\,cm$. Using some trigonometry, the diagonal separating the two opposite corners of the scintillator paddles is found to be approximately 38.5 cm. Travelling roughly at the speed of light, the most time that a muon would take to travel from one scintillator to the other would be 1.3 ns. The circuit produces an 800 ns pulse which allows for more than enough time for a muon to travel from the top to the bottom paddle. However, the frequency of pulses from one paddle one scintillator paddle of the C.R.D. is about $100\,s^{-1}$, which means that the time between each pulse is roughly 0.01 s. Because this time interval is so much larger than 800 ns, it would not be expected that there would be many counts resulting from an accidental coincidence mistakenly being counted as a real coincidence (the passing of a muon).

When using the coincidence counters, one would expect that the frequency of coincident events would be lower than the frequency if only one counter were used. This is because most of the background pulses would be eliminated in the coincidence circuit. The Berkeley Lab Circuit allows for quick verification. Using the PMT switch, it was very easy to see that the frequency pulses of only one PMT, either the top or the bottom, is approximately 10 times faster than the frequency of coincidences.

2.4 THE ALUMINUM BOX

The purpose of the aluminum box is for physical support of the scintillator paddles, the PMTs and the electronic circuit. It is important to realize that the aluminum box does not interfere with the counting of cosmic rays. Cosmic muons are so high in energy that passing through 1.5 mm of aluminum does not decrease their energy by an amount significant enough to prevent them from passing through the scintillator paddles. The aluminum may inhibit other lower energy particles from entering the detector, but that is not of any concern because those particles are of no interest here.

3 BUILDING THE COSMIC RAY DETECTOR

Building the C.R.D. involved several major steps. The scintillator had to be cut to size, polished and glued. The circuit board had to be stuffed and soldered, the PMTs had to be wired up and attached to the scintillator and finally the aluminum box had to be built.
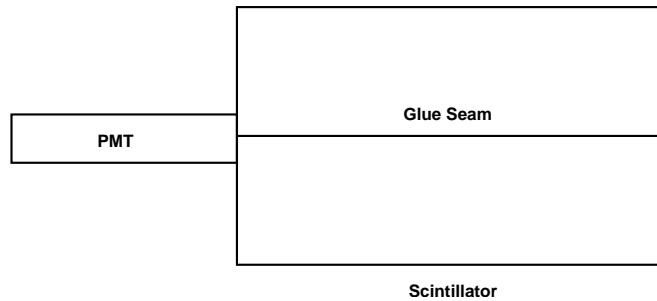
Figure 6: The two pieces of $10.2 \times 30.5\,cm$ scintillator were glued together to make a wider ($20.5 \times 30.5\,cm$) counter. The PMT sees the light from both scintillator paddles.

3.1 THE SCINTILLATOR

The scintillator material used in the C.R.D. was plastic scintillator recycled from a time-of-flight hodoscope used in a Fermilab experiment in the 1970s. It was in the form of thick (2.5 cm) and narrow (10.2 cm) strips. Scintillator is quite an easy material to machine though a lot of coolant must be used to prevent it from melting. A bandsaw was used to cut it roughly to length (the paddles were to be 30.5 cm long). A milling machine with a digital readout was then used to machine the pieces more precisely to size, $10.2\,cm \times 30.5\,cm$. The milling machine left a relatively smooth surface, but the scintillator still had to be polished to get the surface shinier and scratch free. The polishing was done very carefully using 1000 and then 2000 grit sandpaper that had been wet with water. To give an even fuller shine, the surface was then polished using an aluminum oxide paste and a clean soft cloth. The efficiency of the counters increases as the reflective surface of the scintillator is improved since trapped light bounces around longer and has a better chance to encounter the PMT window. The final polishing steps were really only to increase the efficiency of the counters.

Once the scintillator had been polished, it was then ready to be glued. Two pieces of scintillator were glued together because the dimensions of the scintillator on hand was not wide enough. Two pieces of $10.2\,cm \times 30.5\,cm$ scintillator were glued together to make one piece of $20.5\,cm \times 30.5\,cm$ scintillator (see Figure 6). The glue that was used was Bicron 600, a special two-part epoxy made specifically for gluing scintillator. An excess of glue was used to ensure that the seam was free of air pockets . Three bar clamps were used during the gluing to ensure enough and relatively even pressure was exerted on the scintillator during the gluing. It was very important to get as much excess glue off as possible when the glue was wet as scraping and sanding it off later would ruin the scintillator's smooth surface.

3.2 ATTACHING THE PMTs

The PMTs must be physically attached to the scintillator paddles. Normally the window of the PMT is glued directly to the scintillator. This procedure is a very committed
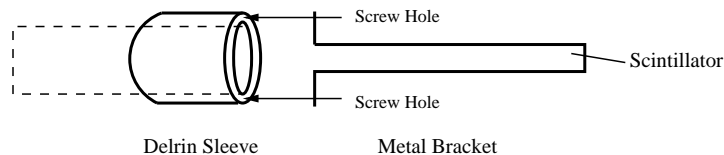
Screw Hole

Scintillator

Screw Hole

Delrin Sleeve   Metal Bracket

Figure 7: The physical support system used to keep the PMTs attached to the scintil-
lator. The PMT's window was covered in optical grease to make good optical contact
between the surface of the window and the surface of the scintillator. The arrows rep-
resent where the screw holes were made.

engagement as it often involves damaging either the PMT or the scintillator if ever the
PMT is to be removed. In an effort to make a less permanent attachment, a different
method was used.

First, a metal bracket was made that fit around the back of the TYVEK-wrapped
scintillator. This bracket attached to a cylindrical sleeve that fit around the PMT (the
cylindrical sleeve was made out of Delrin because it was on hand and easy to work
with). The PMT's window was covered with optical grease and slipped into the tightly
fitting cylindrical sleeve. The metal bracket was screwed into the cylindrical sleeve
(see Figure 7).

3.3   WRAPPING THE PMTS AND SCINTILLATOR

In order to eliminate external light from causing invalid muon counts, the PMTs and
scintillator were made light-tight. The scintillator was first wrapped in TYVEK in an
attempt to recapture escaping photons (see Section 2.1). Once the scintillator was fully
wrapped in TYVEK, leaving only an opening small enough for the PMT's window, the
PMT was attached using the Delrin sleeve and the metal bracket. Both the PMT and
the scintillator were then wrapped in black electrical tape. It required two layers of
black electrical tape to get the counters light-tight, with special attention payed to the
corners of the scintillator.

Once the counters were wrapped they were put aside until further testing of the
light-tightness could be done using the electrical circuit.

3.4   THE COINCIDENCE CIRCUIT

The circuit design as well as the printed circuit board used in this C.R.D. were both
courtesy Howard Matis of Ernest Orlando Lawrence Berkeley National Laboratories.
The PC board needed only to be stuffed with the correct electronic components and
have those components soldered in place.

3.5   CONNECTING PMTS TO THE CIRCUIT BOARD

The PMTs' spec sheet explains the purpose of the four wires at the back of the PMTs.
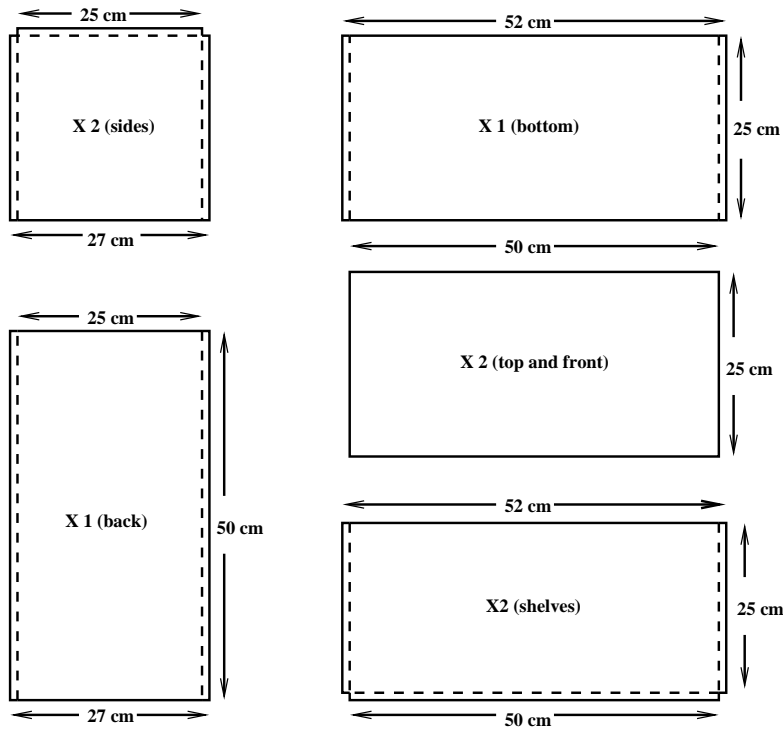To provide more flexible use of the counters lemo connectors were put on as the PMTs'

Figure 8: Above are the diagrams of all of the pieces of sheet aluminum required to build the aluminum box for the cosmic ray detector. The dotted lines represent where the aluminum was bent.

connectors. Once lemo cables were soldered to the DC inputs and PMT outputs, all of the cables were labelled for easier identification.

