Particle Detection by Means of Ionization and Scintillation Detectors.

KVPY Summer Programme Report of
Tanmay S. Patankar.
KVPY Reg. No.: **SA 10910127.**

Place: **Tata Institute of Fundamental Research (TIFR), Mumbai.**
Project Advisors: **Prof. A. Dighe (Department of Theoretical Physics), Prof. B. Satyanarayana (Department of High-Energy Physics).**

Duration: **23-05-2011 to 30-06-2011.**

Abstract:

Elementary techniques by which high-energy cosmic ray particles like muons can be detected were studied. When high-energy cosmic ray muons pass through plastic, they produce a pulse of light, thereby allowing us to detect them. The flux of the muons was measured. In addition, methods used to calculate the muon energy were also studied. Muons lose their energy while penetrating dense media, due to which we can filter them based on their energies.

Introduction.

The project was about cosmic ray particle detectors. The experimental part involved understanding the operation of scintillation detectors and ionization detectors (Resistive Plate Chambers or RPCs) and using them to study some basic properties of particle detectors, counting techniques and error analysis. The flux of the cosmic ray muons coming vertically downwards was measured. In addition, the variation of the noise rate with threshold was studied.

The theoretical part consisted of discussions regarding special relativity, analysis of data, and they also supplemented the experimental setup. Also, techniques used to measure the muon energy were studied. The details can be found in the following chapters.

1. Scintillation Detectors.

Scintillation detectors exploit the property of certain materials to emit light pulses when exposed to high-energy charged particles like muons or electrons.

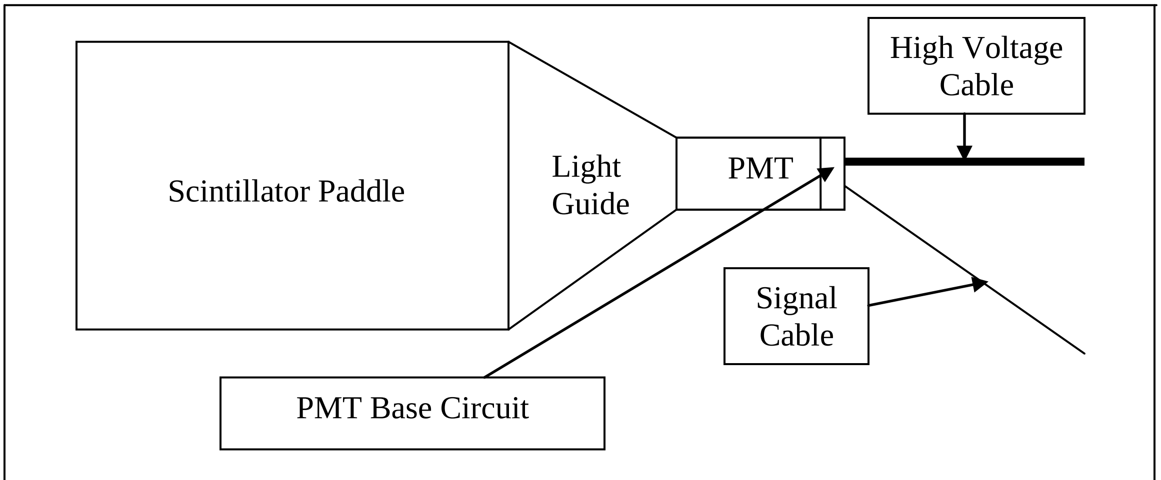


Fig. 1.1: Schematic Diagram of a scintillation detector.

1.1: Construction and working[1]:

A scintillation detector consists of three main parts: a scintillator paddle, a light-guide and a photomultiplier tube (PMT).

A) Scintillator paddle: It has a rectangular cross-section with typical dimensions 40cm x 20cm x 1cm.It is usually made of plastic.

B) Light-guide: It `guides' (carries) the light produced by the paddle towards the PMT. The light is transmitted with minimum possible attenuation. The light-guide is typically made of acrylic.

