Spatial Correlation of Cosmic Rays

Cory McKay
Physics Department
McGill University
3600 University Street
Montreal, QC
Canada, H3A 2T8

The Minh Luong
Physics Department
McGill University
3600 University Street
Montreal, QC
Canada, H3A 2T8

Guiseppe Scardera
Physics Department
McGill University
3600 University Street
Montreal, QC
Canada, H3A 2T8

Abstract

The purpose of this experiment was to collect data on the spatial distribution of cosmic ray showers and the angles at which they arrive at sea level, as well as to explore experimental techniques used in particle detection. We found that the intensity of these particle showers drops off exponentially as you move away from their centre and that most of the showers arrive at sea level at angles close to zenith. We also measured a cosmic ray shower rate of 7.7 +/- 0.7 showers per second per meter squared at sea level.

Introduction

The earth is constantly bombarded with particles from outer space. It has been determined that approximately ten high energy particles due to cosmic rays pass through an area the size of one of our hands each second at sea level. The goal of this experiment is to collect data on the spatial distribution of cosmic ray showers and the angles at which they arrive at sea level, as well as to explore experimental techniques used in particle detection.

It should be noted that the particles detected on the surface of the earth are not the same particles that arrive from space, which are called primary particles. The geomagnetic field and atmosphere of the earth prevent many of these particles from reaching us, and our apparatus is not capable of taking meaningful direct measurements of the primaries. However, secondary radiation is produced when the primaries enter the earth's atmosphere, and this is what we will be dealing with in this lab.

Cosmic rays were first detected when scientists were unable to eliminate residual ionisation in sterile sealed chambers that were being used to measure how the conductivity of air is affected by ionising radiation. When this residual ionisation could not be entirely accounted for by contaminants in the chambers, it was hypothesised that the cause could be extraterrestrial radiation. This hypothesis was supported by experiments involving balloon flights that showed that this ionisation increased with altitude.

There is still some debate as to the exact origin of cosmic rays, but there is a general consensus that there are two types of rays, solar and galactic. Solar cosmic rays are produced by solar flares, and consist mainly of hydrogen and helium nuclei, as well as electrons and some nuclei of heavier elements. However, although there are a great number of these particles incident on the earth, most of them have an energy that is too low to be responsible for the cosmic rays dealt with in this lab, which must have energies greater than 10^{10} electron volts (Pomerantz 1971).

An obvious implication of this is that the cosmic rays that we are detecting cannot be from other stars similar to the sun. The most popular theory is that the high energy rays hitting the earth are produced by supernovae. The immense nuclear explosions involved in the death of large stars (at least eight times the size of the sun) propel particles into space with energies of up to 10^{21} electron volts (Zelik 1992), which is more than high enough to account for the radiation that we are detecting. It is also theorised that pulsars (small, extremely dense neutron stars remaining after a supernova has occurred) could be the source some of this radiation. Pulsars rotate very quickly, producing powerful magnetic fields that accelerate particles to energies high enough to be the source of the rays detected on earth.

There are three mechanisms by which primaries produce secondaries. These mechanisms of energy transfer are, in increasing order of primary energy, transfer through a nucleonic component, a meson component or an electromagnetic component .

The nucleonic component involves high energy neutrons and protons which cause a cascade of disintegration product nucleons as they travel through the earth's atmosphere. These particles do not have enough energy to reach sea level in large quantities, so do not play an important part in this lab. The mesonic component created in the disintegration process is made up of both charged and neutral pi-mesons. The neutral pi-mesons account for the electromagnetic component. The most probable decay of a neutral pi-meson is into two gamma rays, which interact with nuclei in the atmosphere to produce electron-positron pairs through pair production. However, electron and positrons are not highly penetrating, and thus are unlikely to reach us through the Rutherford Physics Building, where our experiment took place, so they do not play a significant role in this lab..

The charged pi-mesons are primarily responsible for what we are detecting in this lab. These particles have half-lives of $2\text{x}10^{-8}$ seconds (Sandstrom 1964), and decay into muons of the same charge and neutrinos. The neutrinos do reach sea level, but they are undetectable with our apparatus. The muons are unstable, with a half life of $2.6\text{x}10^{-6}$ seconds (Sandstrom 1964), and they travel at relativistic speeds. These muons have more than enough energy to penetrate the Rutherford Building, and they are primarily responsible for the cosmic rays that we detected in this lab. According to previous experiments, there are approximately 100 muons per second per meter squared incident on the earth at sea level (MacMillian Encyclopaedia of Physics 1996).

As the muons and secondary particles travel through the atmosphere, atmospheric nuclei cause the particles to diverge from their original path, thus increasing the radius of the shower. The showers are generally of a conical shape, and can often be approximated as being circular. The intensity of the showers is greatest near the axis of the shower, and drops off towards the outer edges. That is, the number of incident particles per unit area decreases as you move away from the axis. Using the nucleon cascade model, it has been theoretically predicted that the root mean square radius of muon particle showers is approximately 600 meters, which is significantly larger than the radius of the electron/positron showers, which have a rms radius of 70 meters (Galbraith 1958).