3.6 THE ALUMINUM BOX

The design of the aluminum is as depicted in Figure 8.

The aluminum box was all made out of soft utility grade sheet aluminum (1.5 mm thick). This sheet metal was soft enough to bend without breaking.

The only tools required to make the box were large shears, a milling machine, a bending machine, a hand drill, and a rivet gun. Before the back panel was attached to the box, a rectangular hole was cut out for a Plexiglas window for the circuit board. The hole was cut out using a milling machine (see figure 9). Once the pieces were all cut and folded, they were clamped together one by one, drilled and riveted. The shelves were put in last.
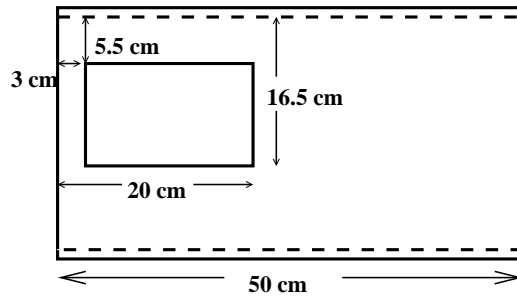
Figure 9: The hole in the back panel for the Plexiglas window. The Plexiglas window is for mounting and viewing the electronic circuit.
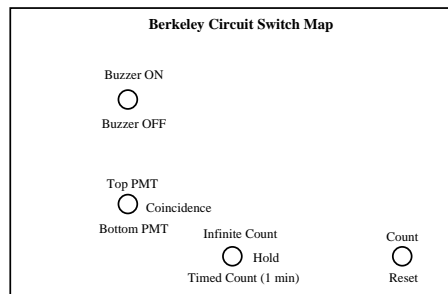

Figure 10: The switch map for the Berkeley PC board is as depicted above.

4 BEFORE USING THE COSMIC RAY DETECTOR

4.1 THE SWITCHES

The Berkeley PC board switches are as shown in Figure 10. There is a green LED located beside the buzzer that lights up whenever the circuit is in counting mode. If the counter is in "Hold" or "Reset" mode, the circuit will not count events and the green LED will not light up. When using the "Timed Count" feature, the circuit holds the count as recorded at the end of one minute until the counter is "Reset". The circuit will start timing as soon as the switch is brought down to "Timed Count", even if still in "Reset" mode. In order to restart a "Timed Count" one can wait until the time is up or disconnect the power supply and start again.

4.2 ADJUSTING THE TIMER

The timer on the Berkeley Lab PC board does not come preset to one minute. The timer is controlled by a $100\,k\Omega$ resistor pot. There is a small screw on the side of the resistor pot which varies its resistance. As the resistance varies the time of the "Timed Count" also varies. To get the right resistance the screw was adjusted and a stop watch was used to time how long the green LED was illuminated during the "Timed Count".

14

4.3 CHECKING THE COUNTERS

Once the counters were made and wrapped and the PC board was stuffed and soldered, the counters were checked. Each counter was checked individually by using the PMT switch on the PC board. The frequency of pulses coming from one counter is very high, roughly 100 counts per second. The PMT switch was then moved to coincidence to ensure that this feature was actually working. To get a rough estimate as to what the coincidence/muon frequency should be, the area of the scintillator paddles must be known. The area of each scintillator paddle in this detector was 620 cm^2. The frequency of muons above 1 GeV (most are around 4 GeV) as recorded in the Review of Particle Physics is roughly 1 muon/cm^2/min/steradian at sea level.[6] It would then be reasonable that at an elevation of $\sim 15\,m$ above sea level in downtown Montreal, on the third floor of a five story building that the frequency of muons was found to be $420 \pm 8\,\mu/cm^2$.

If the counts are too high, the most likely problem is that the counters are not light tight. To test for light leaks a thick black blanket was used and the PMT switch was put on single coincidence of the counter being checked. The counters were wrapped in the blanket one at a time. The blanket was slowly removed while watching the frequency of the counter. When the frequency went very high, the light leak was in the vicinity of what had just been uncovered. The light leaks were then covered with more black electrical tape. This process was continued until the light leaks' exact locations were found.

5 USING THE COSMIC RAY DETECTOR

5.1 Pulse Height Spectrum

When using PMTs it is standard to graph a pulse height spectrum. A PMT outputs a small negative current, and when detected by electronics other than an ammeter, this is converted to a small negative voltage pulse. The pulses vary in size and amplitude depending on the number of photons that struck the PMT's photocathode, (less photons make a smaller pulse). When a muon passes through a certain amount of scintillator it will lose the same amount of energy to the excitation of the particles in its path regardless of how much energy that particular muon had upon entering the scintillator. As a result, the only significant variation in the light emitted by the excited particles falling back to their ground state, is caused by the muons having different path lengths through the scintillator . The actual pulse height is the area under the analog pulse output by the PMT (a slight misnomer). The angular distribution of muons is proportional to $cos^2\theta$, so the majority of the muons are coming straight down through the scintillator paddles. Since the majority of the muons passing through the scintillator are incident at very small angles to the normal of the scintillator, the majority of the muons travel the same distance through the scintillator and hence cause the production of roughly the same number of photons. As a result, the analog pulses output by a PMT due to the passing of a muon are roughly the same size and a graph of their pulse height versus frequency can be fit to a Landau distribution.

---

[6]RPP, page 151

A Landau distribution is very asymmetric. The incline of the Landau is quite steep and it has a long tail that extends towards high x-values. The mathematical formula for a Landau is as in equation 5.

$$L(x) = e^{-\frac{1}{2}\left(\lambda + e^{-\lambda}\right)} \tag{5}$$

Where,

$$\lambda = \frac{x - x_{ave}}{\sigma} \tag{6}$$

The long tail of the Landau fits the pulse height spectrum very well since there exist, though they are rare, very energetic interactions that produce a lot of light (hence large pulse height).

Pulse height spectra are made to ensure that the PMT is operating with optimal gain. If the gain is too low, or the threshold is too high all of the small pulse heights are cut out and a proper Landau distribution cannot be achieved. If the gain is too high, all of the pulse heights are huge, max out the ADC and no useful information is obtained. The gain of a PMT is controlled by varying the high voltage on the PMT since the gain depends on a power of the high voltage.

The lower energy side of the pulse height spectrum most likely due to muons passing through a corner of the scintillator and/or from thermal emission, neither of which cause the production of as many photons as a muon passing directly through the center of the scintillator. These small pulse heights can be fit to a background line, or eliminated by setting the threshold of the discriminator higher.

In figure 11 are the pulse height spectra of the two PMTs used in the cosmic ray detector. These pulse height spectra were obtained by the external trigger experiment explained in Section 5.4. The pulse height spectra were fit to Landau curves as well as a Landau with background line curve. The low pulse height events are not present in the graphs in figure 11 because of the external trigger set up.

5.2 Warm Up Time

PMTs often need time to warm up. When PMTs have been disconnected from high voltage for an extended period of time their gain can vary a lot when they are first turned on. In order to determine if the PMTs used in the C.R.D. required warm up time, a test was done. The PMTs were both disconnected from their power supply overnight. In order to get more useful data the C.R.D. circuit board was not used and each PMT was tested individually using a NIM/CAMAC set up in the McGill HEP lab (see Figure 12). The output of the PMT was put into a splitter (see Appendix). One of the signals from the splitter was put into a discriminator and the other signal was put into a delay loop. While one signal was being delayed, the other signal did the triggering. OR logic with a single input was used for the triggering so that the gate triggered every time a pulse from the PMT was larger than the 50 mV threshold. The output of the OR gate triggered the gate generator which started the recording of the pulse height. The pulse height is obtained by integrating the area under the analog signal that was delayed during the triggering process.
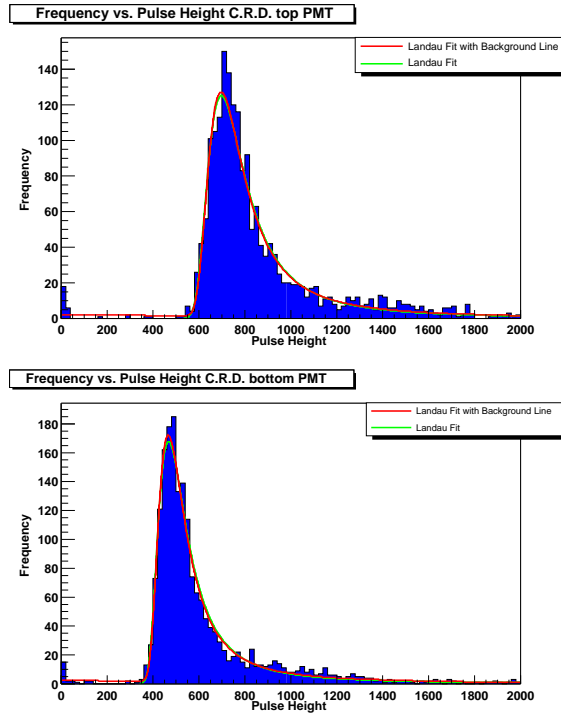
Figure 11: The pulse height spectra of the two counters in the C.R.D. The pulse height spectra were fit to a Landau distribution as well as a Landau with background line. Low pulse height events do not show up here because of the graphs were obtained using the external trigger setup.
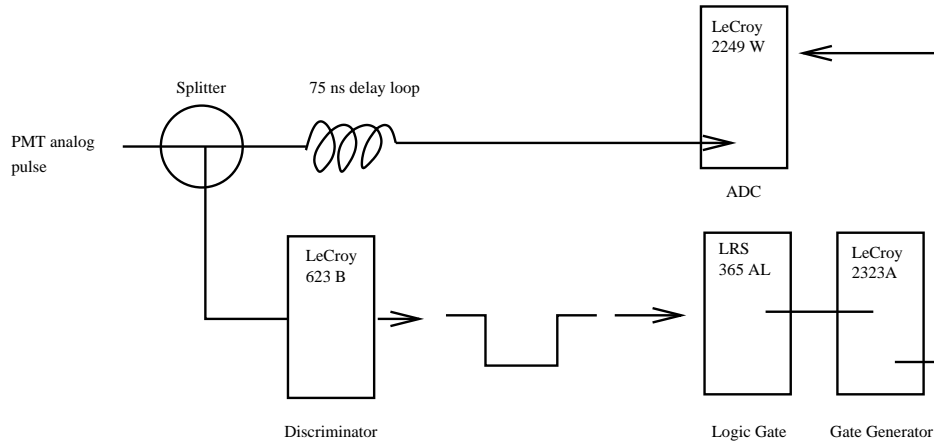