C) Photomultiplier tube (PMT): The function of the PMT is to convert the incident light pulse into an electric signal and amplify it to a reasonably large amplitude (~40-50 mV). It consists of a photocathode, an anode and dynodes. Electrons are liberated at the photocathode, by the photoelectric effect. They are accelerated by a high potential difference, strike the dynodes, in turn, liberating more photoelectrons and thereby amplifying the signal. 10-12 such dynodes are present, giving rise to an amplification of 10^6.

The whole assembly is covered with reflecting Tyvec paper and black Tedler paper in order to minimize light losses and to avoid exposure to ambient light.

When charged particles strike the paddle, they excite the electrons in the plastic to higher energy states. The electrons return to their original energy states, emitting light in the process. This flash of light is converted into an electric signal and amplified by the PMT. The electric pulse thus produced is analog. It is fed to a NIM (Nuclear Instrumentation Module) module, which converts it into a digital form. The NIM module is connected to a visual scaler, which counts the number of pulses produced in a set time interval.

Pulse characteristics:

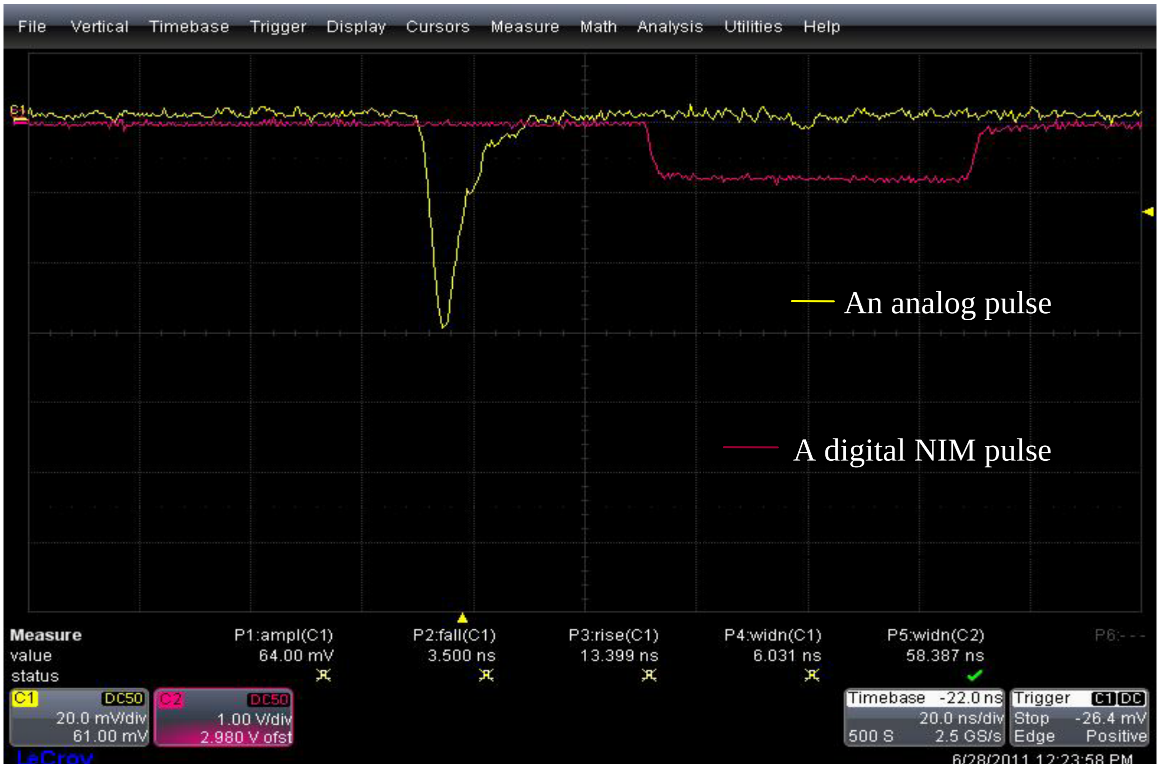


Fig.1.2: A typical paddle pulse.

A typical pulse is shown in fig. 1.2 above. Its amplitude is about 60 mV. The rise time of a pulse is defined as the time taken for the voltage to rise from 10% to 90% of the maximum voltage. It is typically of the order of 10 ns. for plastic materials. The pulse width was 60 ns. for the pulses recorded from the paddles.

