CHAPTER I

INTRODUCTION

1.1 Extensive Air Showers: (Historical)

Extensive Air Showers, characterised by the simultaneous incidence of a large number of coherent particles from the atmosphere, over large areas, were discovered independently by Auger et al. (1938) and Kolhorster et al. (1938) by observing coincidence between the coherent particles with separations varying from 40 cm to few tens of meters. Auger et al. (1939a) obtained coincidences between particles separated by distances of the order of 300 m while Skobelt'syn et al. (1947) presented evidence of the existence of coherent particles separated by distances 1 Km. These and other similar experiments demonstrated the extensive nature of the phenomenon which was appropriately named Extensive Air showers abbreviated EAS.

A predominantly electronic nature of the particles in the EAS was inferred by Auger et al. (1939b) from the study of the secondary effects of these particles. Plate cloud Chamber photographs of the EAS particles (Janossy and Lovell 1938; Auger et al. 1939c) also showed concentration of the tracks, implying production of secondary showers by electrons and photons forming part of the EAS.
Indications of the presence of a penetrating component of the EAS, capable of traversing 20 cm of lead, were already available in the experiments of Auger et al. (1938, 1939b) and the presence of this component was confirmed by Daudin (1945), Rogofsky (1944), Cocconi et al. (1946) and Broadbent and Janossy (1947a, 1947b, 1948). A number of slow proton tracks were seen in cloud chamber photographs of the EAS particles, by Auger et al. (1939b). V.C. Tongiorgi (1948a, 1948b, 1949) in a series of experiments, using BF3 counters, gave evidence of the presence of neutrons in EAS. The presence of a nuclear active component (N-Component) was thus established. Thus, within a short period of the discovery EAS were known to consist of i) an electron-photon component and ii) a penetrating component a part of which contained nuclear active particles.

Extensive Air showers are initiated by the primary cosmic ray particles of energy \( \geq 10^{12} \) eV incident on the earth's atmosphere. The primary particles, which initiate EAS, could either be i) electronic in nature, i.e. consist of electrons and/or photons or ii) nucleons and to a certain extent heavy nuclei.

Because of the predominance of the electron-photon components, the EAS were initially believed to be produced by electrons or photons forming part of primary cosmic rays.
Hulsizer and Rossi (1948), however, gave an upper limit of 1% for the fraction of the electrons of energy \( \geq 4.5 \times 10^9 \) eV in the primary cosmic rays. The possibility of electrons initiating EAS was also ruled out on the ground that bremsstrahlung radiation from the electrons in the galactic magnetic field will not allow the electrons to have energies \( \geq 10^{12} \) eV. A search for 'the photon initiated EAS' was undertaken, in Bolivian Air Shower Joint Experiment (BASJE), based on the idea that such showers will contain extremely small numbers of penetrating particles. Though the results from this experiment (K. Súga et al. 1963; V. Toyoda et al. 1965) as well as the experiment of Polish group (R. FirKowski et al. 1962a, 1962b, 1963; J. Gawin et al. 1968) confirmed the existence of a separate group of such showers, the flux of the primary photons obtained on the basis of the rate of such showers was found to be too small to account for the observed EAS flux, the estimated flux being \( \sim 2.0 \times 10^{-11} \) cm\(^{-2}\) Sec\(^{-1}\) for primary \( \gamma \)-rays of energy \( \geq 3 \times 10^{13} \) eV (Kamata et al. 1968) and \((6 \pm \frac{4}{3}) \times 10^{-9} \) m\(^{-2}\) Sec\(^{-1}\) Sr\(^{-1}\) for the primary gamma-ray energy \( \geq 8 \times 10^{14} \) eV (Gawin et al. 1968). The primary cosmic ray electrons and photons could, then, not be considered as responsible for the production of the majority of the EAS and the only other possibility is
the production through the interactions of primary nucleons and heavy nuclei in the atmosphere. Cloud chamber photographs by various workers (Daudin 1944; Rochester 1946; Bridge et al. 1948) demonstrated that the electrons and photons could be generated through nuclear interactions. The results on the distribution of the ionizing particles in the EAS were also in agreement with the distributions for the showers developed through a process of nuclear cascade (Section I.3; Greisen 1960). It is now, therefore, widely accepted that the majority of Extensive Air showers originate in the nuclear interactions of the primary cosmic ray nuclei, high in the atmosphere.