Figure 12: A schematic of the electronic circuit used to record the pulse height from each PMT to determine whether or not the PMTs need a warmup time.
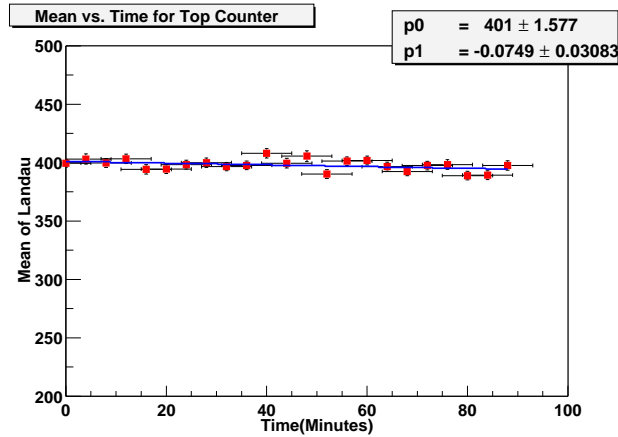
17

Figure 13: The above graph is the mean pulse height versus event number for the top PMT in the C.R.D. The pulse height was recorded while the was "warming up" for approximately and hour and a half. The data were broken up into 1200 event intervals. Each interval was fit to a Landau and the mean was recorded. The mean vs. time graph was fit to a straight line. The parameters for this line are displayed on the graph where p0 is the y-intercept and p1 is the slope. Notice that the slope is of the order $\times 10^{-4}$, which for all purposes is zero. This absence of slope demonstrates that the top PMT does not have any significant warmup time.
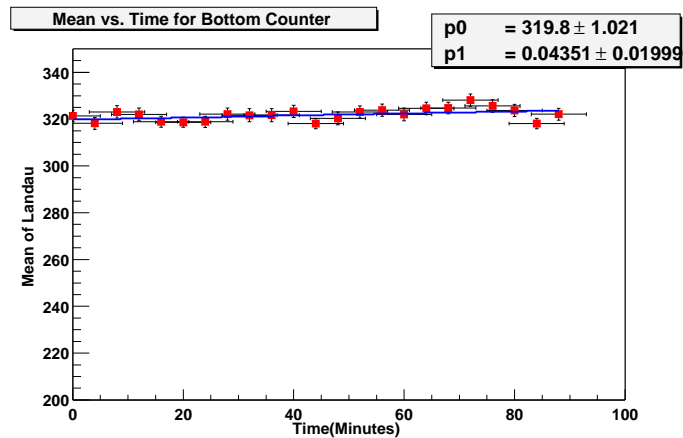

Figure 14: The above graph is as in Figure 13, but for the bottom PMT of the C.R.D.

The pulse height was recorded for 30000 events for each PMT, which took roughly an hour and a half for each PMT. The data from each PMT were broken up into intervals of 1200 events (about four minutes). Each group of 1200 was plotted as a histogram and fit to a Landau curve. The mean of the Landau curve was recorded and it was plotted versus event number (the last event of the interval was recorded as the event number for the point on the graph of Mean vs. Event Number). If there were not a significant warm up time one would expect that over time the mean of the Landau fit to be constant. The graphs of Mean vs. Event Number were fit to straight line, and the slope of the line in both cases was of the order $\times 10^{-4}$(see Figures 13, 14). The mean did not appear to vary any less as time went on and since the slope was effectively zero, it was concluded that the PMTs in the C.R.D. do not require a warm up time.

5.3 FREQUENCY AS A FUNCTION OF FLOOR

Even though cosmic muons have very high energy they can eventually be stopped by large amounts of material. The effect of concrete between the floors on the frequency of muons was investigated in two buildings at McGill University. The Rutherford building is a four story building with a basement. The ceilings are made of cement that has waffle like design. The average thickness of the ceiling is about 12 cm. As one increases in altitude, it would be expected that the muon flux also changes. This part of the experiment was done to show that inside a building it is not only the atmosphere that shields one from some muons (which is a small effect over the scale of the Rutherford building) but also the building's structure itself. A muon loses roughly 3 MeV/g/cm^2. The amount of energy that a muon loses after passing through one floor can be calculated if the density and thickness of the floor are known. Knowing how much energy that a muon loses after passing through a particular floor, however, does not allow a calculation of how many muons are actually stopped. Given that energy is lost after passing through the floor, one can still conclude that is reasonable that the muon flux should decrease with floor number.

The C.R.D. was brought onto each floor of the Rutherford building as well as the basement (1B) and the rooftop. The C.R.D. was set up in roughly the same relative position on each floor. Ten one minute trials were done on each floor. The average frequency was calculated using the following formula:

$$x_{ave} = \frac{1}{N}\Sigma x_i \tag{7}$$

Where N is the number of trials, x_i is the count rate for given trial and x_{ave} is the average. The error on each average was calculated using equation 8.

$$e = \frac{1}{\sqrt{N}}\left(\sqrt{\frac{1}{(N-1)}\Sigma(x-x_{ave})^2}\right) \tag{8}$$

The graph in figure 15 shows that the less concrete that is between the detector and the outside air, the higher the frequency. The increase in the count rate is approximately 24 counts/min/floor (this is the slope of the graph in figure 15). The increase between the fourth floor and the rooftop is about 75 events/min. The large increase from the
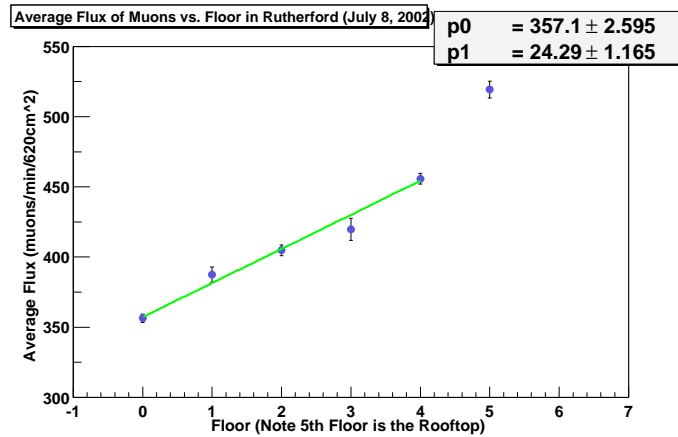
Figure 15: Graph of the average frequency of muons passing through $620\,cm^2$ detector in one minute versus floor in the Rutherford building on July 8th, 2002. The data points (rooftop excluded) were fit to a straight line.

fourth floor to the rooftop may suggest that the very low energy muons are blocked by the first layer of concrete.

This same experiment was carried out in Burnside Hall, a 12 story building on the McGill campus. The results were similar and overall the frequency increased, 6 counts/min/floor, with floor number (as the amount of concrete blocking the detector from outside decreased).

5.4 EXTERNAL TRIGGER

In order to determine the efficiency of the counters in the C.R.D., an external trigger was set up. The efficiency of the counters is a measure of the number of pulses detected by the PMT compared to the number of muons that actually passed through the counters' scintillator. Rather than using the C.R.D. counters to trigger the gate generator, (of the NIM/CAMAC set-up), a trigger outside of the C.R.D. setup was used. The idea was to have other detectors signal when a muon has passed through the C.R.D. counters, then record the pulse height of the C.R.D. counters to see if they detected it.