1.2: The four-fold coincidence experiment:

Most of the events recorded by the scintillator are either due to electronic noise or due to the background radiation and not from the cosmic ray muons. To find the rate at which the muons are striking the paddles, we can perform a simple experiment: we can place 4 paddles, one above the other and connecting their signals to an AND Gate. This will ensure that almost all the signals that are detected are from the cosmic ray events.

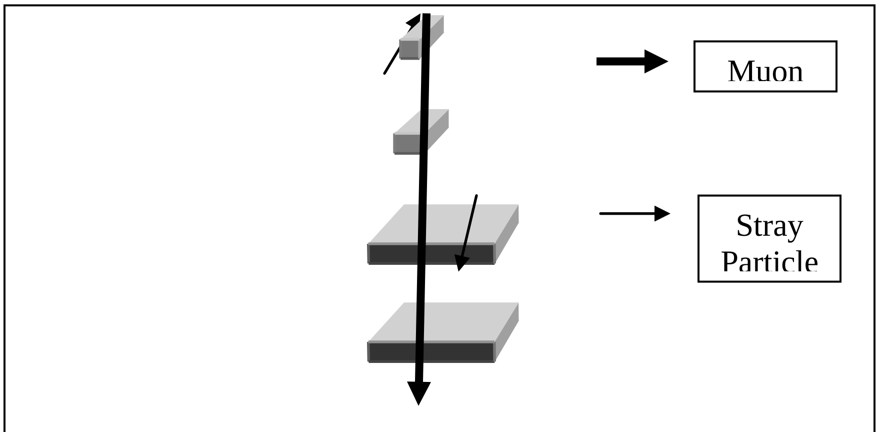


Fig. 1.3: Schematic diagram of the trigger rate experiment.

The resulting rate is known as the 4-fold trigger rate. In my experimental setup, the 4 paddles had respective dimensions:
P1: 30 cm x 2 cm x 1 cm.
P2: 30 cm x 3 cm x 1 cm.
P3: 40 cm x 20 cm x 1 cm.
P4: 40 cm x 20 cm x 1 cm.

The readings for the individual rates and the 4-fold trigger rate are summarised in the following table:

Readings number	Time (s)	P1	P2	P3	P4
1	100	728	619	7526	4736
2	100	777	590	7728	4741
3	100	837	628	8037	4821
4	100	779	562	7799	4784
5	100	820	571	8029	4816
6	100	792	602	8041	4953
7	100	770	595	7953	4875
8	100	786	600	7710	4829
9	100	779	595	8038	4809
10	100	777	610	7798	4820
Total	1000	7845	5972	78759	48184
Average	100	784.5	597.2	7875.9	4818.4
Average Frequency (Hz.)	--	7.845	5.972	78.759	48.184

Table 1.1: Individual paddle signal rate.

Readings number	Time (s)	P1	P2	P3	4-fold trigger
11	600	4829	3859	47789	26
12	600	4960	3676	45892	35
13	600	4692	3618	43981	25
14	600	4781	3785	43109	27
15	10000	80043	61554	628988	429

Table 1.2: 4-fold trigger rate.

The NIM bin in the experimental setup had only four channels. As a result, only 4 readings could be studied at a time.

1.3: The chance coincidence experiment:

An alternate arrangement of paddles is made to measure the background rate, as shown below:

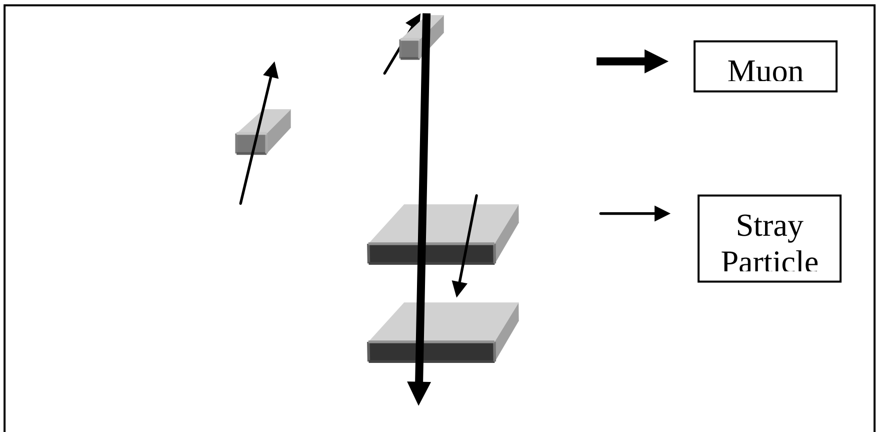


Fig. 1.4: Schematic diagram of the chance coincidence experiment.

This setup is known as the "chance coincidence experiment". There is a small probability that a cosmic ray muon will pass through paddles 1, 3, and 4 and paddle 2 will record either signal or noise, simultaneously. The probability that at a certain time instant, all 4 paddles record a signal is:
$(7.845 \times 60 \times 10^{-9}) \times (5.972 \times 60 \times 10^{-9}) \times (78.759 \times 60 \times 10^{-9}) \times (48.184 \times 60 \times 10^{-9}) = 2.3042 \times 10^{-24}$. This is an extremely low probability and hence there is only a negligible probability of all 4 paddles recording a signal simultaneously purely by chance. A more probable chance coincidence will be that a muon passes through paddles 1, 3, 4, and paddle 2 records any signal (noise/muon). This rate will be $(5.972 \times 60 \times 10^{-9} \times 0.0429) = 1.537 \times 10^{-8}$Hz.
The readings for the chance coincidence experiment are:

Sr. no.	Counting time (s)	P1	P3	Chance coincidence	Average	Average chance coincidence rate (Hz.)
1	10000	81008	670761	12	8.5	0.00085
2	10000	80566	547640	5		

Table 1.3: Chance coincidence rate.

The actual chance coincidence rate is found to be much larger than our estimate of 1.537 x 10^{-8} Hz. This should be due to some other source of noise.

Using the above data, we can compute the actual cosmic ray muon rate. Thus, the actual cosmic ray muon rate is 0.0429-0.00085=0.04205 Hz. In the 4-fold trigger experiment, the only muons that could pass through all 4 paddles were those which passed through the 1^{st} paddle (the paddle with the smallest face area. Thus, 0.04205 muons on an average pass through the area of paddle 1 (60 cm^2 = 6×10^{-3} m^2) per second. Hence, the average muon flux is approximately 7.00833 $s^{-1}.m^{-2}$, or $(7.00833/2\pi)$ $s^{-1}.m^{-2}.sr^{-1}$ = 1.11541 $s^{-1}.m^{-2}.sr^{-1}$.

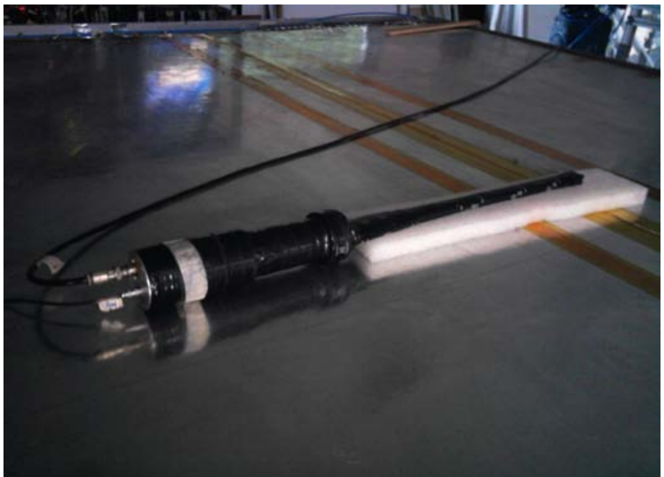


Fig. 1.5: A scintillator paddle on top of an RPC.

