EXPERIMENT 19

COSMIC RADIATION

Equipment List:-
Cosmic Ray telescope:

a) Cosmic Ray "Telescope" frame with four Geiger tubes mounted on it, each with its own interface circuit
b) "Cosmic Ray Telescope" electronics box
c) "Coincidence Counter" unit which records, at the same time, the numbers of 7 different types of coincidence
d) 5 cm thick lead shield on stand
e) Oscilloscope
f) "SUP" logic driver and power supply
g) Special cable with four tails at one end, each with a BNC plug
h) Other connecting cables

Muon Lifetime:

(a) Plastic Scintillators (under bench)
(b) EHT power supply for the photomultipliers of the scintillators
(c) Timing converter
(d) Pulse width analyser

Reference.-.Rossi "High Energy Particles", Prentice Hall 1965.

AIM

This experiment consists of two parts. The first is to determine the nature and direction of cosmic radiation using a cosmic ray telescope. In particular you will be introduced to the technique of coincidence counting that is used extensively by the telescope. The second part involves measuring the lifetime of muons that are in cosmic rays.

INTRODUCTION

The cosmic radiation studied in this experiment is the secondary radiation arriving at the earth's surface which is produced by the interactions of the primary cosmic rays with air atoms of the upper atmosphere. The primary radiation consists largely of highly energetic protons and heavier nuclei.

The secondary radiation consists mainly of high energy electrons and positrons, gamma photons and positive and negative muons, all with energies up to a few GeV. These particles occur individually and sometimes in groups called showers, the latter being produced in cascade processes from a single high energy cosmic ray primary particle.

PART 1 - COSMIC RAY TELESCOPE

1. COINCIDENCE TECHNIQUES

The purpose of this section is to introduce the idea of coincidence techniques. These enable one to select from a large number of events only those that are of particular interest. Here coincidences are used to separate, from all the counts produced in an array of Geiger counters, those counts due to cosmic rays arriving from a particular direction. We can then investigate the directional properties of the cosmic rays.

An ionizing event inside a counter will cause that counter to "fire" and produce an electrical pulse. The event could be the passage of a cosmic ray secondary particle or a secondary electron from a gamma ray of terrestrial origin (Uranium in the concrete floor for example). Later on you will see how the coincidence technique discards the latter class of events. An interface circuit on each counter produces pulses standardised for digital logic levels. These travel down cables to the "Cosmic Ray Telescope" box and enter by colour coded connectors on the left side. EHT and low voltage power for the counters and interface circuits come from connectors on the right side. None of these power connectors should be disconnected.

Inside the box each pulse is further standardised by the use of a mono (monostable multivibrator) so that its width is T. These pulses are fed to various coincidence (AND logic) and anticoincidence (NAND logic) circuits which give outputs if the original Geiger pulses occur in coincidence (anti-coincidence). For a particular coincidence circuit this can occur only when an ionising particle traverses the particular counters which are connected to the coincidence circuit or when separate particles fire each counter together (accidental coincidences). The counters do not have to fire exactly at the same time for a coincidence to be recorded. Geigers, like any other detector, have a response time (around 0.5 μs for Geigers) which is subject to **jitter**. A particle traversing near the counter's centre wire will produce a pulse rather earlier than a particle traversing near the outer cylinder. T is set at 5 μs in the box to allow for this jitter. This corresponds to the RESOLVING TIME switch being set to NORMAL. The RESOLVING TIME can be defined as the allowable gap between the beginning of the pulses, which will still result in an output coincidence pulse. Note that the electronic circuitry usually does not "care" which pulse comes first.

The colour coding used in the experiment is Blue (B), Red (R) and Green (G) for the three in-line counters (Red being the central one) and Yellow (Y) for the off-line counter. The "Cosmic Ray Telescope" box hasm7 different outputs, numbered 1 to 7, corresponding to different types of coincidences between the counters. These are shown pictorially on the front panel of the box and are as given in the table below.

