2.1 Introduction

Neutron and meson monitors are being very extensively used for continuous monitoring of cosmic ray intensity. Comparison of time variation observations from the low latitude meson monitors having a high energy response with the high latitude neutron monitor observations, provides valuable data, covering a large energy range. Even though both Geiger-Muller counters as well as scintillation detectors have been used for monitoring mu-meson intensity, the fast response of the plastic scintillator \((10^{-9} \text{ sec.})\), ease in machining and fabrication and the practically unlimited life-time have favoured the choice of scintillators for time variation studies. With such scintillators, it is possible to measure cosmic ray intensities collected from a large area of the order of several square meters, thus providing a good statistical accuracy.

The operation of a scintillation counter is based on the conversion of the energy of a single particle into light quanta. The incident particle impinging on the scintillator dissipates part of its energy in the ionization and excitation of molecules, a fraction of which is converted into photons. These photons are detected by the photocathode of the photomultiplier, the output pulse of which is amplified, discriminated
and finally recorded automatically. In the succeeding sections, a brief description is given about the experimental set up of scintillation detectors as well as the electronic assembly used for the continuous registration of mu-meson intensity.

2.2 Scintillation Detector set up

2.2.1 Working Principle

The technique of scintillation counting for the detection of ionizing radiation is extensively described in literature by Birks, (1953); Curran, (1953); Mott and Sutton, (1958); and Akimov, (1965). The sequence of events in this technique is briefly summarised here.

An incident particle having an energy $E_i$, in passing through a scintillator dissipates a part (fraction) $F E_i$ of its energy in ionization and excitation of molecules of the scintillators, which is converted into photons. The number of photons ($I_0$) radiated, which depends on the conversion efficiency ($C_i$) of the scintillator may be written as

$$I_0 = \frac{F E_i \times C_i}{E_p}$$

where $E_p$ is the energy required to produce a single photon in the scintillator. The number of units of these photons decay as $I = I_0 e^{-t/t_0}$ where $t_0$ is the decay time, which is of the order of $10^{-9}$ sec for fast (organic) scintillators. Out of
these photons only a fraction of the photons are generally detected by the photomultiplier.

The number of emitted photons that reach the photocathode is governed by the following two factors (i) the optical transparency \( T \) of the scintillators to its own radiation and (ii) the light collection efficiency \( C_d \) of the detector set-up. In other words the number of photons \( I' \) reaching the photocathode is given by

\[
I' = I \times T \times C_d \quad \text{........ 2.02}
\]

In the case of organic scintillators, the system efficiency is vastly improved by appropriately shifting the spectrum of emitted photons to match the photocathode response of the multiplier tube by adding suitable substances known as wave length convertors and wave-length shifters. In order to improve the collection efficiency \( C_d \) of the detector box, where multiple reflections are likely to occur a reflector with a high reflectance and low absorption coefficient, in the wave length region of interest, is generally used.

The number of photoelectrons \( n \) produced, when \( I' \) photons impinge on the photocathode is given by

\[
n = I' \times C_{pe}(\lambda_p) \quad \text{........ 2.03}
\]

where \( C_{pe}(\lambda_p) \) is the photoelectric conversion efficiency of the photocathode at its optimum frequency. The photoelectrons
released from the photocathode get multiplied at the subsequent dynode stages of the photomultiplier by secondary emission. The output of the photomultiplier is further amplified prior to discrimination and final recording. The signal to noise ratio is generally unaffected by the multiplication process in the photomultiplier since both are similarly amplified. Thus it is important that the signal \( n \) should be large. Hence the factors, \( F, C_p, T, C_d \) and \( C_{\text{phot}} \) affecting the value of \( n \) must be optimised.

2.2.2 Design considerations

The response of the scintillation detector to a particle depends on the efficiency of the scintillators, the attenuation length of the emitted light and the design of the detector box, which includes the geometry of the counter, reflectivity of the counter walls and the fraction of the wall area covered by the photomultiplier.

Since large area counters are needed for giving better statistical accuracy, fast response scintillators (i.e. organic scintillators) are preferable for monitoring purposes.