The external trigger circuit was set up as in Figure 17. Two small ($7\,cm \times 7\,cm$) detectors were used to detect the muons that were passing through the C.R.D. counters. One of the detectors was centred with the C.R.D. counters and was placed approximately 5 cm above the top counter. The other detector was centred with the C.R.D. counters and placed approximately 5 cm below the bottom counter. Since area of the triggers' scintillator was much smaller than the area of the C.R.D. counters and the detectors were placed at such a small distance away from the C.R.D. counters, every muon that was detected by the trigger counters also passed through the C.R.D. counters. It would therefore be expected that if the efficiency of the C.R.D. were very high, that there would be very few events recorded with a pulse height of zero.
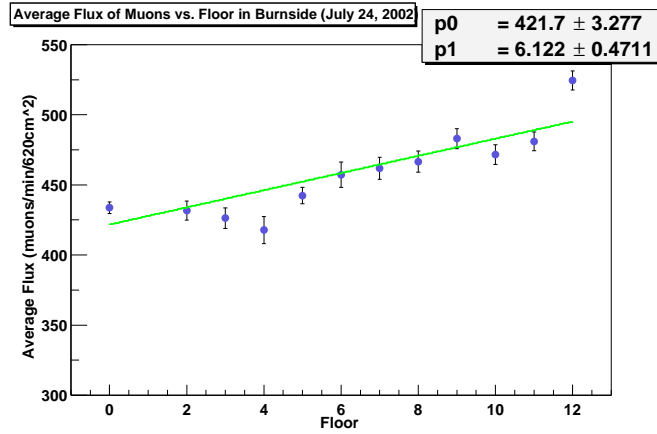
Figure 16: Graph of the average frequency of muons passing through $620\,cm^2$ detector in one minute versus floor in Burnside Hall on July 24th, 2002. The data points were fit to a straight line.
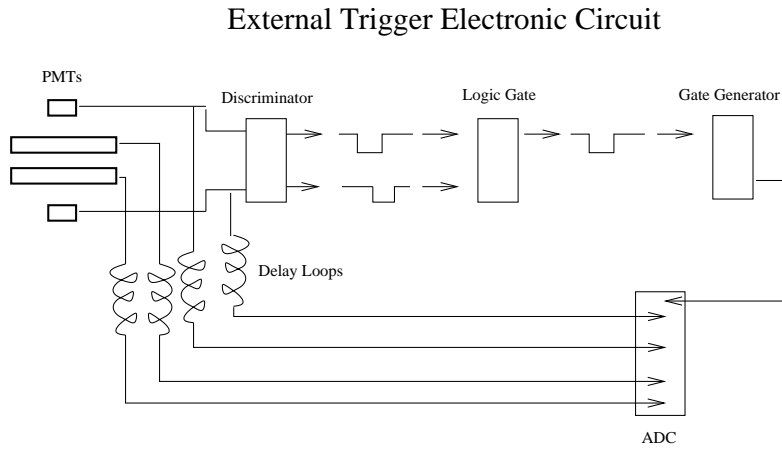

Figure 17: The electronic circuit used for the external trigger. The two small PMTs (top and bottom) were the triggers.
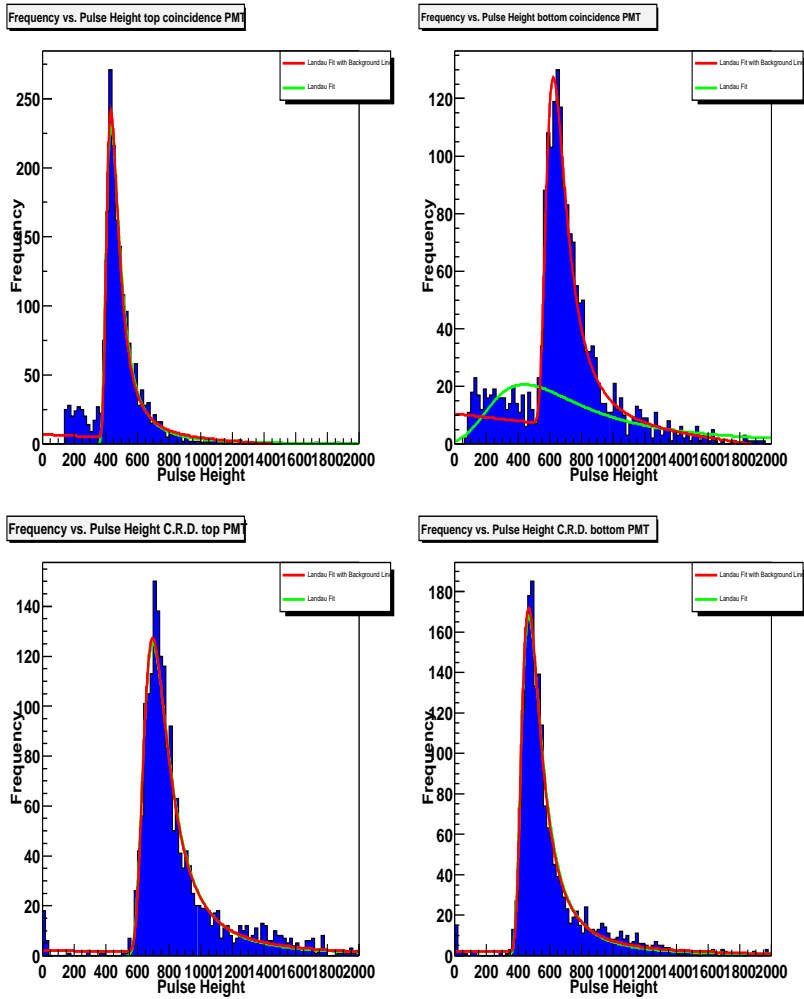
Figure 18: The above graphs are the frequency versus pulse height histograms for all four counters in the external trigger set up. The top left histogram is the top trigger counter, top left is the bottom trigger counter, the bottom left is the top C.R.D. counter and the bottom right is the bottom C.R.D. counter.

The pulse height spectra of all four counters used are shown in figure 18. The most important characteristic is that there are virtually no zero pulse height events on the C.R.D. counters. This means that for virtually every trigger, the PMTs of each counter in the C.R.D. did in fact detect the passing of a muon. The fact that the two external trigger counters, seen in the top two histograms, do have events with low pulse heights can be explained by geometry. A muon may have grazed the corners of the trigger counters creating a small number of photons in each and hence a small pulse height, but that same muon would have passed right through the centre of the C.R.D. counters because they are much larger in size and creating much larger pulse heights.
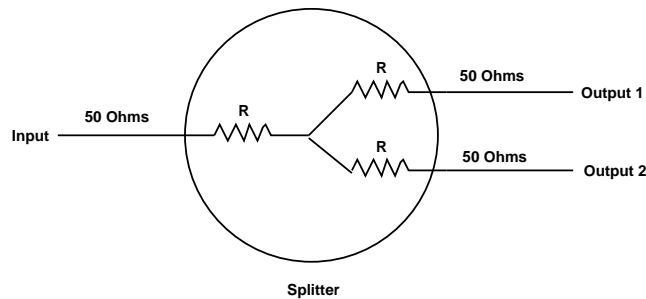
Figure 19: The above figure shows the resistors used in the splitter. The resistors inside the circle make up the splitter. All of the resistors have the same value, R for impedance matching purposes.

APPENDIX

THE SPLITTERS

Splitters are used when it is necessary to input a pulse, without changing it, into two separate devices. A splitter is designed to split the signal without introducing impedance mismatches. When a signal is input into the splitter it must see 50 Ω. Once the signal has entered the splitter, the impedances must also be matched (see figure 19).

All of the resistors inside the splitter must therefore have the same resistance, R. To find the value of R, the following calculation is done:

$$50 = R + \frac{1}{\frac{1}{R+50} + \frac{1}{R+50}} \tag{9}$$

Solving for R,

$$R \cong 17\Omega \tag{10}$$

Total Internal Reflection

Total internal reflection is a phenomenon that can only be observed when light is travelling from a medium of higher to lower index of refraction. When the incident light is at an angle larger than what is called the critical angle, all of the incident light is reflected off of the surface that forms the boundary between the two media and none is transmitted into the material of lower index of refraction. Total internal reflection is the means by which optical fibres and scintillator work. When light is incident on the surface of the scintillator, or the optical fibre, the idea is to trap that light by total internal reflection inside the material so that the light continues to propagate within.

The index of refraction of the scintillator is very important, because the larger it gets, the smaller the critical and the greater the chances that the light incident on its surface stays within the scintillator by means of total internal reflection. Recall from Section 2.1, that for total internal reflection to occur:
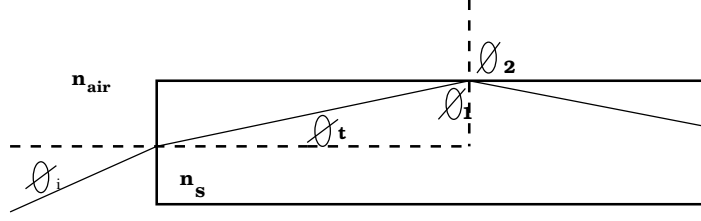
24

Figure 20: The figure above shows light incident on the surface of the scintillator, then continuing on to reflect off of the surface between the scintillator and air. For total internal reflection $\theta_1 \geq \theta_c$.

$$sin\vartheta_1 \geq \frac{1}{n_s} \tag{11}$$

Where ϑ_1, is the incident angle as in figure 20, and n_s is the index of refraction of the scintillator. It is clear then, that as the index of refraction increases, the critical angle decreases in size. As the critical angle decreases in size, the chances of total internal reflection occurring increase.