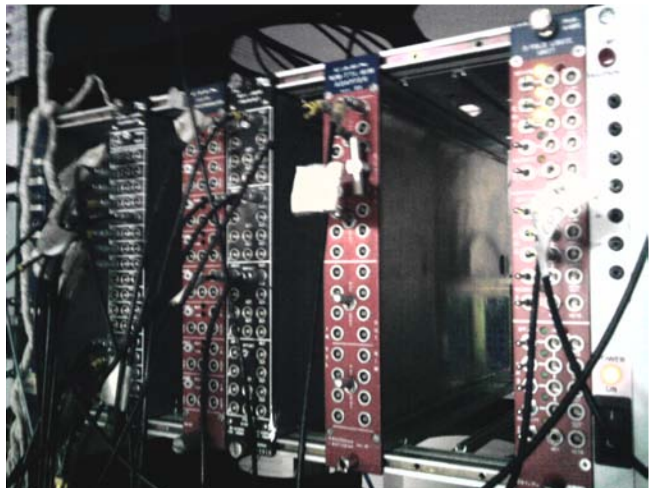


Fig. 1.6: A NIM bin.

Fig. 1.7: A scintillator paddle.

2. Resistive Plate Chambers.

Resistive Plate Chambers (RPCs) are used to collect information related to the path of cosmic-ray particles. By virtue of their copper pickup plate channels, they can track particles.

2.1: Construction:

An RPC consists of 10 layers. They are:

1) Gas chamber,
2) Top mylar sheet,
3) Bottom mylar sheet,
4) Graphite paint,
5) Button spacers,
6) Top copper pick-up strips (64 strips placed horizontally),
7) Bottom copper pick-up strips (64 strips, placed horizontally but perpendicular to the top pick-up strips.),
8) High-voltage point,
9) Grounding cable,
10) Gas pipe.

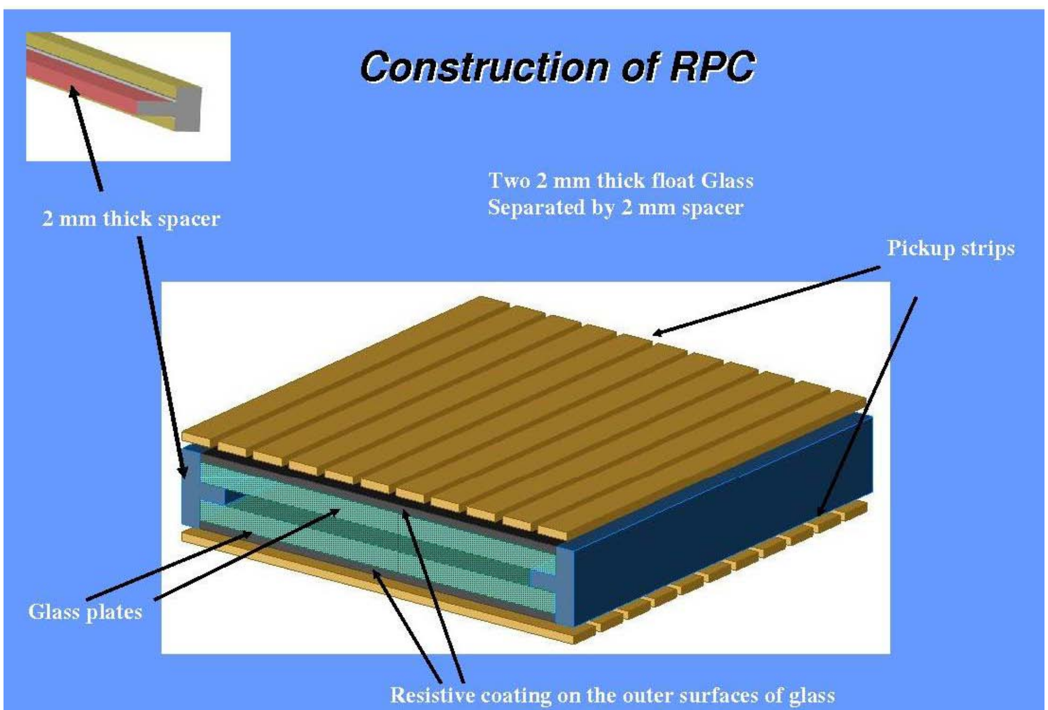


Fig. 2.1: Construction of an RPC.