Eventhough both liquid and solid scintillators can be used as large area detectors, liquid scintillators (such as toluene, terphenyl) are unsuitable because of several reasons. The liquid is usually volatile, inflammable and toxic. It is difficult to avoid the leakage and spillages. The liquid being
For the registration of relativistic cosmic ray particles, the detector system ideally should have the following characteristics:

(i) **Stability**

Cosmic ray time variation experiments which require continuous monitoring over long periods of time demand that the efficiency of the detector should remain stable over a long period. In other words, it is important to ensure that the reflecting properties of the reflector or the transmitting properties of the scintillators do not appreciably deteriorate with time.

(ii) **Uniformity of response**

The response of the detector over the whole of the effective counting area should be fairly uniform. However when one is concerned with counting the particles only, the condition of uniformity is not so strict as in experiments where one desires to measure the energy of the particles also.

In addition to the normal statistical fluctuations in the scintillation processes and in the photomultiplier, the following factors also contribute to the broadening of the pulse height distributions and thereby influence the performance of the large area detector.

(a) **Non-uniform luminescence efficiency of the scintillators**, due to defects in the manufacturing processes of the slabs (for example, presence of bubbles, white patches or any other optical
flaws in the scintillators). The variations in the efficiency of different slabs, when a number of slabs are used in one detector.

(b) Variations in the light collection efficiency of the detector, which can be minimized by suitable choice of the reflector and the optical geometry of the detector.

(iii) Counting efficiency

All the particles incident on the effective counting surface of the detector within the allowed solid angle of the telescope must be counted. The counting efficiency depends on the (i) number of photoelectrons emitted by the photocathode and (ii) the resolution time of the counting circuits.

2.2.3 Scintillation Telescope set-up at the Physical Research Laboratory

From the known properties of the average diurnal and the semi-diurnal anisotropy of cosmic radiation, it has been recognised that for carrying out further significant investigations on time variation of cosmic radiation, on a day to day basis, a large counting rate of the order of about 1 million/hour is necessary. Therefore, large area scintillation telescopes, consisting of eight plastic scintillation detectors each having an area of 4 sq. meters, have been installed at the Physical Research Laboratory, Ahmedabad. Absorber of about 200 gms/cm² surrounds the detector set-up which serves to cut-off
Fig. 2.01 Geometrical set-up of four scintillation detectors forming two vertical and two inclined telescopes.

Fig. 2.02 Geometry of the multi-directional meson telescopes at Ahmedabad with eight scintillation detectors.
a light-proof wooden box having a pyramidal shape (Figure 2.01). One side of the box can be opened for service purposes. All the inner sides of the box and the bottom surface of the scintillators are coated with a high reflectance white paint (Titanium dioxide). Scintillators are of a trapezoidal form and placed in close optical contact with each other. Thickness of these scintillators at each of their corner is shown in Figure (2.03). The entire tray of sixteen scintillators is shaped such that the thickness is greatest at the corners and decreases smoothly towards the centre. The increased thickness at the corner compensates for the light losses due to the path length variation in the detector box. The entire tray of scintillators is viewed by a single 14" Du'Mont (K-1328) photomultiplier tube mounted at the top of the pyramidal box.

Great care need to be exercised in the choice of the paint which has to satisfy the conditions of very high reflectance in particular wave-length region and the ability to maintain its optical properties over a long period of time. Small scale experiments were conducted with a number of reflectance paints and were compared with the performance of the aluminium foil. It was found that the water based TiO₂ paint which has a reflectivity of ≈ 0.8 in the transmission band of 4000-7000° A, was the most suitable diffuse reflector for the geometry of our present set-up. Figure (2.04) shows the comparison of TiO₂ with aluminium foil for a typical set-up. The light output obtained
Fig. 2.03 Arrangement of 16 scintillator slabs in one detector. Number in the circle indicates the thickness of the scintillator slab at that corner.