The scintillator paddles are wrapped in TYVEK in an attempt to recapture the escaping photons back into the scintillator. Once the photons are back in the scintillator, the idea is for them to continue to propagate by means of total internal reflection over and over until reaching the window of the PMT. For the photons to get reflected back into the scintillator and undergo total internal reflection, there is a minimum index of refraction that the scintillator can have. Snell's Law states that for the first surface (the photons are travelling from air into the scintillator):

$$n_{air}sin\vartheta_i = n_s sin\vartheta_t \tag{12}$$

Where $n_{air} \cong 1$, ϑ_i is the angle of incidence (measured from the normal of the surface), n_s is the index of refraction of the scintillator and ϑ_t is the angle of transmission (again measured from the normal of the surface, see figure 20). $sin\vartheta_t$ can then be expressed as:

$$sin\vartheta_t \cong \frac{sin\vartheta_i}{n_s} \tag{13}$$

From simple trigonometry it can be shown that:

$$sin\vartheta_1 = cos\vartheta_t \tag{14}$$

Hence,

$$sin\vartheta_1 = cos\vartheta_t \geq \frac{1}{n_s} \tag{15}$$

$$cos\vartheta_t = \sqrt{1 - sin^2\vartheta_t} \geq \frac{1}{n_s} \tag{16}$$

25

Using equation 13, the above expression can be rewritten as:

$$\sqrt{1 - \left(\frac{1}{n_s}\right)^2 sin^2 \vartheta_i} \geq \frac{1}{n_s} \tag{17}$$

Finally, solving for n_s gives:

$$n_s \geq \sqrt{sin^2 \vartheta_i + 1} \tag{18}$$

The maximum value of the sine function is one, therefore,

$$n_s \geq \sqrt{2} \tag{19}$$

The index of refraction of the scintillator used in the C.R.D. paddles was 1.58, which is greater than $\sqrt{2}$.

photodetector package
P30CW5 data sheet

electron tubes

1 description

The versatile P30CW5 photodetector package can be used for all three modes of photomultiplier operation - pulse counting, analogue detection or photon counting. It comprises a 9125B, 30 mm diameter, fast end-window photomultiplier (pmt) with a blue-green sensitive bialkali photocathode and a -HV power supply, encapsulated within a cylindrical metal case. The signal output is connected directly to the pmt anode allowing the user freedom to work into a range of electronic circuitry.

The effective photocathode diameter is 25 mm. The pmt high voltage is set by any one of the two methods described in section 7.

Variants of the P30CW5, available to special order, include photomultipliers with uv transmitting windows and with enhanced-green or infra-red photocathode response.

2 applications

- battery powered instruments
- portable instruments
- industrial instruments
- university research

3 features

- easy to operate
- compact cylindrical geometry
- 2 modes of HV control
- direct connection to the anode

4 characteristics

|	
photocathode type	bialkali
photocathode active diameter	25 mm
spectral response range	280 to 630 nm, see curve
peak QE at 400 nm	28 %
output pulse (into 50 Ω)	
output pulse amplitude	
output pulse rise time	4.5 ns
output pulse fwhm	7.5 ns
output impedance	$>10^5 \, \Omega$
dark counts at 20 °C (typ.)	100 s^{-1}
(max.)	200 s^{-1}
power input (typ.)	+5 V, 35 mA
tube voltage/control volt. ratio	1000:1
warm up time	less than 10 s
ratings	
temperature (operating)	+5 °C to +55 °C
(storage)	-40 °C to +55 °C
weight	285 g
operating position	any
finish	matt black

us $540 each
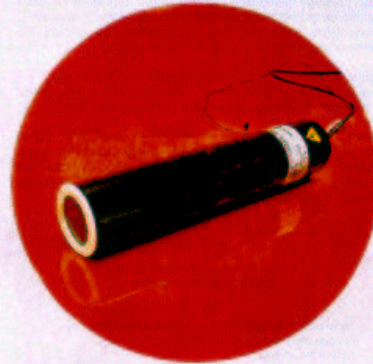
5 photocathode spectral response
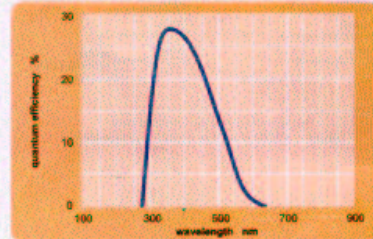
6 dynamic range - photon counting mode
(illustrating photon counting performance with an external amplifier-discriminator, type AD6)

Extended dynamic range can be obtained by dark count subtraction and by dead time correction to compensate for departure from linearity at high countrates due to pulse pile up.
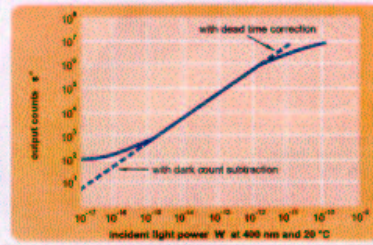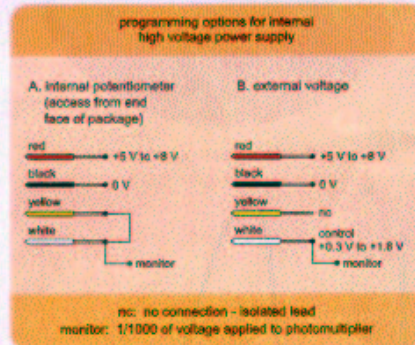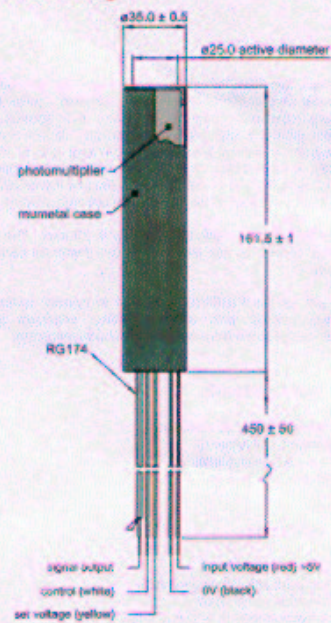
7 installation and operation

Each package is supplied with test data. Wherever possible installation should be carried out in subdued light. Exposure to strong lights, particularly those containing a high uv content, can result in a temporary increase in dark counts.

Remove the protective cap from the package. If necessary, the photomultiplier window can be cleaned using a lens tissue moistened with alcohol. Do not use any other solvent.

Mount the package and make power input and signal connections. Where the signal lead is longer than 200 mm, it should be terminated into 50 Ω. Do not expose the photomultiplier tube photocathode to strong lights while the package is energised.

programming options for internal high voltage power supply

A. internal potentiometer (access from end face of package)

red — +5 V to +8 V
black — 0 V
yellow
white — monitor

B. external voltage

red — +5 V to +8 V
black — 0 V
yellow — no
white — control +0.3 V to +1.8 V — monitor

nc: no connection - isolated lead
monitor: 1/1000 of voltage applied to photomultiplier

8 outline drawing mm

ø35.0 ± 0.5
ø25.0 active diameter
photomultiplier
mumetal case
161.5 ± 1
RG174
450 ± 50
signal output
control (white)
set voltage (yellow)
input voltage (red) +5V
0V (black)

9 warning

The pmt cathode is operated at -HV. To guarantee stable performance and for safety reasons, the entire window should be isolated by a distance of at least 3 mm from any ground plane or components. The use of PTFE for insulation is recommended.

No attempt must be made to repair or dismantle this product. High voltage used within the package may present an electric shock hazard.

Operation beyond the maximum ratings, or reversal of the input voltage may result in loss of performance or permanent damage to the product.

8 voltage divider distribution

k	d_1	d_2		d_x	d_9	d_{10}	d_{11}	a	
A	2R	R	....	R	R	R	R	R	Standard
B	2R	R	....	R	2R	3R	4R	3R	High Pulsed Linearity

Characteristics contained in this data sheet refer to divider A unless stated otherwise.

9 external dimensions mm

28.2 max
112 ± 3
9.5 max
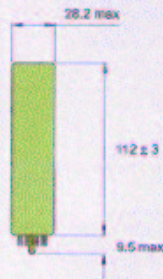
10 base configuration (viewed from below)

B14B

'ic' indicates an internal connection

Our range of B14B sockets, available for this series, includes versions with or without a mounting flange, and versions with contacts for mounting directly onto printed circuit boards.

11 ordering information

The 9125B meets the specification given in this data sheet. You may order **variants** by adding a suffix to the type number. You may also order **options** by adding a suffix to the type number. You may order product with **specification options** by discussing your requirements with us. If your selection option is for one-off order, 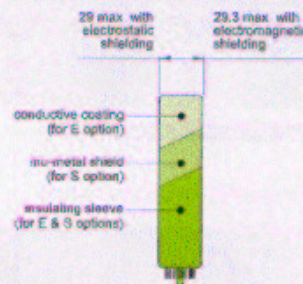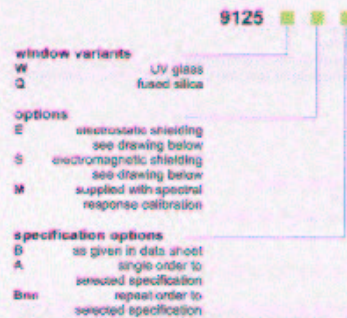then the product will be referred to as 9125A. For a repeat order, Electron Tubes will give the product a two digit suffix after the letter B, for example B21. This identifies your specific requirement.