2.2: Principle:

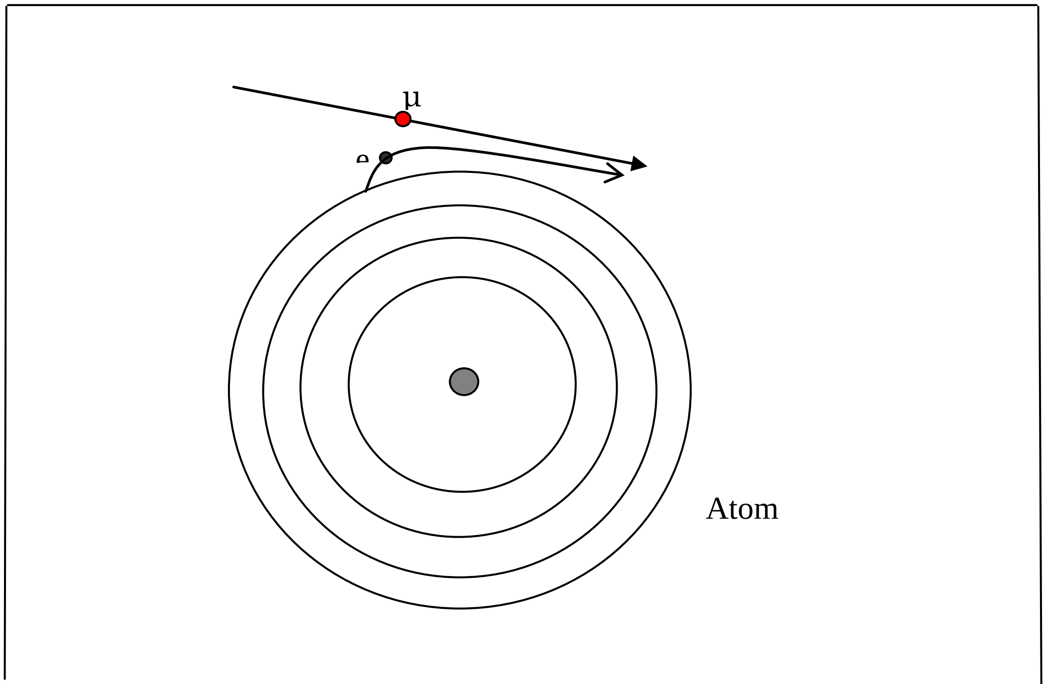


Fig. 2.1: Ionization of atoms by muons.

When a high-energy charged particle penetrates a gaseous medium, it produces ionization of the gas (Fig. 2.1).

If, further, the gas in question is placed in a strong electric field, the ionization is increased. This ionization can be recorded by a series of parallel strips of copper. The top pick-up plate of the 2m x 2m RPC consists of 64 parallel strips. The bottom pick-up plate consists of 64 similar strips, but placed perpendicular to the top layer. This serves as a coordinate system. Thus, we can determine the point at which the muon has struck the RPC. By keeping several such RPCs in a vertical stack, we can track the motion of cosmic ray particles.