Fig. 2.04 Counting rate as a function of discriminator level for prototype scintillation detector with (a) TiO₂ and (b) crumpled aluminium foil as a reflector.
by using TiO$_2$ as a reflector is at least $\approx 15\%$ more than that obtained using aluminium foil. A reasonably uniform response can be obtained by placing the photomultiplier at a great distance from the scintillators, so that the optical path length from photocathode to different parts of the scintillator tray becomes approximately same. However this will sharply reduce the photon intensity. Hence a choice is being made of a reasonable optimum distance. In the present set-up, the increased thickness of the corners of the scintillation detector provides some compensation for the increased path length. The vertical separation between the photocathode and the scintillator which is 95 cms in our set-up has been worked out for optical performance taking into consideration, the conflicting requirements mentioned above.

The scintillator slabs were manufactured by the Technical Physics Division of the Atomic Energy Establishment, Trombay, according to our specifications and using the raw materials (a) Styrene Monomer PL 50 TBC (b) P-terphenyl (NE-504) and (c) POPOP (NE-502) of scintillators grade. The composition of these material by weight was $\approx 99\%$, $1\%$ and $0.05\%$ respectively.

The scintillators were subjected to infra-red radiation treatment for removing the white patches and other minor manufacturing defects. They were further machined and polished with a fine grade 2/0 and 4/0 waterproof emery papers and aluminium oxide and buffed with a buffing wheel to obtain optically high quality scintillators for the present usage.
A 12 stage Du'Mont K-1328 photomultiplier tube having a photocathode of 1\(^{\prime}\) diameter and an S-11 spectral response is used in the present set-up. The phototube has a rated average gain of \(8 \times 10^5\). This photomultiplier tube has a metal support cone for the cathode surface, which also provides some magnetic shielding and a focussing electrode whose potential can be varied to give optimum overall electron collection efficiency.

2.3 **Electronic Circuits**

The block diagram of the entire electronic circuitry associated with one typical channel of meson telescope is shown in Figure (2.05). The circuits are fully transistorized except for the high voltage units. In order to avoid the losses along the coaxial cable, the preamplifier is mounted near the base of the photomultiplier tube. The recording system including the high voltage units, is fed from the mains through a radio frequency suppressor and a constant voltage-transformer to provide better stability.

Two stabilized high voltage units, supply the voltages to the eight photomultipliers. The high voltage unit has a continuously variable output from 500 to 2000 volts. Stability of the power supply is 1 part in 1000 and has a current capacity of 1 mA. The high voltage supplies are well tested to ensure that spurious pulses due to discharge or leakage across the capacitors are absent.
Fig. 2.05  Block diagram of the electronic circuits for one channel of meson telescope.

HV - High Voltage Supply  A - Main Amplifier
DB - Distribution Box  D - Discriminator
SCN - Scintillators  C - Coincidence
PM - Photomultiplier  BC - Binary Counter
PRE - Preamplifier  R - Recorder
To provide independent adjustment of voltages on individual photomultipliers, a distribution box containing four, five-step switches is connected with each high voltage supply. High voltage connection to each photomultiplier is decoupled to ensure from any radio-frequency and microphonic pick-up. The high voltage connection to the photomultiplier base is shown in Figure (2.06).

Positive voltage is applied at the anode of the tube. The output of the photomultiplier is a negative pulse of \( \sim 3 \) to 10 millivolts height.

### 2.3.1 Preamplifier

The preamplifier circuit is shown in Figure (2.07). To match the high output impedance of the photomultiplier the effective input impedance and high frequency response of the input circuit of preamplifier is increased by cascading three emitter followers with feedback from the third emitter to the input base resistor. The effective input impedance being nearly two megaohms, the time constant of the exponential decay of the photomultiplier pulse is not affected by the transistor characteristics. The rest of the preamplifier consists of a feedback, commonbase voltage amplifier (gain \( \pm 10 \)), with an emitter follower output to drive the coaxial cable (of 120Ω impedance), which carries the signal to the main amplifier.
2.3.2 Main amplifier

The main amplifier shown in Figure (2.08) consists of three feedback loops. The total gain of the preamplifier and amplifier combination is about 3000 which is adjustable from 300 to 3000. The amplifier has a rise time of 0.2 µ sec. and provides an output of ≤ 11 volts. The signals after amplification are fed to the discriminator circuit which is shown in Figure (2.09).