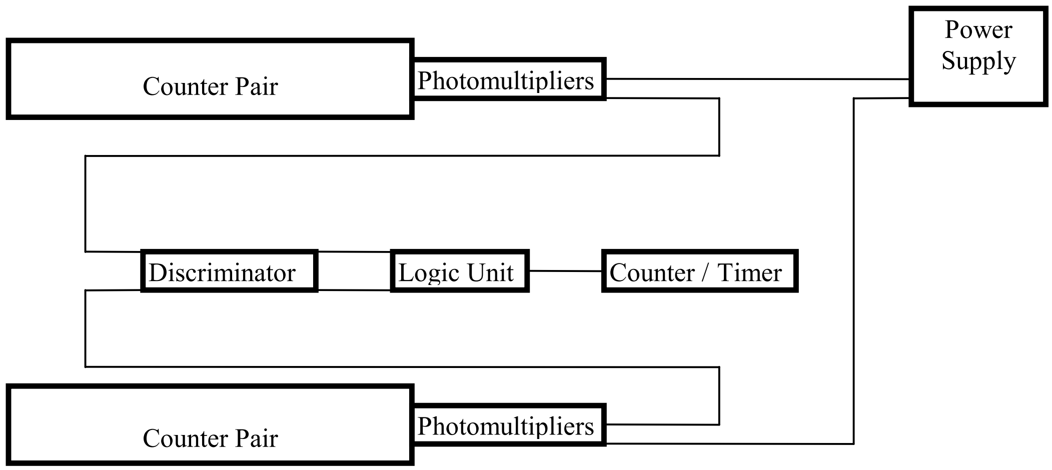


Figure 1: Block diagram showing our experimental setup.

Since particles that reach sea level at a large angle from zenith must traverse a greater amount of atmosphere than particles that arrive normal to the surface, it is expected that there will be greater numbers of cosmic rays that arrive at angles close to zenith than far from it.

Experimental Methods

This experiment took place on the second floor of the Rutherford Physics Building, in a darkroom. We used counters made of scintillating material to detect cosmic rays. The atoms of the counters absorb some of the kinetic energy of incoming particles and become excited. They then return to their ground states, releasing photons as they do so. We covered the counters with black sheets to ensure that no outside light would leak in and give false readings. The counters each had dimensions of 0.71 +/- 0.01 m by 0.13 +/- 0.01 m. This means that they had an area of 0.092 +/- 0.007 m^2. The counters were each connected to photomultipliers, which amplified the light signals and outputted them to our electronics as electrical pulses.

The photomultipliers have a photocathode which absorbs the photons from the counters and emits photoelectrons. These photoelectrons are then accelerated to hit dynodes that are at different electrical potentials. More photoelectrons are emitted each time they strike a dynode, due to the energy they gained while traveling between the dynodes. At the final stage of the photomultiplier, of the order of a million electrons hit the final dynode, producing a sizable negative electric pulse at the anode. The size of this pulse depends on the number of incident particles, their energies and the voltage supplied to the photomultiplier. The photomultipliers requires large voltages to operate, which we supplied with a Harrison 6516A DC 0 to 3000 volt power supply.

We then connected the photomultipliers to a Lecroy octal discriminator through cables of equal length (so that pulses emitted by separate counters due to particles that arrived at the same time would arrive at the discriminator at the same time). The discriminator allowed us to eliminate some of the noise from the counters and photomultipliers by only giving an output signal when the input signal had a pulse height greater than a certain voltage threshold which we could set. It also allowed us to control the width of the output signal. The output from the discriminator was a NIM logic pulse (-0.8 volts).

The discriminator was in turn connected to a four-fold logic unit. We were able to set this unit to only give an output pulse when pulses from each of the separate counters arrived simultaneously (this is called a coincidence). This eliminated a great deal of noise from sources unrelated to cosmic rays, such as thermal excitation in the photomultipliers, which did not arrive from each of the counters at the same time. The output from the logic unit was also a NIM pulse.

Finally, we connected the logic unit to a digital counter/timer, which let us record how many coincidences were observed. We used a stopwatch to measure the duration of each data collection session. It should be noted that it was necessary to make sure that the cables connecting the photomultipliers to our electronics were terminated, in order to avoid the reflection of pulses.

Of course, we had to do a great deal of calibration before we were able to implement the above setup. Each of the counter/photomultiplier sets needed to be supplied with a different voltage in order to operate optimally. If the supplied voltage is too small, the output pulse from the photomultiplier might be too small to cause the discriminator to fire when a cosmic ray shower is detected. On the other hand, a voltage that is too large can cause the photomultiplier to output many noise pulses due to sources other than cosmic rays which can result in false coincidences being registered. Unfortunately, we only had one single channel power supply, so we had to choose one voltage which would give us a compromise between our different counters/photomultiplier sets.

To do this, we first took individual count rates for each of our six counters at various voltages. We then chose the four counters that gave the closest results at each voltage (counters 1, 3, 6 and 7). To help compensate for some of the remaining differences, we set the discriminator threshold voltage at different levels for each counter. This was only effective to a certain degree, however, because the levels could not be set below 30 mV, and settings above 60mV would result in many of the true cosmic ray detections being missed. The threshold voltage settings that we used were 60 mV for counter 1, 50 mV for counter 3, 60 mV for counter 6 and 50 mV for counter 7.