Output number	Type of coincidence
1	BR
2	RG
3	BG
4	BRG
5	BGY
6	$BR\overline{G}$
7	BR or RG

(N.B. $\overline{G}$ means "not Green")

The outputs, as well as being available on the front panel of the box, are fed to the "Coincidence Counter" unit which records the numbers of coincidence of the different types in any specified time.

Before using the coincidence circuitry you should check that the outputs are as indicated in the above table by using pulses from the pulse generator, SUP.

- Disconnect from the inputs the leads from the Geiger counters. Use the four-tailed cable to connect the up-pulse output, P, of SUP to all the four inputs.
- Connect the down-pulse output, $\overline{P}$, of SUP to the Channel 1 input of the oscilloscope which should be set to internal CH1 triggering.
- Feed the pulse from each of the Outputs 1 to 7, in turn, to the Channel 2 input. The logic may be tested using the LOGIC switches to the four inputs. When one of these switches is placed in the TEST position its normal input is disconnected and a DC voltage of the same size as the input pulse is supplied, thus simulating an input pulse at all times. The logic may also be tested by removing appropriate cables from the inputs.
- Now replace the pulse generator signals with the pulses from the Geigers.
- Connect Output 4 to the oscilloscope.
- Put the B, R and G switches in the TEST position. Now, in turn, set one of the three switches to the RUN position. You are seeing the individual pulses of the three Geigers in turn. With two of the switches in the RUN position you see the rather infrequent two-fold coincidences due to cosmic ray secondary particles traversing the two Geigers selected. Almost all of the pulses due to terrestrial radioactivity have been excluded.
- Estimate the background count rate/minute for each of the four counters. These rates will be used later to assess background coincidences.
- Set all four input LOGIC switches to RUN for the rest of the experiment.

2. DIRECTION OF ARRIVAL OF COSMIC RAYS - ZENITH ANGLE DISTRIBUTION

The counting rate of double coincidences depends on the zenith angle θ setting of the telescope - more particles arrive from small zenith angles. The zenith is defined as the angle between the vertical and the plane containing the three counters RGB for any orientation. Note the protractor on the telescope reads 180-θ.

The building introduces a complication in this experiment as it strongly absorbs the electron and photon secondaries (but hardly attenuates the muon component).

- For your measurements you should arrange the telescope so that the tracks of incoming particles do not intersect the building, except for small zenith angles when it cannot be avoided.

- Set the axes of the B and G counters so that they lie 6 cm from the axis of the R counter and record the number of counts over 10 minute intervals as θ is varied from 0 to 80 degrees in 10 degree steps.

The rate from Output 4 is fairly small because the "telescope" formed by the two outer counters has a small **solid angle/area** product (see Appendix 2). The fact that the inner R counter has to fire is not important; most pulses that fire B and G also fire R. Output 5 shows that occasionally we have BG coincidences not caused by single particles but by **showers** of particles. We will investigate this phenomenon later in the overnight run.

- Use Output 7's data to plot a **zenith angle distribution** rather than output 4 because the statistical fluctuations in the latter are relatively large. (Note that the best estimate of the standard deviation of the count is equal to the square root of the count).

The counting rate turns out to be very close to being proportional to $\cos^n\theta$. There is no theoretical reason for such a simple dependence. However one may assume a law of this type and find n.

- Do this by plotting log counts vs log cosθ and fitting a straight line to the graph. Show errors on your graph and hence arrive at an estimate for the error in n.

NB. The counters accept particles over the range of angles θ ± β.

- Calculate β in the present case, given that the counter diameter b is 2.1 cm.

C1 ▷ **Tutor checkpoint. Obtain tutor's signature before proceeding.**

3. MEASUREMENT OF COSMIC RAY INTENSITY

(Overnight run)

To increase the number of counts and hence the accuracy, the readings in this section are obtained by leaving the equipment running overnight. Set the telescope's zenith angle to 30 degrees so as to allow the electron photon component to enter without passing through the concrete floors above the apparatus.