2.3.3 Discriminator circuit

The level discriminator used in the present set-up is adjusted to eliminate the background noise from the photomultiplier. The discriminator circuit is followed by a pulse shaper, which provides a constant square wave output. Negative output from the pulse-shaper is used for monitoring the tray rate for test purposes. The sharp positive output from the pulse-shaper after differentiation, is fed to the coincidence circuit. Discriminator level, is adjusted using a ten turn linear potentiometer.

2.3.4 Coincidence circuit

Figure (2.10) shows the schematic of the coincidence circuit. The resolving time of the circuit is adjusted at 0.4 µ sec. The output pulses from the coincidence circuit, which are of the order of 6 volts and of 1 µ sec. duration, are fed to the scalers for counting.
Fig. 2.08 Main Amplifier (Linear)

Fig. 2.09 Discriminator circuit.
2.3.5 Scaler and Recording System

The basic binary scaler shown in Figure (2.11), is of Eccles-Jordan type bistable multivibrator. Scaling factors of 128 and 512 are used for inclined and vertical telescopes respectively. Output of the scaler is recorded by a telephone type mechanical recorder (Figure 2.12). A panel consisting of all recorders which are attached to different vertical and inclined telescopes, along with information giving the year, date and the time is automatically photographed every twelve minutes, through a motor clock control circuit (Figure 2.13). The description of the operating characteristics and testing procedure is discussed in the next section.

2.4 Operating Characteristics and Test Procedure

2.4.1 Choice of operating conditions

The three governing factors which control the complete operation of the scintillation detector set-up are the choice of the high voltage to the photomultiplier tube, the adjustment of the amplifier gain and fixation of the discriminator level. Appropriate choice of these parameters is necessary to obtain the optimum operating conditions of the detector and maximum stability of the counting rate against instrumental drift.

It is customary to initially adjust the photomultiplier high voltage to a reasonable value and then fix the amplifier gain to bring the response of the detector within the operating region.
Fig. 2.10 Coincidence circuit

Fig. 2.11 Scaler circuit
Fig. 2.12 Recorder circuit

Fig. 2.13 Camera control circuit
of the discriminator. Once the amplifier gain is fixed, the performance of the scintillation detector depends primarily upon the photomultiplier voltage and the discriminator level. An optimum combination of these parameters is obtained by determining the characteristic dependence of the counting rate as a function of the photomultiplier voltage and the discriminator level.

2.4.1.1 High Voltage

Figure (2.14) shows the dependence of the count rate of the detector on the high voltage of the photomultiplier for two different discriminator levels. Curve (a) and (b) shown in the figure represents the count rate variation of any single detector with the applied photomultiplier voltage for two discriminator levels 3 and 4 volts respectively. Curve (c) shows the counting rate characteristics of a typical vertical telescope (i.e. two detector units in coincidence), the discriminator level being adjusted at 3.5 volts. All the curves display a minimal plateau of about 50 to 75 volts with a slope of about \( \approx 0.16\%/\text{volt} \), for a single detector and of about \( \approx 0.07\%/\text{volt} \) or less for the coincidence arrangement. The high voltage for the photomultiplier tubes are carefully adjusted taking into consideration the slope and the extent of the plateau region to provide the maximum possible long term stability.

2.4.1.2 Discriminator setting

After fixing the appropriate high voltage for the photomultipliers, the appropriate discriminator level settings can be
Fig. 2.14  (A) The counting rate of a single scintillation detector as a function of the photomultiplier voltage for two discriminator levels.

(B) The coincidence counting rate of a vertical telescope as a function of the photomultiplier voltage.
determined by knowing the counting rate of the individual detectors and the telescope arrangement as a function of the discriminator threshold levels. The integral counting rates of two individual detectors (upper and lower detector, forming vertical telescope) and of the vertical telescope are shown in the Figure (2.15). In this figure, curves 1 and 2 represent the integral counting rate of one upper and lower detector respectively. Curve 3 shows the integral counting rate of a vertical telescope formed by the above two detectors. These curves which represent the integral pulse height distribution of the scintillator, are also contaminated with the background noise, besides the genuine counting rate due to cosmic ray muons. Since, ideally such background can be almost completely eliminated by coincidence arrangement, one should expect to obtain a flat plateau region at the maximum meson counting rate. However, due to the broadening of the meson pulse-height distribution in a large area detector, a completely flat plateau is seldom realised in practice.