We then separated our counters into two pairs, and mounted each pair on separate racks which held the counters in one pair directly above one another at a vertical separation of 0.09 +/- 0.01 meters, and the counters in the other pair directly above one another at the same vertical separation as the first pair. This enabled us to take separate coincidence readings for each pair when necessary.

Next, we set the discriminator to emit pulses with a width of 20 nanoseconds. This width was small enough to make it unlikely that random noise signals from separate counters would overlap when they reached the logic unit, and produce a false coincidence count. This pulse width was also large enough to help ensure that true cosmic ray detections outputted by the discriminator would not be missed by the logic unit.

We used a Kikusus oscilloscope with a built in discriminator to perform many of these calibrations. It allowed us to

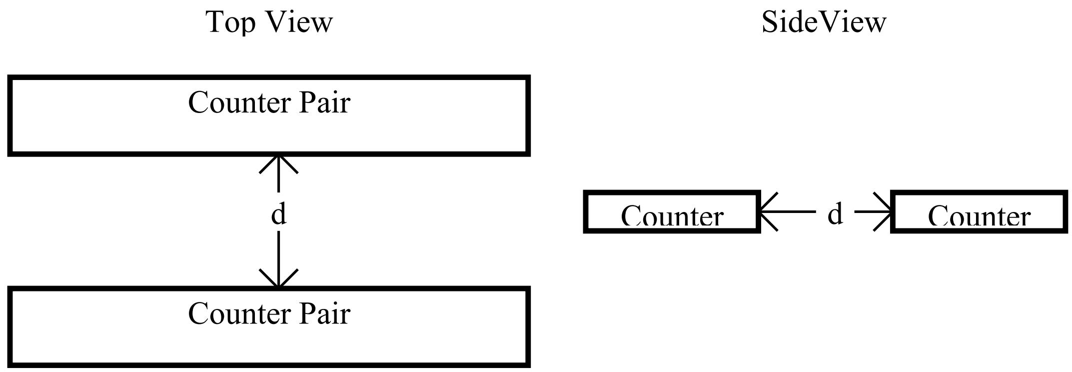


Figure 2: Orientation of counters in horizontal counter separation experiment. The distance between counters, d, is variable.

visually see the shape and amplitude of the output signals from the photomultipliers, and let us quickly adjust our calibration settings before fine-tuning them using quantifiable readings from our digital counter/timer.

The next step was to find the optimal operating voltage for each of our photomultpliers. If we had had equipment capable of supplying different voltages to each multiplier, we could have used a technique called plateauing to do this. This involves taking one of the pairs of counters and feeding them through the discriminator and logic unit, with the logic unit set to give an output pulse when pulses arrive from both counters simultaneously. We would have then held one of the counters at a constant voltage, and varied the voltage supplied to the other counter. Theoretically, this would have resulted in a graph of coincidence rates versus supplied voltage that would have had a flat section which would indicate the optimal voltage, which gives the best compromise between minimizing missed cosmic rays and minimizing noise. We would have done this for all of the counters.

Since we only had one power supply, we were only able to do an inferior version of this plateauing. Instead of holding the voltage supplied to one counter constant while we varied the voltage of the other counter, we had to change the voltage of both plates together. To give us an idea of the relative amount of noise getting through the logic unit at each voltage, we also placed a long delay cable between the output of the discriminator and the logic unit for one of the counters. This cable caused all pulses passing through the delay cable to arrive at the logic unit at a later time than any pulses emitted at the same time from the other counter which did not go through the delay cable. This means that no true coincidences due to cosmic rays could be registered, and the only output from the logic unit was due to noise. Although the noise registered this way was not exactly the same as the noise registered when there is no delay cable, it id give an idea of the relative noise at different voltages. Using our results from our pseudo-plateauing, we decided to use a voltage of 1250 volts (see the results section for more details) as our operating voltage.

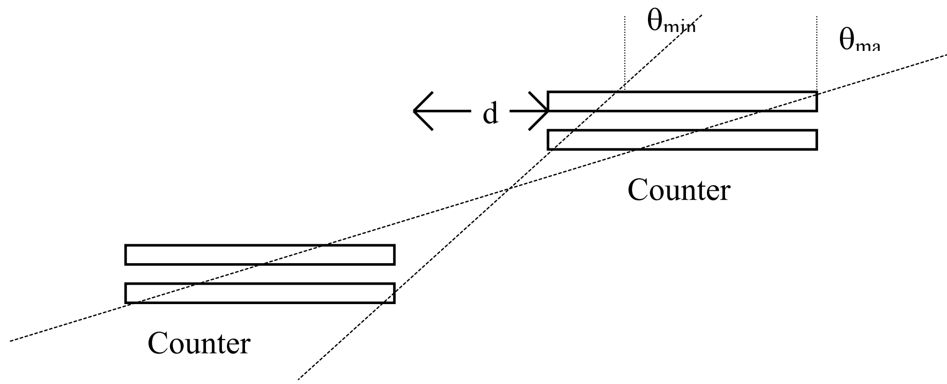


Figure 3: Orientation of counters in angular variation experiment as shown in a side view. The top view is the same as in figure 2. The vertical distance between the counters is constant at 0.85 +/- 0.01m. The horizontal distance between the counters, d, is varied. θ_{min} and θ_{max} are the range of angles from zenith at which a muon could strike both counters.