9125 ☐ ☐ ☐

window variants
W — UV glass
Q — fused silica

options
E — electrostatic shielding see drawing below
S — electromagnetic shielding see drawing below
M — supplied with spectral response calibration

specification options
B — as given in data sheet
A — single order to selected specification
Bnn — repeat order to selected specification

29 max with electrostatic shielding
29.3 max with electromagnetic shielding

conductive coating (for E option)
mu-metal shield (for S option)
insulating sleeve (for E & S options)

12 voltage dividers

The standard voltage dividers available for these pmts are tabulated below:

	k	d_1		d_x	d_9	d_{10}	d_{11}	a
C637A	2R	R	....	R	R	R	R	R
C637C	2R	R	....	R	2R	3R	4R	3R
C686	2V	V	....	V	V	V	V	V

R = 300 kΩ

30 mm (1⅛") photomultiplier
9125B series data sheet

electron tubes

1 description

The 9125B is a 30 mm (1⅛") diameter, end window photomultiplier with blue-green sensitive bialkali photocathode and 11 high gain, high stability, SbCs dynodes of linear focused design. The 9125WB and 9125QB are variants for applications requiring uv sensitivity.

2 applications

- wide range of applications
- spectroscopy
- x-ray & gamma-ray spectroscopy
- photon counting of bio- and chemi-luminescent samples

3 features

- high gain
- low operating voltage
- good SER
- good pulse height resolution

4 window characteristics

	9125B borosilicate	9125WB UV glass	9125QB fused silica
spectral range** (nm)	280 - 630	170 - 630	160 - 630
refractive index (n₁)	1.49	1.48	1.46
K (ppm)	300	6500	<10
Th (ppb)	250	30	<10
U (ppb)	100	30	<10

* note that the sidewall of the envelope contains graded seals of high K content
** wavelength range over which quantum efficiency exceeds 1 % of peak

5 typical spectral response curves
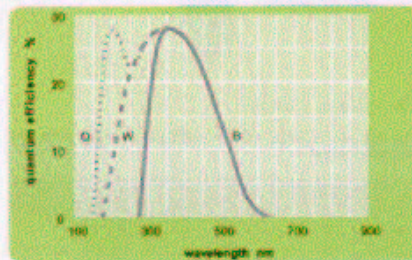
6 characteristics

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		25	
quantum efficiency at peak	%		28	
luminous sensitivity	µA/lm		65	
with CB filter		7	11	
with CR filter			1	
dynodes: 11LFSbCs				
anode sensitivity in divider A:				
nominal anode sensitivity	A/lm		200	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		850	1100
overall V for max. rated A/lm	V		1100	
gain at nominal A/lm	x 10⁶		3	
dark current at 20 °C:				
dc at nominal A/lm	nA		0.2	5
dc at max. rated A/lm	nA		2	
dark count rate	s⁻¹		100	
afterpulse rate:	%		1	
afterpulse time window	µs	0.1		6.4
pulsed linearity (-5% deviation):				
divider A	mA		25	
divider B	mA		100	
pulse height resolution				
single electron peak to valley	ratio		2	
¹³⁷Cs with 1" x 1" NaI(Tl)			7.8	
rate effect (I₁ for Δg/g=1%):	µA		20	
magnetic field sensitivity:				
the field for which the output decreases by 50 %				
most sensitive direction	T x 10⁻⁴		2	
temperature coefficient	% °C⁻¹		± 0.5	
timing:				
single electron rise time	ns		4.5	
single electron (fwhm)	ns		7.5	
single electron jitter (fwhm)	ns		4	
transit time	ns		33	
weight:	g		60	
maximum ratings:				
anode current	µA			100
cathode current	nA			50
gain	x 10⁶			30
sensitivity	A/lm			2000
temperature	°C	-30		60
V (k-d)⁽¹⁾	V			2000
V (k-d1)	V			300
V (d-d)⁽²⁾	V			300
ambient pressure (absolute)	kPa			202

⁽¹⁾ subject to not exceeding max. rated sensitivity ⁽²⁾ subject to not exceeding max. rated η(k-d)

7 typical voltage gain characteristics
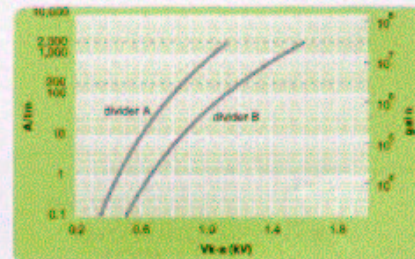
The ROOT Code - Graphing

(www.root.cern.ch)