The slope of the plateau at the operating level provides a direct measurement of the stability of the instrument against drift in gain. For individual detectors, even near the plateau, the count rate change is observed to be 8 to 10% for one volt change in the discriminator threshold. The corresponding change in count rate for the coincidence (telescope) arrangement is observed to be only 4 to 6%. Because
of the increase in the chance coincidence, curve (3) shows a rising trend at the lower discriminator level.

In the coincidence arrangement an accurate adjustment of two discriminator levels (say $D_1$ and $D_2$, for two detectors) have been achieved by using the following procedure. Coincidence rate (integral rate) of the telescope was measured as a function of the discriminator threshold voltage $D_2$, for different fixed values of $D_1$. Results obtained for one typical telescope in the present set-up are shown in the Figure (2.16). From such a curve it is possible to identify the region in which the change in the coincidence rate is very low for change in the discriminator level $D_1$ and $D_2$. From figure (2.16) the optimum threshold level for the discriminators is observed to be between $3 \ & 4$ volts.

In the actual set-up, the focussing electrode of each of the photomultiplier is operated at the appropriate voltage, to achieve maximum collection efficiency. Typical curve showing the counting rate efficiency as a function of the focussing electrode voltage is shown in Figure (2.17).

2.4.2 Uniformity of response of the detector

To test the uniformity of response of the detector, the following experiment was carried out. A proto-type unit with one scintillator of 50 cms. x 50 cms. size was built. The positions of all the sixteen scintillators inside the large area detector box were numbered (marked) according to the thickness of the
Fig. 2.15 The counting rate of the individual scintillation detectors (1) & (2) and the coincidence counting rate of a vertical telescope (3) as functions of discriminator level.

Fig. 2.16 Coincidence counting rate of a typical vertical telescope versus the discriminator level of the upper detector ($D_1$), for different fixed discriminator levels of the lower detector ($D_2$).
scintillator (as shown in figure 2.03). All the scintillators were removed from the detector box. Then one scintillator was placed at its proper place inside the detector box. The prototype unit was kept directly below this scintillator and integral coincidence rates were taken between the detector and the prototype unit for different discriminator levels. The first scintillator was removed and a second scintillator was placed at its appropriate place. Prototype unit was brought directly below the second scintillator and again coincidence rate was taken between the detector and the prototype unit. This method was repeated for all the sixteen scintillators. Since the position of different scintillators being different with respect to the position of the photomultiplier in the detector-box, the count rates obtained from the above experiment for all the scintillators will provide an estimate of the uniformity of response of the detector.

Three positions 'a', 'b' and 'c' are shown in Figure (2.18) where 'a' corresponds to the four innermost scintillators while 'c' corresponds to the four outermost scintillators. The integral counting rate obtained for these three positions 'a', 'b' and 'c' are shown in Figure (2.19). It is found that the change in the count rate efficiency between the centre and the corner scintillators, i.e. 'a' & 'c', is less than 8 to 10%.

2.4.3 Routine Check-up

The regulated output from the high voltage supplies, the
Fig. 2.17 Counting rate of a scintillation detector as a function of the focussing electrode voltage of the photomultiplier tube.

Fig. 2.18 Bottom-view of the scintillation detector showing the three different positions 'a', 'b' and 'c' of the scintillator slabs.
photomultiplier voltages, the low voltage supplies and the focussing electrode voltages are checked every day. The performance characteristics of the telescopes are tested by well known statistical methods. The overall stability of the detection system is tested at frequent intervals, by determining the counting rate plateau.

Fig. 2.19 Integral coincidence counting rate between the proto-type unit and the detector with a single scintillator slab placed at three different positions 'a', 'b' and 'c'.

Fig. 2.19 Integral coincidence counting rate between the proto-type unit and the detector with a single scintillator slab placed at three different positions 'a', 'b' and 'c'.