After this calibration was completed, we were ready to begin our actual measurements of cosmic rays. In our first set of readings, we placed the two counter pairs side by side at the same height. We then took readings until a sizable amount of coincidences had been recorded. By repeating this procedure at various horizontal counter separations and recording the frequency of coincidences, we were able to get some idea of the spatial distribution of cosmic ray showers, since coincidences were only recorded when the shower size was large enough that particles hit both pair of counters at the same time.

For our second experiment, we placed one of the counter pairs on a rack so that the vertical distance between the top counter on the rack and the bottom counter that was not on the rack was 0.85 +/- 0.01 meters. We then varied the horizontal distance between the two pairs of counters while keeping their vertical separation constant. This enabled us to take data related to the angle from zenith at which cosmic rays hit the earth.

Results

1) Error Analysis

Before quoting our results, a description of our error analysis methods should be made. The error on our distance and time measurements are due simply to instrumental error. When propagating these errors through calculations, we used the following formulae:

$$\sigma_u = \mathrm{sqr}(\sigma_x^2 + \sigma_y^2) \quad (1)$$

$$\sigma_u = A\sigma_x \quad (2)$$

$$\sigma_u = u\ \mathrm{sqr}[(\sigma_x/x)^2 + (\sigma_y/y)^2] \quad (3)$$

$$\sigma_u = \mathrm{sqr}[\sigma_x^2(du/dx)^2 + \sigma_y^2(du/dy)^2] \quad (4)$$

In all of these equations, σ_u is the propagated error on the calculated value and u is the function that was used in the calculation. x and y are the directly measured quantities and σ_x and σ_y are the errors on them. Equation 4 is a general formula for any u, and equations 1 through 3 may be derived from it. Equation 1 is used when u=x+y or u=x-y, equation 2 is used when u=Ax where A is a constant and equation 3 is used when u=xy or u=x/y. These equations were found in *Radiation Detection and Measurement*, by Glenn Knoll.

Since the detection of cosmic rays is a random event, there is a statistical error associated with our coincidence frequencies. This is given by

$$\sigma = N^{1/2} / t \quad (5)$$

where σ is the error, N is the total number of counts taken and t is the total time in which they were taken. This formula was also found in *Radiation Detection and Measurement*. Although there is a measurement error (+/- 1 second) associated with all of our t values, the values of t are so large compared to this error that it had no effect on most of our error calculations.

To find out whether we were measuring a significant number of false counts due to thermal excitation of electrons in the photomultipliers even after putting all our discriminator output through the four way logic unit, we used our count rates for each separate counter pair at the operating voltage of 1250 volts that we got while plateauing (3.30 +/- 0.09 counts per second (R_1) for counters 3 and 7 and 9.72 +/- 0.16 counts per second (R_2) for counters 1 and 6). Since the total time per second (t_1) that the discriminator channel connected to counters 3 and 7 is outputting a pulse is

$$t_1 = R_1\tau \quad (6)$$

where τ is the pulse width output by the discriminator (20 ns), the rate of random coincidences, R_{random}, is

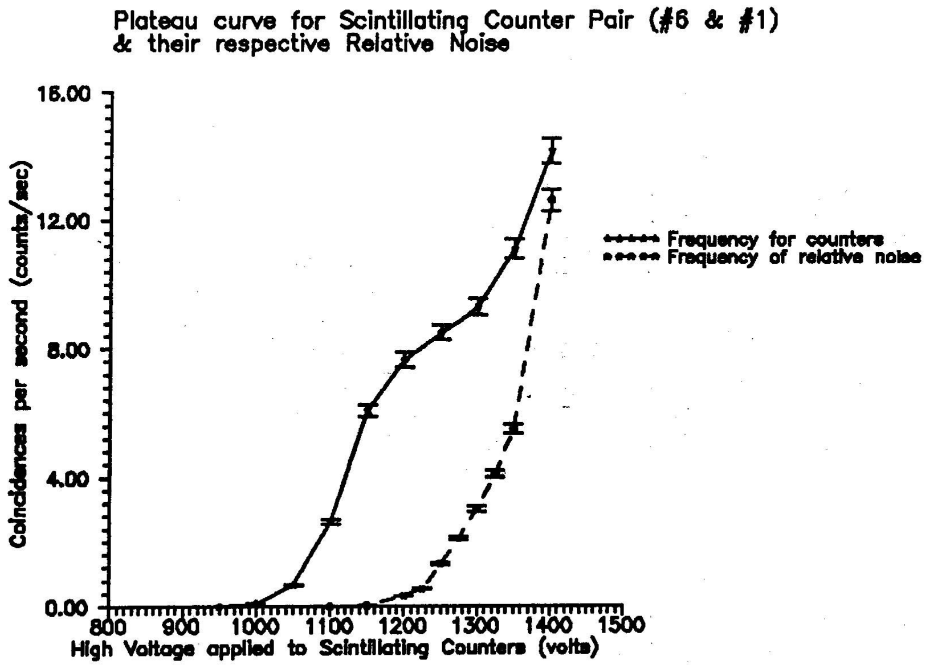
$$R_{random} = R_1R_2(2\tau) \quad (7)$$