The External Trigger Graphs

```
//Written by Josie Herman
//June 2002
//This program reads in four columns of data, and plots four separate histogram
//each with their own Landau fit.

{
  gROOT->Reset();

  //Next few lines of code request the data file to be plotted

  char datafile[20];/*an array of (max. 20) characters*/
  printf("Histogram and Landau Curve with Background Line\n");
  printf("Enter Data Fle Name:\t ");
  scanf("%s", datafile);

  //Open the file that the data is in
  FILE *fp = fopen(datafile, "r");

  //Create a canvas to put the histogram in
  c1 = new TCanvas("c1","The muon Histogram",200,10,900,800);
  c1->SetFillColor(10);
  c1->GetFrame()->SetBorderSize(6);
  c1->GetFrame()->SetBorderMode(-1);
  c1->Divide(2,2);

  gStyle->SetOptStat(0);
  gStyle->SetOptFit(0);
  //get rid of the ugly stats box

  //Declare some of the required variables
  Int_t nrows = 0;
  Int_t topc, botc, crd1, crd2;
  Int_t ncols;

  //Some constants specific to data file.
  Int_t xlow = 0;
  Int_t xup = 2000;
  Int_t rowtotal = 9000;
  Int_t nbins = 100;
  //Careful, too many nbins seems to be the only thing that will screw the fits up
```

```
//Create FOUR histograms one for each PMT
TH1F *h1 = new TH1F("h1", "Frequency vs. Pulse Height top coincidence PMT", nbins, xlow
//xlow is the smalles data value, xup is the largest.
//binwidth = (xup-xlow)/nbins
h1->SetFillColor(4);
h1->GetXaxis()->SetTitle("Pulse Height");
h1->GetYaxis()->SetTitle("Frequency");
h1->GetXaxis()->CenterTitle();
h1->GetYaxis()->CenterTitle();

TH1F *h2 = new TH1F("h2", "Frequency vs. Pulse Height bottom coincidence PMT", nbins, x
h2->SetFillColor(4);
h2->GetXaxis()->SetTitle("Pulse Height");
h2->GetYaxis()->SetTitle("Frequency");
h2->GetXaxis()->CenterTitle();
h2->GetYaxis()->CenterTitle();

TH1F *h3 = new TH1F("h3", "Frequency vs. Pulse Height C.R.D. top PMT", nbins, xlow, xup)
h3->SetFillColor(4);
h3->GetXaxis()->SetTitle("Pulse Height");
h3->GetYaxis()->SetTitle("Frequency");
h3->GetXaxis()->CenterTitle();
h3->GetYaxis()->CenterTitle();

TH1F *h4 = new TH1F("h4", "Frequency vs. Pulse Height C.R.D. bottom PMT", nbins, xlow, xu
h4->SetFillColor(4);
h4->GetXaxis()->SetTitle("Pulse Height");
h4->GetYaxis()->SetTitle("Frequency");
h4->GetXaxis()->CenterTitle();
h4->GetYaxis()->CenterTitle();

//The following statement read the data from a file of four columns
//Prints out the data, and fills the corresponding bins of four separate his.

while (nrows < rowtotal)
  {
    ncols = fscanf(fp, "%d %d %d %d", &crd1, &crd2, &topc, &botc);
    if (ncols < 0) break;
    if (nrows < rowtotal) printf("crd1=%d\tcrd2=%d\ttopc=%d\tbotc=%d\n",crd1, crd2, top
    h1->Fill(topc,1.0);
    h2->Fill(botc,1.0);
    h3->Fill(crd1,1.0);
    h4->Fill(crd2,1.0);
    //the 1.0 is the weighting by default
    nrows++;
```

```
   }
printf("found %d points\n", nrows);

//To draw each histogram in its own pad.
c1->cd(1);
gPad->SetFillColor(10);
//gPad->SetGrid();
gPad->SetBorderMode(3);
//border mode 3 is shaded right and bottom
gPad->SetBorderSize(3);

Double_t par[20];
//Define an array par with too many spaces

p1 = new TF1("p1","pol1", 0, 2000);
l1 = new TF1("l1","Landau", 0, 2000);
//Define a function for the fitting.

p1->SetLineWidth(2);
p1->SetLineColor(3);
l1->SetLineWidth(2);
l1->SetNpx(3000);
l1->SetLineColor(3);

total1 = new TF1("total1","pol1(0)+Landau(2)", 0, 2000);
//parameters 0,1 for pol1
//parameters 2,3,4 for Landau2

total1->SetLineColor(2);
total1->SetLineWidth(2);
total1->SetNpx(3000);

h1->Fit("p1","R0+");
h1->Fit("l1","R+");

//"R" is an option to use range defined by function
//"R+" option use range def. by function and redefine function with new para
//"R0+" option all above AND doesn't draw it.

p1->GetParameters(&par[0]);
l1->GetParameters(&par[2]);
//To get parameter values make sure you call on the right function

total1->SetParameters(par);

h1->Fit("total1", "R+");
```

```
//Notice there is no h1->Draw command, the Fit function draws (without "0")

//Create a legend
//TLegend(x1, y1, x2, y2) are the parameters
//The "l" option draws a little line the same color as the fit
leg = new TLegend(0.5, 0.8, 0.98, 0.90);

leg->SetFillColor(10);
leg->AddEntry(total1, "Landau Fit with Background Line", "l");
leg->AddEntry(l1, "Landau Fit", "l");
leg->Draw();

c1->cd(2);
//gPad->SetGrid();
gPad->SetBorderMode(3);
gPad->SetBorderSize(3);

Double_t par2[20];
//Define an array par with too many spaces

p2 = new TF1("p2","pol1", 0, 2000);
l2 = new TF1("l2","Landau", 0, 2000);
//Define some functions for the fitting.

p2->SetLineWidth(2);
p2->SetLineColor(3);
l2->SetLineWidth(2);
l2->SetLineColor(3);
l2->SetNpx(3000);

total2 = new TF1("total2","pol1(0)+Landau(2)", 0, 2000);
//parameters 0,1 for pol1
//parameters 2,3,4 for Landau2

total2->SetLineColor(2);
total2->SetLineWidth(2);
total2->SetNpx(3000);
//this command changes the number of points used to draw the fit
//More points, smoother curve

h2->Fit("p2","R0+");
h2->Fit("l2","R+");
//"R" is an option to use range defined by function
//"R+" option use range def. by function and redefine function with new para
//"R0+" option all above AND doesn't draw it.
```

```
p2->GetParameters(&par2[0]);
l2->GetParameters(&par2[2]);
//To get parameter values make sure you call on the right function

total2->SetParameters(par2);

h2->Fit("total2", "R+");
//Notice there is no h1->Draw command, the Fit function draws (without "0")

//Create a legend
//TLegend(x1, y1, x2, y2) are the parameters
//The "l" option draws a little line the same color as the fit
leg = new TLegend(0.5, 0.8, 0.98, 0.9);
leg->SetFillColor(10);
leg->AddEntry(total2, "Landau Fit with Background Line", "l");
leg->AddEntry(l2, "Landau Fit", "l");
leg->Draw();

c1->cd(3);
//gPad->SetGrid();
gPad->SetBorderMode(3);
gPad->SetBorderSize(3);

Double_t par3[20];
//Define an array par with too many spaces

p3 = new TF1("p3","pol1", 0, 2000);
l3 = new TF1("l3","Landau", 0, 2000);
//Define some functions for the fitting.

p3->SetLineWidth(2);
p3->SetLineColor(3);
l3->SetLineWidth(2);
l3->SetLineColor(3);
l3->SetNpx(3000);

total3 = new TF1("total3","pol1(0)+Landau(2)", 0, 2000);
//parameters 0,1 for pol1
//parameters 2,3,4 for Landau2

total3->SetLineColor(2);
total3->SetLineWidth(2);
total3->SetNpx(3000);
//this command changes the number of points used to draw the fit
//More points, smoother curve
```

```
h3->Fit("p3","R0+");
h3->Fit("l3","R+");
//"R" is an option to use range defined by function
//"R+" option use range def. by function and redefine function with new para
//"R0+" option all above AND doesn't draw it.

p3->GetParameters(&par3[0]);
l3->GetParameters(&par3[2]);
//To get parameter values make sure you call on the right function

total3->SetParameters(par3);

h3->Fit("total3", "R+");
//Notice there is no h1->Draw command, the Fit function draws (without "0")

//Create a legend
//TLegend(x1, y1, x2, y2) are the parameters
//The "l" option draws a little line the same color as the fit
leg = new TLegend(0.5, 0.8, 0.98, 0.9);
leg->SetFillColor(10);
leg->AddEntry(total3, "Landau Fit with Background Line", "l");
leg->AddEntry(l3, "Landau Fit", "l");
leg->Draw();

//Finally the last histogram, crd2
c1->cd(4);
//gPad->SetGrid();
gPad->SetBorderMode(3);
gPad->SetBorderSize(3);

Double_t par4[20];
//Define an array par with too many spaces

p4 = new TF1("p4","pol1", 0, 2000);
l4 = new TF1("l4","Landau", 0, 2000);
//Define some functions for the fitting.

p4->SetLineWidth(2);
p4->SetLineColor(3);
l4->SetLineWidth(2);
l4->SetLineColor(3);
l4->SetNpx(3000);

total4 = new TF1("total4","pol1(0)+Landau(2)", 0, 2000);
//parameters 0,1 for pol1
//parameters 2,3,4 for Landau2
```

36

```
    total4->SetLineColor(2);
    total4->SetLineWidth(2);
    total4->SetNpx(3000);
    //this command changes the number of points used to draw the fit
    //More points, smoother curve

    h4->Fit("p4","R0+");
    h4->Fit("l4","R+");
    //"R" is an option to use range defined by function
    //"R+" option use range def. by function and redefine function with new para
    //"R0+" option all above AND doesn't draw it.

    p4->GetParameters(&par4[0]);
    l4->GetParameters(&par4[2]);
    //To get parameter values make sure you call on the right function

    total4->SetParameters(par4);

    h4->Fit("total4", "R+");
    //Notice there is no h1->Draw command, the Fit function draws (without "0")

    //Create a legend
    //TLegend(x1, y1, x2, y2) are the parameters
    //The "l" option draws a little line the same color as the fit
    leg = new TLegend(0.5, 0.8, 0.98, 0.9);
    leg->SetFillColor(10);
    leg->AddEntry(total4, "Landau Fit with Background Line", "l");
    leg->AddEntry(l4, "Landau Fit", "l");
    leg->Draw();

    fclose(fp);

    }
```

The (Landau) Mean vs. Event Number Graphs

```
    //Written by Josie Herman
    //July 12, 2002

    //This program will read through a datafile containing TWO columns of data, chop it //into
    //execute the gmuon_Landau_fit.c program and record the results on each
    //interval and save the mean, error and event number in an output file

    {
      gROOT->Reset();
```

```
  char datafile[20], output[20], inputfile[20];

  printf("Enter the name of the INPUT data file => ");
  scanf("%s", inputfile);
  printf("The output data file name (MUST be a new file) =>  ");
  scanf("%s", output);
  Int_t event = 0;
  Int_t interval = 0;
  Int_t totalevents = 30000;
  Double_t mean[2000][20];
  //number of rows, number of columns

  //Open the file with the data to be cut
  FILE *df = fopen(inputfile, "r");

while (event < totalevents)
  {

    //Declare some of the required variables
    Int_t counter = 0;
    Int_t crd1, crd2;
    Int_t ncols;

    //Some constants specific to data file.
    Int_t xlow = 0;
    Int_t xup = 2000;
    Int_t int_size = 600; //number of events in each interval
    Int_t nbins = 100;

TH1F *h1 = new TH1F("h1", "Frequency vs. Pulse Height top coincidence PMT", nbins, xlow,
 //xlow is the smalles data value, xup is the largest.
 //binwidth = (xup-xlow)/nbins

TH1F *h2 = new TH1F("h2", "Frequency vs. Pulse Height bottom coincidence PMT",nbins, xlow

    while (counter <= int_size)
        {
          ncols = fscanf(df, "%d %d", &crd1, &crd2);
          if (ncols < 0) break;

          h1->Fill(crd1,1.0);//the 1.0 is the weighting, 1 by default
          h2->Fill(crd2,1.0);

          counter++;
```

```
        }

printf("found %d points\n", counter);

Double_t lpol1para[20];
Double_t totalpara[20];
//Define an array with too many spaces to hold parameters later

p1 = new TF1("p1","pol1", 0, 2000);
l1 = new TF1("l1","Landau", 0, 2000);
//Define functions for the fitting.

total = new TF1("total","pol1(0)+Landau(2)", 0, 2000);
//parameters 0,1 for pol1
//parameters 2,3,4 for Landau2

total->SetNpx(2000);
//Npx number of points to make fit

h1->Fit("p1","R0+");
h1->Fit("l1","R0+");
TF1 *lfit1 = h1->GetFunction("l1");
Double_t eLandau1 = lfit1->GetParError(1);
//"R" is an option to use range defined by function
//"R+" option use range def. by function and redefine function with new para
//"R0+" option all above AND doesn't draw it.

p1->GetParameters(&lpol1para[0]);
l1->GetParameters(&lpol1para[2]);
total->SetParameters(lpol1para);
//To get parameter values make sure you call on the right function

h1->Fit("total", "MR0+");
TF1 *tfit1 = h1->GetFunction("total");
Double_t etotal1 = tfit1->GetParError(3);
total->GetParameters(&totalpara[0]);

//Print the parameters out and then output them eventually


FILE *mt;
mt = fopen(output, "a");
//open the file and append info onto the end
```

```
if (totalpara[3] <= 1.0e+00 || totalpara[4] < 0.00e0)
      {
        printf("Landau is the good fit\n");
        mean[interval][0] = lpol1para[3];
        mean[interval][1] = eLandau1;
      }
    else if
      {
        printf("Landau with Background is good fit\n");
        mean[interval][0] = totalpara[3];
        mean[interval][1] = etotal1;
       }


   Double_t lpol1para2[20];
   Double_t totalpara2[200];
   //Define an array par with too many spaces

   p2 = new TF1("p2","pol1", 0, 2000);
   l2 = new TF1("l2","Landau", 200, 2000);
   //Define some functions for the fitting.
   total2 = new TF1("total2","pol1(0)+Landau(2)", 0, 2000);
   //parameters 0,1 for pol1
   //parameters 2,3,4 for Landau2
   h2->Fit("p2","R0+");
   h2->Fit("l2","R0+");
   TF1 *lfit2 = h2->GetFunction("l2");
   Double_t eLandau2 = lfit2->GetParError(1);
   p2->GetParameters(&lpol1para2[0]);
   l2->GetParameters(&lpol1para2[2]);
   total2->SetParameters(lpol1para2);
   h2->Fit("total2", "MR0+");
   TF1 *tfit2 = h2->GetFunction("total2");
   Double_t etotal2 = tfit2->GetParError(3);
   total2->GetParameters(&totalpara2[0]);

   if (totalpara2[3] <= 1.0e+00 || totalpara2[4] < 0.00e0)
      {
        printf("Landau is the good fit\n");
        mean[interval][2] = lpol1para2[3];
        mean[interval][3] = eLandau2;
      }
    else if
      {
        printf("Landau with Background is good fit\n");
        mean[interval][2] = totalpara2[3];
```

```
                        mean[interval][3] = etotal2;
                      }
            mean[interval][4] = event;

            fprintf(mt,"%e\t%e\t%e\t%e\t%e\n",mean[interval][0], mean[interval][1], mean[interval

            event += int_size;
            interval ++;

        fclose(mt);
          }
     fclose(df);
        }
```