I.2 Development of EAS in the Atmosphere:

The majority of primary cosmic ray particles, which initiate EAS, are protons with a small fraction of \alpha-\text{particles} and heavy nuclei. The primaries undergo nuclear interactions with air nuclei. The interactions, being inelastic, a fraction \eta of the primary energy is given to the interaction which results in the production of new particles, e.g. pions, Kaons, nucleon - antinucleon pairs, hyperons etc. Pions are the most abundant among the created particles and the neutral pions, having a very short life time (\sim 2 \times 10^{-16} \text{sec}) decay almost instantly into two \gamma-rays.
The primary particle survives either as a proton or a neutron or in some excited non-strange isobar state with an energy \((1 - \gamma)\) of the total energy. The surviving particle together with other nuclear-active particles, produced in the proceeding interactions, undergoes further interactions in the atmosphere giving rise to more particles. A nuclear cascade is, thus, generated.

For unstable charged particles, e.g. pions and kaons there is a competition between the nuclear interaction and the decay. A fraction of these particles then decays into muons. Muons have very high penetrating power, since their interactions with matter are weak. Most of the accurate muon-nucleon scattering experiments give limits to the cross-section which are at least three orders of magnitude smaller than the geometric cross-section. Moreover, the decay probabilities for the high energy muons, during their traversal through the atmosphere, are practically negligible because of a rather large life time \((\sim 2 \times 10^{-6} \text{ Sec})\) and the relativistic time dilation. The mu-mesons thus form a highly penetrating component of EAS.

The \(\gamma\)'-rays of sufficient energy, produced by the decaying neutral pions, initiate electron-photon cascade. The number of particles in these cascades keeps on multiplying till i) the electron energies are
oreduced below $\varepsilon_c$, the critical energy of electrons, ii) the photon energies are in the region where Compton-scattering and photo-ionization processes predominate over the pair-production process and iii) the energy source, i.e. the nuclear cascade, becomes depleted.

The particles, at the time of their production, acquire transverse momenta and are also subjected to deflections due to Coulomb-scattering and magnetic field of the earth. Hence, they are distributed in lateral plane and are spread over large areas around the axis or core of the EAS. The core preserves the direction of the initiating primary and exhibits a high density of the particles.

The particles in the EAS can then be classified into following categories:

a) a soft component consisting of electrons and photons which form a majority of the particles and

b) a penetrating component comprised of i) the N-component containing particles capable of undergoing nuclear interactions and ii) the muons and neutrinos.

1.3 Electron Component of EAS:

A large amount of experimental as well as theoretical effort, in the studies of EAS, has been
directed to the study of electron—photon component and is confined, to a great extent, to the understanding of the distribution of the electrons around the axis of the EAS and the measurements of the frequency of EAS as a function of total number of ionizing particles.

The experimental results on the lateral distribution of the ionizing particles (consisting, mainly, of electrons) in the EAS indicate a near invariance of the distribution with respect to the size of the shower as well as the altitude of their observation. The main source of the lateral spread of the electrons in EAS is the multiple Coulomb—scattering and the lateral spread is generally expressed in terms of Moliere unit defined as

\[ r_1 = \frac{E_S X_0}{\xi_c} = \frac{73.5}{P} \cdot \frac{T}{273} \text{ m} \quad ...(1.3.1) \]

where \( E_S = 21 \text{ MeV} \) is the characteristic scattering energy of the electrons, \( \xi_c \) the critical energy and \( X_0 \) is the radiation length. \( P \) is the atmospheric pressure and \( T \) the temperature in °K. The density \( \rho (r) \) of a particle at distance \( r \) from the axis can be written as

\[ \rho (r) = \left( \frac{N}{r_1^2} \right) \cdot f \left( s, \frac{r}{r_1} \right) \quad ...(1.3.2) \]

The function \( f (s, r/r_1) \) is known as the lateral distribution function normalised such that

\[ \int_0^{\infty} f \left( s, \frac{r}{r_1} \right) \cdot 2 \pi r_1 d\left( \frac{r}{r_1} \right) = 1 \quad ...(1.3.3) \]
The parameter $s$ is called the age parameter of the shower and is related to the longitudinal development of the shower.