Using this formula, the rate of random coincidences getting through the logic unit when all four counters were connected to it was $1.3 \pm 0.1 \times 10^{-6}$ counts per second, which is several orders of magnitude smaller than any of the coincidence rates that we measured in this lab (see tables 1 and 2). Of course, equation 7 is only a rough approximation, and does not take into account the fact that many of the counts in R_1 and R_2 are real cosmic ray detections. However, the approximation is good enough to show that our discriminator and logic unit were successful in filtering out virtually all significant noise in our horizontal separation and angular distribution measurements. Unfortunately, none of this says anything about the possibility that we are missing some cosmic ray detections. This should not effect the relative coincidence readings that we get as we vary counter separations though.

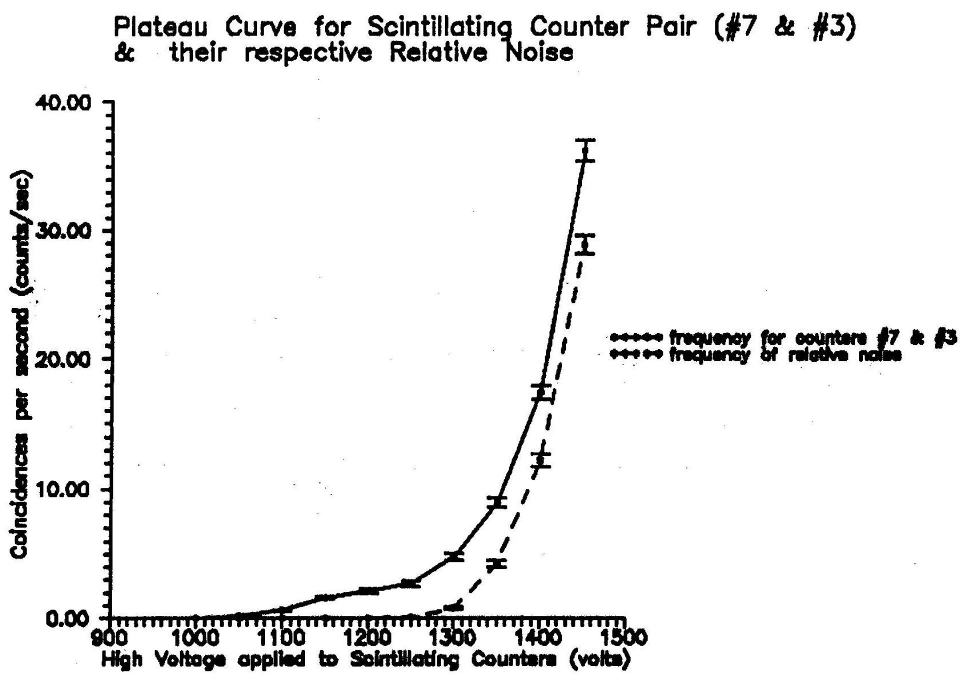
2) Plateauing

The results for both counter pairs are shown in graphs 1 and 2. Graph 1 shows an approximate plateau in coincidences in the region between 1200 and 1300 volts. The amount of noise shown in this range is not insignificant, but it is still relatively small. Graph 2 shows a plateau in the region between 1150 and 1250 volts, and the measurements using the delay cable show almost no noise at these voltages. Based on the data on these graphs we chose an operating voltage of 1250 volts for this experiment, as it is the best compromise between the two pairs.

It should be noted that the coincidence rate at 1250 volts for the pair of counters 1 and 6 was 9.72 +/- 0.16 counts per second compared to 3.30 counts per second for the pair of counters 3 and 7. This inconsistency is due to the fact that each of the counters probably have true operating voltages that are different from 1250 volts, and if either counter 3 or 7 has an ideal operating voltage significantly higher than 1250



Graph 1: Plateau and relative noise curves for counter/photomultiplier sets 1 and 6. Error bars were found using equation 5 (this error was combined with the error on the total time during which counts were taken using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). There is an approximate plateau in the region between 1200 and 1300 volts. The amount of relative noise shown in this region is not insignificant, but it is still relatively small.



Graph 2: Plateau and relative noise curves for counter/photomultiplier sets 3 and 7. Error bars were found using equation 5 (this error was combined with the error on the total time during which counts were taken using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). There is an approximate plateau in the region between 1150 and 1250 volts, and there is very little relative noise in this region.

volts, the coincidence rate of that pair will drop accordingly. Also, some of the counter/photomultiplier sets may simply be more efficient than others, regardless of their operating voltage. Finally, it should be remembered that we were unable to do true plateauing in this experiment, which would have involved varying the voltage of one photomultiplier while the other was kept at a constant voltage. Since the number of coincidences recorded was limited by the least sensitive of our counter/photomultiplier sets, this means that the rate of coincidences detected may be significantly smaller than the true rate of showers passing through our counters. However, our measured rate should still be proportional to the true rate, so our measurements regarding spatial distribution are still useful, since the *relative* rates at different counter separations measured should be the same as if we were detecting all of the incident particles.