- Record the counts from outputs 3, 4 and 5 noting that output 5 shows mostly cosmic ray showers. Now proceed as follows:-

    - By comparing the outputs 3 and 4 estimate the efficiency η of the middle red counter. It is a reasonable assumption to assume a similar efficiency for all the counters.

    - Estimate the true single particle rate at 30º, by calculating $\frac{1}{\eta^3}\left[\text{BRG - BYG}\right] =$

      $N(30) = \frac{1}{\eta^3}\left[\text{output 4 - output 5}\right]$ and dividing by the total elapsed time.

    - The value N(30) corrected for showers and inefficiency can now be used to find the intensity at 30º, J(30), by using the area/solid angle product for the telescope. The latter is just the ratio ($\frac{N}{J}$) which is solely dependent upon the geometry of the telescope and can be determined using the approximation given Appendix 2. The counters have a sensitive length of 24 cm and an inside diameter of 2.1 cm. Note that the relevant separation is between the outermost counters as these define the solid angle.

    - Finally, from J(30) calculate J(0) using the value of n obtained earlier.

You are now in a position to quote the flux in a standardised form which can be compared with other experiments in other places perhaps using quite different equipment.

C2 ▷ **Tutor checkpoint. Obtain tutor's signature before proceeding.**

4. COMPARISON OF THE ELECTRON FLUX WITH THE TOTAL PARTICLE FLUX

As previously mentioned, the flux of secondary particles at sea level consists, partly of electrons, positrons and photons, and partly of muons of both signs. There are also small numbers of hadrons - strongly interacting particles such as pions, kaons, nucleons and other baryons. In this section you will do a simple measurement to find the proportion of the electron flux to the total flux at 30 degrees zenith angle, here near sea level. The basis of the method is discussed in Appendix 1.

- Take the telescope, set the zenith angle to 30 degrees and increase the distance between the Geigers so that it can be swung in a position with the red and green Geigers on either side of the 5 cm thick lead block. The lead block can be rotated into position but may need a little force.

- Now adjust the blue and green Geigers so that they remain at equal distances from the red tube but this distance is as small as possible. Record Outputs 1 and 2.

- Run until Output 1 gives around 200 counts and use the data to obtain the ratio of the electron flux to the total flux.

- Output 1 records all particles and Output 2 records muons (almost exclusively). Muons at sea level have average energies in the GeV range. Their energy loss is almost entirely due to ionisation and at a rate of about 2 Mev per g/cm^2. Clearly most muons go through 50 mm (ie 55 g/cm^2) of lead with "great ease".

5. ACCIDENTAL COINCIDENCES

As indicated earlier, there is a finite but usually small probability that separate unrelated particles will produce a coincidence. The first particle fires one counter and the second sets off the second within the resolving time T. These accidental coincidences must always be taken into account in coincidence counting, and this accidental rate will be independent of the separation of the counters.

- Set the Geiger counters as far apart as possible in the horizontal plane - so that the number of true coincidences is very small.

- Place the radioactive gamma sources (in the yellow wood blocks) near the outside counters to increase the counts to about between 2500 and 5000 counts/minute. The yellow blocks may have been placed on the other side of the table on the ground to keep them as far away as possible from your previous readings.

- Measure the individual rates R_1, R_2 and R_3 of each channel B, R and G (by placing the other Geiger's switches in the TEST position).

- **Now put all the switches down (RUN setting)** and record over a half-hour period. A large proportion of the double coincidence counts are now due to accidental coincidences. Compare the measured numbers of accidental counts with those calculated from the formulae for the **predicted rates**

  Doubles accidental rate = $2 R_1 R_2 T$
  Triples accidental rate = $3 R_1 R_2 R_3 T^2$

T is the width of the output pulses (5 μs).

- If time permits, a second run could be taken with T increased to 15 μs (resolving time set to WIDE), thus enhancing the number of accidentals and increasing the probability of seeing some triples. In comparing measured and predicted counts it is important to realise that the count numbers are subject to Poissonian fluctuations: if in a time interval the expected number of counts is μ then the probability of seeing n is given by

$$p(n) = \exp(-\mu)\, \mu^n/n!$$

For accidentals one often has $\mu \ll 1$. In the present set up you should note that cosmic ray showers will be responsible for a number of coincidences which look like accidentals, especially the triples.