To graph the output of the above program the following program was used

```
//Written by Josie Herman
//July 2002


//This program graphs the results of mtt.c
//It graphs the results of both pmt's Mean vs High voltage
//WITH ERRORS on the mean of the Landau fit
//Also fits a straight line to the data points

{
  gROOT->Reset();

  //Prompts you to enter the data file to plot
  char input[20];
  printf("What datafile would you like to input? ");
  scanf("%s", input);

  //Opens the data file in read only mode
  FILE *in = fopen(input, "r");

  //Create a canvas to put the histogram in
  c1 = new TCanvas("c1","Mean vs. Time for Four PMT Set-Up",0,0,800,800);
  c1->SetFillColor(10);
  //c1->SetGrid();
  c1->GetFrame()->SetBorderSize(6);
  c1->GetFrame()->SetBorderMode(-1);
  //c1->Divide(1,2);

  gStyle->SetOptFit(11);
```

41

```
//get rid of the ugly stats box

//Give lots of room for the input
Float_t in_crd1, in_crd2, in_time;
Float_t in_ecrd1, in_ecrd2;
Float_t crd1[1000], crd2[1000], time[1000];
Float_t ecrd1[1000], ecrd2[1000], etime[1000];
Int_t nrows = 0;
Float_t ncols;

while (nrows < 50)
  {

    //ncols=fscanf(in, "%e %e %e %e %e", &in_crd1, &in_ecrd1, &in_crd2, &in_ecrd2, &in_t
    ncols=fscanf(in, "%e %e %e", &in_crd1, &in_ecrd1, &in_time);
    if (ncols < 0) break;

    crd1[nrows] = in_crd1;
    ecrd1[nrows] = in_ecrd1;
    //crd2[nrows] = in_crd2;
    //ecrd2[nrows] = in_ecrd2;
    time[nrows] = in_time;
    etime[nrows] = 0.0;

    nrows++;
  }
c1->cd(1);
//hcx = new TH2F("hcx", "Zoom Out", 50, 0, 3000.0, 50, 0, 500.0);
//hcx->SetStats(0);
//hcx->Draw();
TGraphErrors *gcrd1 = new TGraphErrors(nrows, time, crd1, etime, ecrd1);
gcrd1->SetTitle("Mean vs. Time for Top Counter");

p1 = new TF1("p1", "pol1", 0, 40000);
p1->SetNpx(2000);
p1->SetLineColor(4);
gcrd1->Fit("p1", "R");
gcrd1->SetMarkerColor(2);
gcrd1->SetMarkerStyle(21);
//This marker is an "x"
gcrd1->Draw("AP");
gcrd1->GetXaxis()->SetTitle("Time (Events)");
gcrd1->GetYaxis()->SetTitle("Mean of Landau");
gcrd1->GetYaxis()->CenterTitle();
gcrd1->GetXaxis()->CenterTitle();
```

```
    gPad->SetTicks(0);
    gcrd1->Draw("AP");


    /*c1->cd(2);
    TGraphErrors *gcrd2 = new TGraphErrors(nrows, time, crd2, etime, ecrd2);
    gcrd2->SetTitle("Mean vs. Time for Bottom Counter");
    p2 = new TF1("p2", "pol1", 0, 40000);
    p2->SetNpx(2000);
    p2->SetLineColor(4);
    gcrd2->Fit("p2", "R");
    gcrd2->SetMarkerColor(2);
    gcrd2->SetMarkerStyle(21);
    //This marker is an "x"
    gcrd2->Draw("AP");
    gcrd2->GetXaxis()->SetTitle("Time (Events)");
    gcrd2->GetYaxis()->SetTitle("Mean of Landau");
    gcrd2->GetYaxis()->CenterTitle();
    gcrd2->GetXaxis()->CenterTitle();
    gPad->SetTicks(0);


    gcrd2->Draw("AP");*/


  fclose(in);



  }
```

The Frequency vs. Floor Graphs

```
    //Written by Josie Herman
    //July 2002


    //This program reads in two columns of data (freq, floor)
    //Graphs the results as (x,y)


    {
      gROOT->Reset();

      //Prompts you to enter the data file to plot
      char input[20];
      printf("What datafile would you like to input? ");
      scanf("%s", input);

      //Opens the data file in read only mode
```

```
        FILE *in = fopen(input, "r");

        //Create a canvas to put the histogram in
        c1 = new TCanvas("c1","The muon Histogram",0, 0,500,400);
        c1->SetFillColor(10);
        //c1->SetGrid();
        c1->GetFrame()->SetBorderSize(6);
        c1->GetFrame()->SetBorderMode(-1);

        gStyle->SetOptStat(0);
        //get rid of the ugly stats box

        //Give lots of room for the input
        Float_t in_floor, in_average, in_error;
        Float_t floor[100], average[100], error[100], ef[100];
        Int_t nrows = 0;
        Float_t ncols;

        while (nrows <= 200)
          {
            ncols=fscanf(in, "%f %f %f", &in_floor, &in_average, &in_error);
            if (ncols < 0) break;
            //printf("floor= %f\tave= %f\terror= %f\n",in_floor, in_average, in_error);
            floor[nrows] = in_floor;
            average[nrows] = in_average;
            error[nrows] = in_error;
            ef[nrows]=0.0;
            printf("floor= %f\tave= %f\terror= %f\n",floor[nrows], average[nrows], error[nrows]
            floor[nrows] = in_floor;
            nrows++;
          }

        TGraphErrors *gr = new TGraphErrors(nrows, floor, average, ef, error);
        gr->SetTitle("Average Frequency of Muons vs. Floor in Rutherford (July 8, 2002)");
        gr->SetMarkerColor(9);
        gr->SetMarkerStyle(8);
        //This marker is an "x"
        gr->Draw("AP");
        gr->GetXaxis()->SetTitle("Floor (5th Floor is the Rooftop");
        gr->GetYaxis()->SetTitle("Average Frequency (muons/min/620cm^2)");
        gr->GetYaxis()->CenterTitle();
        gr->GetXaxis()->CenterTitle();
        gr->Draw("AP");

        fclose(in);
}
```

Acknowledgements

References

[1] Griffiths, David. "Introduction to Elementary Particle Physics". John Wiley & Sons, Inc. Canada. 1987.

[1] Impey, Chris. Hartmann, William K. "The Universe Revealed". Brooks/Cole. Toronto, Canada. 2000.

[2] Leo, W.R. "Techniques for Nuclear and Particle Physics Experiments Second Revised Edition". Springer-Verlag.

[3] "The European Physical Journal C, Review of Particle Physics". Springer. Volume 15, Number 1-4, 2000.

[4] www.scionixusa.com/charged_particle.html

[5] www.bicrondirect.com

[6] www.root.cern.ch