3) Horizontal Separation Measurements

These results correspond to the experiment where we varied the horizontal distance between counters while keeping them at the same vertical elevation. These results are shown on table 1 and graph 3. The coincidence frequencies were found using the relation

$$f = N / t \qquad (8)$$

where f is the coincidence frequency, N is the total number of counts recorded and t is the total time during which counts were taken.

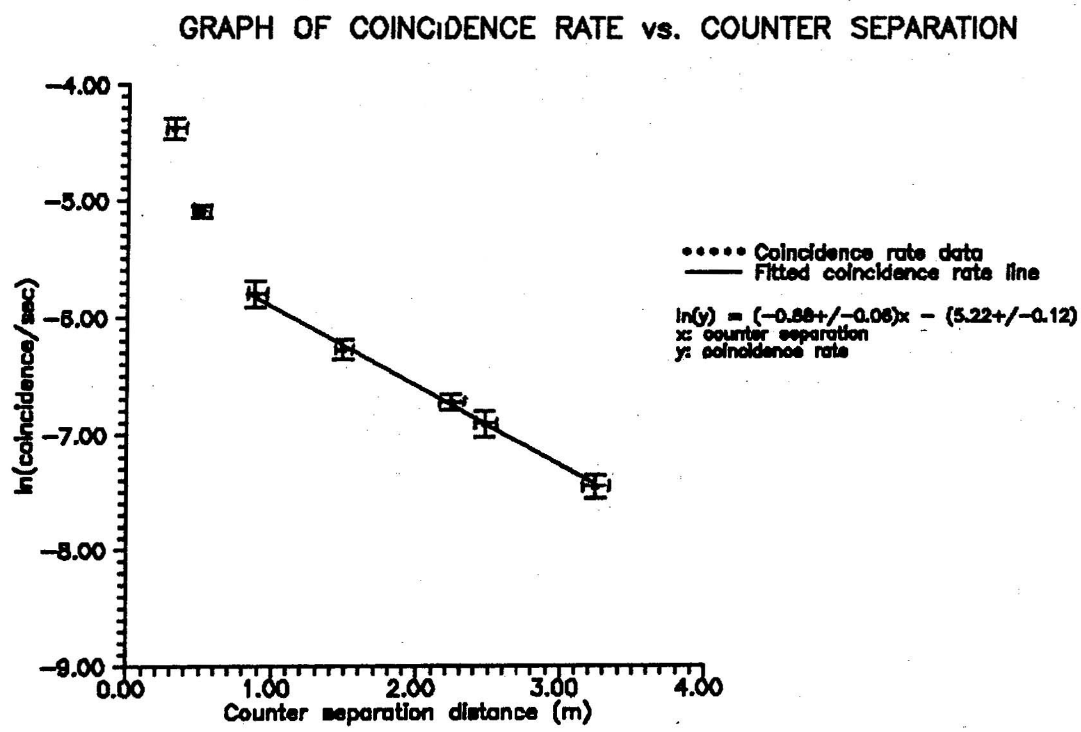
The linear fit shown on graph 3 was determined by putting the last five points through the linfit.bas linear regression program. As can be seen on graph 3, this line falls well within the error bars of all five points. See the discussion section for possibilities as to why the points corresponding to horizontal separations of 31 and 50 cm do not fall on the line. The equation of the line indicates that the coincidence rates of incident cosmic rays drops off exponentially with increasing counter separation according to the experimentally determined formula

$$f = \exp[(-0.68 \pm 0.08)d - (5.22 \pm 0.12)] \qquad (9)$$

where f is the coincidence rate and d is the horizontal counter separation.

Separation Between Centers of Counters (cm)+/-1cm	Total Number of Coincidences (counts)	Total Time Interval (seconds)+/-1s	Coincidence Frequency (count/s)	Standard Error on Coincidence Frequency (counts/s)
0	592	8.33×10^2	0.711	0.029
31	112	8.880×10^3	0.0126	0.0012
50	402	6.5340×10^4	0.00615	0.00031
87	80	2.6880×10^4	0.0030	0.0003
148	132	7.0800×10^4	0.00186	0.00016
223	185	1.52880×10^5	0.00121	0.00009
247	70	7.1220×10^4	0.00098	0.00012
337	96	1.64700×10^5	0.00058	0.00006

Table 1: Data for horizontal separation measurements with counter pairs kept at the same altitude. The standard error was found using equation 5 (this error was combined with the error on the total time using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). The row corresponding to 0 m separation between counters corresponds to when we stacked all four counters on stop of each other.



Graph 3: Graph of natural logarithm of coincidence rates as horizontal separation between counters was varied while counters were at the same elevation. The error bars on the ordinate were calculated using equation 5 (this error was combined with the error on the total time using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). The error bars on the abscissa were found by adding the half width of the detection area to the uncertainty of the counter separation measurement (using equation 1). The line shows the mathematically fitted relation between coincidence rates and counter separation.

4) Angular Variation Measurements

These results correspond to the experiment where we varied the horizontal separation between the counter pairs, while keeping them at different but fixed altitudes (the top counter of the raised pair was 0.85 +/- 0.01 meters above the bottom counter of the other pair). These results are shown on table 2.