- Using the individual background rates measured at the beginning of the experiment; estimate the contribution of accidentals to the coincidence counts observed in the zenith angle runs performed earlier.
- Comment.

C3 ▷ **Tutor checkpoint. Obtain tutor's signature before proceeding.**

When accidental rates are excessive one may be able to reduce T, provided genuine coincidences are not excluded by jitter. Increasing the "order" of the coincidence (say from two to three) can produce dramatic improvement.

PART 2 - MUON LIFETIME
(overnight run)

In a second overnight run you will measure the mean lifetime of the muon: one of the most common components of cosmic radiation. Low energy muons will stop in the large block of four plastic scintillators situated under the bench in a light-tight box. The scintillators are viewed by eight photomultipliers whose signals are passively mixed and fed into a timing converter. To understand the purpose of the converter, we should firstly understand the physics of the muon decay.

When a low energy muon slows down and stops in the scintillator, a short prompt pulse is emitted by the scintillators - the actual stopping time being of the order of a few nanoseconds. Another point of interest is that the muons of different sign behave differently in the scintillator material. The negative muons (μ^-) are captured like electrons in an atomic orbit and are subsequently captured by the nucleus. The large muon mass makes the orbits of very small radius - resulting in the muon spending most of its time within the nucleus - so the fact that they are captured is not surprising. The positive muons (μ^+) however are not captured in this way and wait around in the scintillator until they decay via the reaction

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

As the rest mass of the muon is over two hundred electron masses, there is a large mass difference in the interaction showing up as kinetic energy of the products. Hence an electron is emitted relativistically and will give a second pulse in the scintillators. The distribution of time differences between the prompt stopping pulse and the subsequent decay pulse gives a measure of the lifetime of the muon. The usual decay relation holds for muons - namely

$$N(t) = N(0) \exp(-t/\tau)$$

where N(t) is the number of muons remaining undecayed at time t, given an original number N(0), with a **mean life** or **lifetime** τ.

By differentiating this expression against t you can show that the rate of decay also falls off (as it does with more conventional radioactive sources) as $\exp(-t/\tau)$. Moreover the number of counts in a time (like 2μs) which is comparable with τ, should also fall off as $\exp(-t/\tau)$. So provided the counting interval is constant for all channels, you can obtain τ from the slope of the graph.

- The purpose of the timing converter is to accept pulse pairs and to give an output whose height is proportional to the time difference between these pulses. These output pulses are then sent to a multichannel analyser card installed in the computer. Use the "Maestro" programme to access the multichannel analyser card.

- Turn on the equipment and check that the voltage supply is running at 1780 volts.