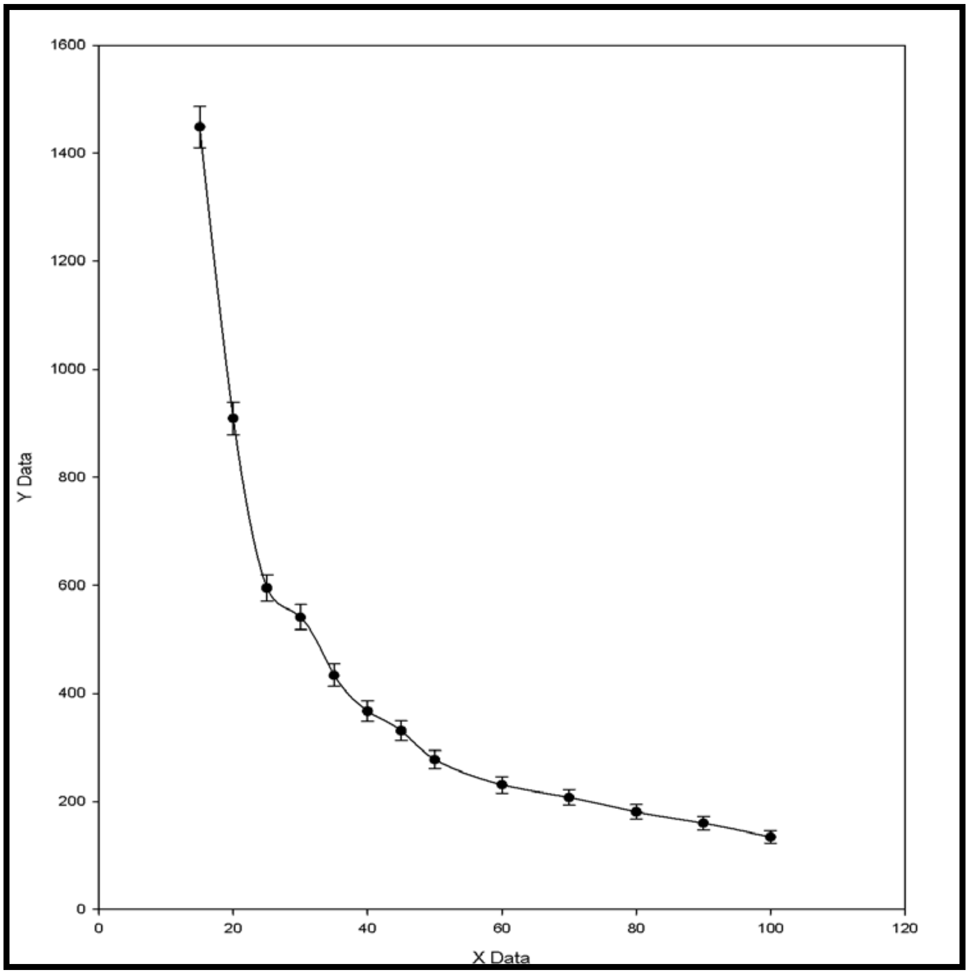
2.3: The threshold plotting experiment:

The RPC signals are similar to the signals produced by the scintillator paddles. They have to be converted to a digital form. For this purpose, NIM convertors are used. We have to set a threshold value of the voltage in order to filter the real pulses from the electronic noise. By varying the threshold, we can study the relation between threshold and noise rate. The following readings were obtained:

Threshold (V)	Run	Time (sec.)	Count	Average frequency (Hz.)
-15	1	10	1424	**144.87**
	2	10	1457	
	3	10	1465	
-20	1	10	935	**90.9**
	2	10	871	
	3	10	921	
-25	1	10	557	**59.533**
	2	10	620	
	3	10	609	
-30	1	10	576	**54.1**
	2	10	549	
	3	10	498	
-35	1	10	437	**43.367**
	2	10	444	
	3	10	420	
-40	1	10	379	**36.733**
	2	10	376	
	3	10	347	
-45	1	10	339	**33.1**
	2	10	341	
	3	10	313	
-50	1	10	279	**27.767**
	2	10	274	
	3	10	280	
60	1	10	229	**23.1**
	2	10	232	
	3	10	232	
-70	1	10	179	**20.767**
	2	10	211	
	3	10	233	
-80	1	10	175	**18.067**
	2	10	176	
	3	10	191	
-90	1	10	165	**16**
	2	10	149	
	3	10	166	
-100	1	10	140	**13.433**
	2	10	133	
	3	10	130	

Table 2.1: Variation of signal rate with threshold.

We can hence plot a graph of the signal rate versus the threshold value. It is comprised of noise and the muon signals.



For low T, more noise will be recorded as a signal, as is evident from Fig. 1.3. For very high T, most of the actual pulses will not be recorded as signals at all. Thus, it is necessary to identify the plateau region, in which most of the pulses are recorded as signals and negligible noise is recorded.