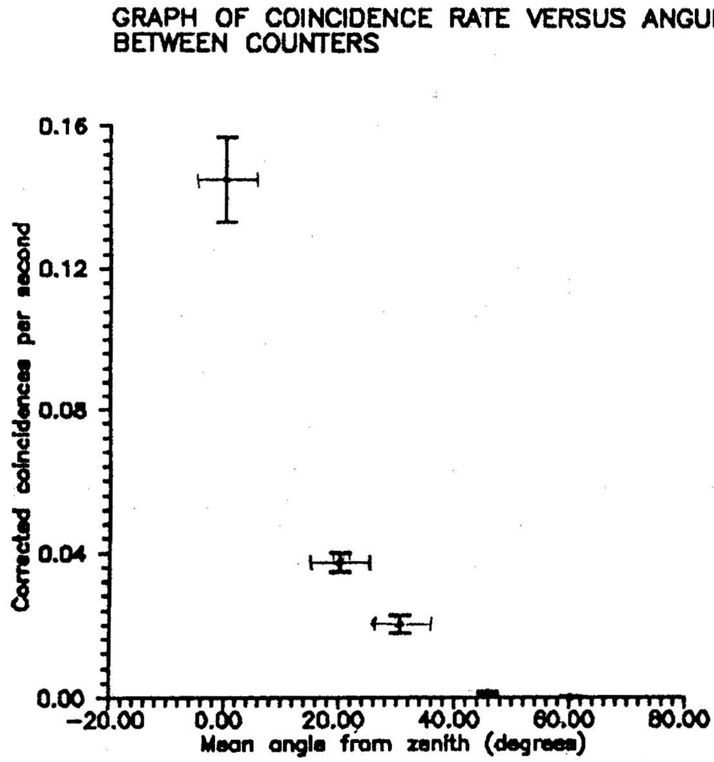
With the experimental setup we used in this part of the lab, single muon passing through our detectors with an angle from zenith between θ_{min} and θ_{max} could pass through all four counters. This resulted in higher coincidence frequencies than we got in the experiment when there was no vertical separation between the counter pairs, since the frequencies measured in this experiment include both the particles arriving at the given angles as well as the separate particles due to a single shower which were measured in the first experiment. By subtracting the coincidence frequencies for the corresponding horizontal counter separations that we got from the first experiment from our coincidence frequency measurements in this experiment, we were able to get rates related to the angle from zenith at which cosmic ray showers strike the earth's surface. Graph 4 shows how the coincidence rates decreased as the angle from zenith increased.

Horizontal Separation Between Centers of Counters (cm)+/-1cm	Range of Angles (θ_{min} / θ_{max}) (degrees) +/- 1° or less	Mean Angle Between Counters (degrees) +/- 1° or less	Total Number of Coincidence (counts)	Total Time Interval (s)+/-1s	Coincidence Frequency (count/s)	Corrected Coincidence Frequency (counts/s)
0	-4 / 4	0	157	1080	0.145 +/-0.012	0.145 +/-0.012
31	16 / 24	20	457	9120	0.0501 +/-0.0023	0.0375 +/-0.0026
50	27 / 34	31	108	4080	0.0265 +/-0.0026	0.0204 +/-0.0026
87	44 / 48	46	286	64380	0.00444 +/-0.00026	0.0014 +/-0.0004
148	59 / 61	60	27	13800	0.0020 +/-0.0004	0.0001 +/-0.0004

Table 2: Data for angular variation measurements with counters pairs kept at vertical separation of 0.85 +/- 0.01 meters. θ_{min} and θ_{max} are the range of angles from zenith at which a muon could strike both counters. The mean angle is the average angle between the counters. The error on the mean angle was found using equation 4. The corrected coincidence frequency is the coincidence frequency not counting muons arriving outside the range of angles. The error on the coincidence frequency was found using equation 5 (this error was combined with the error on the total time using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). The error on the corrected coincidence frequency was found by combining the error on the coincidence frequency in this experiment with the error on the coincidence frequency for the same counter separation found in the first experiment using equation 1.

Discussion

Although we verified that we did not register a significant number of false coincidences when all four counters were going through the discriminator and logic unit, we may well have missed a good deal of real cosmic ray shower detections. In other words, it is unlikely that we got rates higher than the true rates, but it is certainly possible that we got rates which were too low. The fact that we got two different coincidence rates at 1250 volts while plateauing (9.72 +/- 0.16 counts per second for the pair of counters 1 and 6 compared to 3.30 counts per second for the pair of counters 3 and 7) could support this, and we had no reliable way to measure the true rate of incoming muons and cosmic ray showers. The best that we can do was use the rate that we got when all four counters were placed directly on top of each other (0.711+/-0.029 coincidences per second) and divide it by the area of the counters (0.092 +/- 0.007 m^2), to get 7.7 +/- 0.7 detections per second per m^2 (equation 3 was used to propagate the error). The unreliability of our measurements is due to the fact that our counter/photomultiplier sets were not all equally efficient, and we were forced to supply them all with the same voltage, since we only had one power source. Despite making what compromises we could, our measurements were still only as good as our least efficient counter/photomultiplier set.