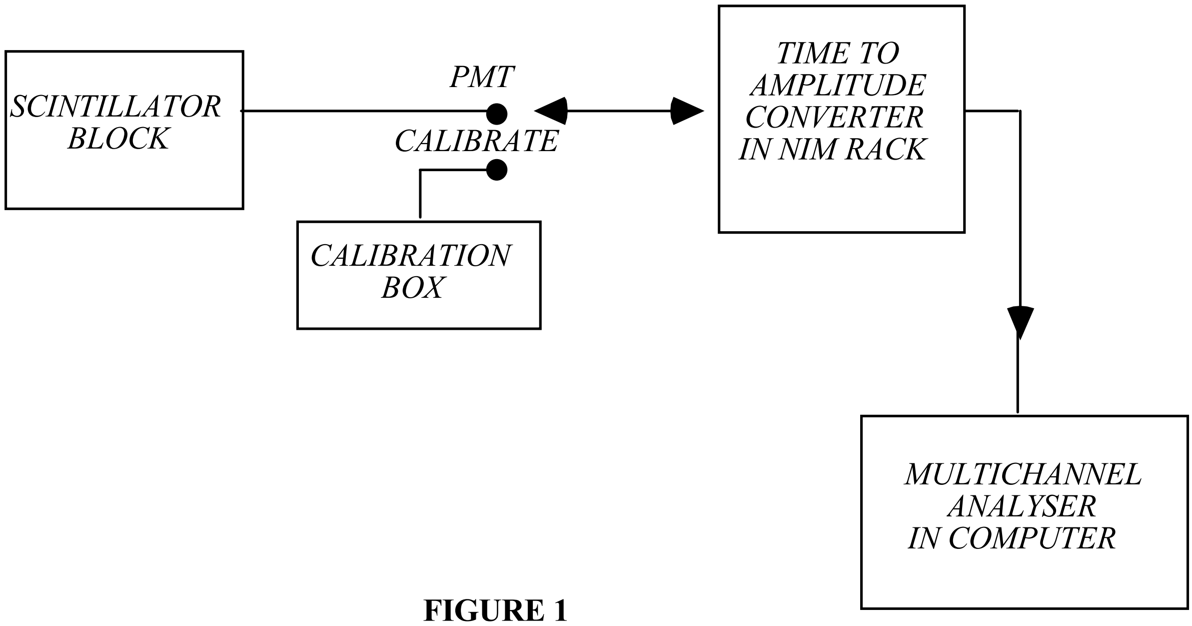

FIGURE 1

Schematic Diagram of Muon Lifetime Experiment

- The multichannel analyzer for this experiment is controlled by the program Maestro in the computer on the adjacent bench. Start this program and set the number of channels to the maximum value, 2048.

First it will be necessary to calibrate the system with pulses separated by known time intervals generated by the electronics beside the high voltage supply.

- Switch the junction box to “Calibrate”.
- Set Maestro to acquire data (“Start” in the “Acquire” menu) and leave it running for the duration of the calibration.
- Activate the red button on the calibration box which initialises a 30 s train of pulse pairs each separated by the preset dial interval. Each setting should give sharp spike restricted to just one or two channels width.
- When the data has been collected for all time intervals, stop the acquisition. Note the maximum channel for each delay setting.
- Use “ORIGIN” to plot the delay settings as a function of channel number, and fit a straight line to obtain the calibration equation.
- Now switch the junction box to “PMT”. Clear the calibration from Maestro, start the acquisition, and leave the equipment to acquire for a long period (preferably overnight).

- Stop the acquisition, and save the data onto disk as a “MyData.chn” file. Use the “Export…” command from the “File” menu to convert “MyData.chn” file to ASCII format. The file named “MyData.txt” will be created.

- In “ORIGIN” use “Import ASCII…” command to get your spectrum data into the worksheet. Add one column to the worksheet and set it’s values using formula slope*col(A) + intercept , where “slope” and “intercept” are values obtained from the calibration procedure. Column C becomes the delay time between pulses expressed in µs.

- Remove from the worksheet all rows in column C with values less than 1 or greater than 12 μs.

- Make a scatter plot using column C as an X and column B as a Y. You can use the “Fit exponential decay” command from the “Analysis” menu. The t_1 parameter is a mean lifetime of the muon.

- Alternatively, there is some advantage in changing the Y axis to natural logarithm, and fitting to the straight line part of the plot. This ensures that only that part of the plot which is exponential is fitted (this judgement will be harder to make when the axis is linear). If background is present the plot will depart from exponential eventually.

- Compare both methods and decide which result is more reliable.

C4 ▷ **Tutor checkpoint.**

APPENDIX 1

Attenuation of the Electron/Photon Component, Cascade Showers

As previously mentioned, the flux of secondary particles at sea level consists, partly of electrons, positrons and photons, and partly of muons of both signs. There are also small numbers of hadrons - strongly interacting particles such as pions, kaons, nucleons and other baryons.