The purpose of conducting this experiment is to identify the "plateau region" (region of the graph at which the curve becomes almost flat, and then drops again to zero). Typically, this region lies in the threshold range of around -20 to -30 mV. for different paddles/RPCs. For the data points obtained, the threshold point is at around -25 mV.

We can try to find a curve that best fits the above given data. For example, we might assume that the noise rate decays exponentially with increasing threshold value. A trial function would be:

$$N=S+Be^{-T/T_0}$$

Where, N=number of counts,

S=background rate (due to cosmic ray muons),

T_0=standard threshold.

To determine these unknowns S, B, T_0, we can use the method of minimizing χ^2 [1]. The parameter χ^2 is defined as $\Sigma\,(d_i^2/\sigma_i^2)$, where, d_i is the difference between the value calculated on the basis of the formula and the value obtained experimentally, and σ_i is the error on the i^{th} measurement (which is equal to $\sqrt{N}$ for large N). χ^2 will be a function of S, B, and T_0. By putting the partial derivatives $\partial \chi^2/\partial S$, etc. equal to zero, we can solve for S, B, and T_0.

The above calculation was done with the standard plateau region (-20 mV, -25 mV, -30 mV, -35 mV). As a result this function is not a very good fit for larger values of threshold, but it can describe the behaviour of noise rate at smaller values of threshold. The values of S, B, T_0 obtained [2] are, respectively: 415.101, 15716.9, 5.75822.

3. Measurement of muon energy.

3.1: Theoretical background:

Cosmic-ray muons are found in a wide range of energies- from 100 MeV to 10 GeV. The total muon energy is given by the relativistic formula [3]:

$E = \gamma mc^2$.

Where, γ is the Lorentz factor and E is the total relativistic energy.

$\gamma = (1-v^2/c^2)^{1/2}$

A 1 GeV muon has a velocity of 99.436% of the speed of light. The typical distance between two scintillator paddles or RPCs is of the order of 30 cm, which means that such muons will take around 1.00567 ns. to cover that distance, which light would take 1 ns. to cover. The time delay is hence of the order of 6 ps, which is difficult to measure experimentally except by very precise apparatus. As a result, this is not a very practical method.

Another possible method could be to pass muons through a chamber filled with a uniform magnetic field and to measure their deflection, and then to calculate their momenta, energies and velocities. The radius of curvature of the muon is given by the formula [3]:

$r = \gamma mv/qB$

We can estimate the magnetic field required to produce a radius of curvature of around 1 m. It is of the order of 3.5 T for 1 GeV muons, which is a large field.

3.2: Measurement of muon energy:

The method commonly used in practice is as follows: a stack of 10-12 RPCs is kept with identical spacing between the individual RPCs. The function of these RPCs is to detect the muons. Lead blocks of the same thickness are kept on top of each RPC. The principle used here is that muons lose their energy while passing through a dense medium like lead. Consider a thick block of lead, with a muon passing through it in the positive X-direction. The rate at which it loses energy is expressed in terms of the parameter dE/dx. Bethe and Bloch have showed [1] that dE/dx is approximately constant over the energy range of muons. Hence, if a certain lead block is capable of reducing the muon energy by 100 MeV, and a certain muon passes through 5 of such blocks (but not through the 6th), then it is clear that its energy must lie between 500 and 600 MeV.

A stack of 10 RPCs and lead blocks that reduce the energy by 100 MeV can determine the energies of muons between 100 MeV to 1 GeV, to an error of less than 100 MeV.

The above mentioned procedure is the principle behind the procedure that will be employed at the India-based Neutrino Observatory (INO) to measure the energies of typical cosmic-ray muons. However, it was not a part of this project.

Acknowledgements.

I sincerely thank KVPY for giving me a unique opportunity to present this project. I have no words to express my gratitude towards Prof. A. Dighe and Prof. B. Satyanarayana for their constant support and encouragement. I would also like to thank all staff members of TIFR for all their help.

References.

[1] `Techniques for Nuclear and Particle Physics Experiments' –W. R. Leo, Springer-Verlag.
[2] www.integrals.wolfram.com
[3] `An Introduction to Special Relativity'-R. Resnick, Wiley.