Graph 4: Graph of corrected coincidence rates as a function of the mean angle from zenith of the counter pairs. The error bars on the ordinate were calculated using equation 5 (this error was combined with the error on the total time using equation 3, but the results were the same as when just equation 5 was used, since the error on the time is very small compared to the time itself). The error bars on the abscissa were found by adding the error on the mean angle between counters from table 2 to the ranges of angles at which a single muon could hit all four counters using equation 1.

However, even if our rates may have been lower than the true rates, they were lower by the same factor for all of measurements. Any comparisons between readings is still good, such as the comparison of readings at different counter separations. In other words, our relative readings are still good.

It should also be noted that our coincidence rates may have been affected by the weather, since the particles that we were looking for had to pass through the atmosphere before reaching us. The weather during the times that we collected data ranged from clear skies to heavy snow.

Our results for the experiment where we varied the horizontal separation of the counters show that the number of coincidences drops off with counter separation in a manner proportional to equation 9. Since the particle showers must encompass both counter pairs in order for there to be a coincidence, this gives us a very approximate idea of how large particle showers are. Unfortunately, our measurements cannot give us the characteristic size of the showers, since our measurements are only proportional to the true values, for reasons dealt with in the last two paragraphs. Also, we were only able to collect information on muons energetic enough to cause pulses large enough for us to register coincidences. If particle intensity decreases with distance from the center of showers, as theory predicts, we may well have missed a good deal of muons. We were thus unable to arrive at a reliable number to compare to the theoretical root mean square radius of muon showers of 600 meters.

The coincidence rates corresponding to counter separations of 31 +/- 1 and 50 +/- 1 cm do not fall upon the fitted line on graph 3. There are two possible explanations for the elevated coincidence rates at these two points. Firstly, the counters in each pair are separated by vertical distances of 0.09 +/- 0.01 meters. When the horizontal separation between the counters, d ,is large, the angle between the top counter of one pair and the bottom counter of the other counter is so large that it is very unlikely that a single muon will travel through all four plates and cause a coincidence. However, when d is small, as is the case with 31 +/- 1 and 50 +/- 1 cm, the angle is small enough that this type of coincidence will occur, thus resulting in elevated coincidence rates. The other possibility is that particles other than muons were hitting the concrete of the Rutherford building and causing local air showers (rather than the extensive air showers that we dealt with in this lab) of small radius that were only detected when d was small.

Our results for the angular variation experiment clearly show that the number of muons arriving at small angles from zenith are much greater than those arriving at large angles from zenith, as predicted by theory. The number of particles arriving past 44 degrees are 160 times or more smaller than those arriving at angles close to zenith. However, it is difficult to get anything more precise than this from our data. For one thing, the error on our results is fairly large, as shown on graph 4. Also, there are several problems with the experimental setup that we used. For example, our counters were always oriented parallel to the ground, so muons passing through them at large angles traveled a greater distance through the counters than muons passing through them at small angles. The muons traveling a greater distance through our counters spent more time generating photons, which may have resulted in two coincidences being registered by our electronics rather than just one. A superior setup for the angular variation experiment that would have eliminated this problem would have been to place all four counters directly above one another at a fixed vertical distance on a rack that could itself be rotated.

A good possible future improvement to this experiment would have been to have more than one power supply so that the counter/photomultiplier sets could be operated at their optimum voltages. It would also be useful to have more operational counters. This way, separate coincidence rates could be measured for separate counter pairs at different locations, which would supply useful data on finding the spatial distribution of cosmic ray showers. Of course, more equipment means more expenses, and monetary limitations are always a consideration in the real world of science.

This lab was very valuable in that in gave us a great deal of experience in attempting to compensate for limitations in equipment and in solving the many difficulties that arise when trying to calibrate an experimental setup and get it working. It also provided very interesting insights into the techniques used in astrophysics and particle physics.

Conclusions

We found that the frequency or incident muons as a functions of counter separation is given by equation 9. The intensity of cosmic ray showers drops off as you move away from the center of the shower. We detected 7.7 +/- 0.7 showers per second per m^2 passing through our counters when they were stacked on top of each other. We also found that most cosmic ray showers strike the earth at sea level at angles close to the zenith.

References

Arley,N., "Stochastic Processes and Cosmic Radiations" ,John Wiley & Sons, New York, 1943.

Galbraith, William, “Extensive Air Showers”, Butterworths Scientific Publications, New York, 1958.

Hillas, A.M., "Cosmic Rays", Pergamon Press, Oxford, 1972.

Hooper,J.E., Scharff,M., "The Cosmic Radiation", Methuen & Co, Ltd, London, 1958.

Knoll, Glenn, “Radiation Detection and Measurement”, Wiley & Sons, New York, 1979.

Montgomery, D.J., "Cosmic Ray Physics", Princeton University, Princeton, 1949.

Pomerantz, M., "Cosmic Rays", Van Nostrand Reinhold, New York, 1971.

Risden, John ed., “MacMillan Encyclopedia of Physics”, Volume 1, MacMillan Publishing, New York, 1996.

Sandstrom, A.E., “Cosmic Ray Physics”, Wiley & Sons, New York, 1964.

Zeilik, M., Gregory, S., Smith E., "Introductory Astronomy and Astrophysics." Saunders College Publishing, Fort Worth, 1992.