The electrons, positrons and photons are lumped together for a good reason. Consider a photon, formed say from the decay of a neutral pion. (This pion could have come from a charged particle interaction some distance above the equipment). The photon can “materialise" i.e. suffer a pair production event anywhere along its path, providing nuclei are present to take off momentum; otherwise the interaction is kinematically impossible. The mean free path P for this process can be calculated and is given to adequate accuracy by:- (see Rossi page 81)

$$1/P = (4\alpha N\ r_e^2 Z^2/A) \left[(7/9)\ \ln (183Z^{-1/3}) - 1/54 \right] \text{ in cm}^2/\text{g}$$

where α is the fine structure constant (1/137), N is Avogadro's number, Z and A are the atomic number and mass number of the medium where pair production occurs and r_e is the "classical" radius of the electron

$$r_e = e^2/(4\pi\varepsilon_o mc^2) = 2.82 \text{ fm}$$

The electrons and positrons produced by this process can interact with matter to produce bremsstrahlung photons. The mean free path for this (X) is given to adequate accuracy by

$$1/X = (4\alpha N\, r_e^2 Z^2/A)\ \ln(183Z^{-1/3})\ \text{cm}^2/\text{g}$$

(Rossi page 50). X is called the radiation length. Note that it is approximately equal to 7/9 times P. For air at ground level X is 42 g/cm^2 or 320 metres (at sea level) and in lead it is 5.9 g/cm^2 or about 5 mm.

The twin processes of pair production and bremsstrahlung cause a **cascade** process in the medium. At some nodes photons disappear and two electrons take each photons place and at other nodes an electron radiates a photon. On the average, at either type of node we have a sharing of the energy between the two outgoing particles. If the initiating particle has sufficient energy, after n generations of the cascade, we should have 2N particles and these particles would have an average energy equal to the initiator's energy divided by 2N. This cascade or **shower** process can not go on indefinitely. It stops (approximately speaking) when the electron energy reaches the **critical energy.** The latter is defined as the energy where the electron loses energy by ionisation of the medium at the same rate [eV/(g/cm^2)] as it does on the average by radiating bremsstrahlung. For air this energy is about 80 Mev and for lead 7.4 Mev.

The shower does not suddenly cease when all electrons reach the critical energy; fluctuations in the cascade's energy sharing, at the interactions and the fluctuations in free paths, mean that the decay of the cascade is "gradual".

A piece of lead 5 cm or 10 radiation lengths thick will stop electron photon cascades quite efficiently because a potential degrading of particle energy by something like 2 occurs. Thus incident electrons or photons of energies less than 7.4 MeV x 1024 = 7 GeV should have their cascade fully absorbed in the lead. Most of the photons and electrons in the secondary component at sea level have energies just above the critical energy in air, namely 80 MeV.

APPENDIX 2

Notation for Cosmic Ray Intensities

The following symbols may be defined:-

$N(\theta)$ - the number of coincidences per second with the telescope at an angle θ to the vertical. (zenith angle)

$J(\theta)$ - the intensity of cosmic rays arriving in the direction θ, i.e. the number of particles per cm^2 per steradian per second.

Let **a** be the sensitive length of each counter, **b** the diameter of its sensitive region (the internal diameter of the outer cathode cylinder) and d be the separation of the axes of the two counters forming a telescope.

The solid angle subtended by the top counter at any point on the cross section of the bottom counter is approximately ab/d^2, and the sensitive area of cross section of the bottom counter is **ab**. Hence $N(\theta)$ and $J(\theta)$ are connected by the following approximate equation

$$N(\theta) = J(\theta)\,(ab/d^2)ab = J(\theta)\left(\frac{ab}{d}\right)^2$$

$N(\theta)/J(\theta)$ has the dimension of area and is called the **solid angle area** product of the telescope. This expression is sufficient for this experiment although it is only approximate.

A more accurate expression for it can be obtained as follows: We define two angles η_1 and η_2 which define the direction of a notional particle with respect to a suitable standard direction (which is set conveniently to be the line connecting two points, one on each counter's axis half way along it). Seen from this direction the telescope subtends an area A, such that a particle passing through A is recorded. The solid **angle area** product is merely the integral of $A(\eta_1, \eta_2)$ over the range of these two angles.