Theoretical calculations, based on the electromagnetic cascade theory, have been done by a number of authors. Moliere (1946) derived the lateral distribution functions for the showers at the maxima of their development. The calculations were limited by inaccuracies at low energy. Nishimura and Kamata (1950, 1951, 1952) have derived the distribution functions for showers at all stages of their development and following Greisen (1956) the Nishimura – Kamata (NK) distribution function can be written as

$$f(s, r/r_1) = c(s) \left(\frac{r}{r_1}\right)^{s-2} \left(1 + \frac{r}{r_1}\right)^{s-4.5}$$

.... (1.3.4)

$$c(s) = \frac{(4.5 - s)}{2} \int_1^s (s). \int_0^{(4.5 - 2s)}$$

This formula, known as NKG-formula, gives a good fit to the NK-distribution function for $0.6 \leq s \leq 1.8$ and $0.01 \leq r/r_1 \leq 10$. Derivation of NK-distribution function involves following definition of $s$

$$s = \frac{3t}{(t + 2\ln(E_0/E_c) + 2\ln(r/r_1)}$$

.... (1.3.5)
which implies a variation of $s$ with $r$. However, the $r$ dependence of $s$ is rather weak for $-1 \leq r/r_1 \leq 1$ and a single value of $s$ can be used in this region of $r$.

The most extensive measurements of the lateral distribution of the ionizing particles in EAS have been carried out by Russian workers (Dobrovolsky et al. 1956; Dovchenko and Nikolaev 1955; Khristiansen et al. 1956; Zatsepin et al. 1963). Measurements have also been done by M.I.T group (Clark et al. 1957) and a number of other groups. The experimentally obtained lateral distributions can be fitted to the NK-distribution with the age parameter $s \sim 1.2$ to 1.3 (Cocconi 1958; Khristiansen 1958; Greisen 1960).

It is thus seen that the lateral distribution of all ionizing particles in EAS resembles closely the one obtained on the basis of a pure electromagnetic cascade. However, it is also observed that the variation in the shape of the distribution with the altitude of the observation of the showers is extremely slow contrary to what one would expect on the basis of a pure electromagnetic cascade. Also the variation of $s$ with $r$ is not in confirmation with the predicted one.

Thus the electron - photon component in EAS is not a pure electromagnetic cascade but an admixture of a number of such cascades generated during the longi-
I.4 The penetrating component of EAS:

a) Percentage of penetrating particles:

Various investigations, (e.g., those of Broadbent et al. (1947), Chowdhuri (1948), Cocconi et al. (1949a), McCusker (1950) and McCusker and Millar (1951) at sea level and those of Treat and Greisen (1948), Sitte (1950, 1952) and Kasnitz and Sitte (1954) at mountain elevations) to study the penetrating component of EAS, involved the detection of EAS, by means of unshielded counters, and examining the penetrating particle detector in coincidence with the showers. Majority of experiments were aimed at obtaining the ratio \( R_p \) of the penetrating particles to the total number of ionizing particles. A value of \((2 \pm 0.2)\%\) was obtained for \( R_p \) by Chowdhuri (1948) and other experiments were in broad agreement with this value. However, results of McCusker and Millar (1951) gave an average value of \( \sim 6\% \) for \( R_p \). It was also shown that under certain conditions \( R_p \) approached 100%. Later experiments of Eidus et al. (1952) at sea level and of Zatsepin et al. (1953) at mountain...
elevations demonstrated a variation of \( \text{Rp} \) with distance \( r \) from the axis of the shower. At large distances \( \text{Rp} \) increases linearly with \( r \) the variation becoming less rapid at small distances with the \( \text{Rp} \) value levelling off to \( \sim 1\% \) near the axis, (Greisen 1956).

Size variation of \( \text{Rp} \) was demonstrated by Cocconi et al. (1949b) and Ise and Fretter (1952) at mountain elevations and by Milone (1952) at sea level and could be expressed as

\[
\text{Rp} \propto N_e^{-0.13} \quad \text{or} \quad N_p \propto N_e^{0.87},
\]

where \( N_p \) is the total number of penetrating particles in showers of size \( N_e \). It is thus seen that the number of penetrating particles in a shower increases less rapidly than the total number of particles.

b) Ratio of Interacting to non-interacting penetrating particles in EAS:

The penetrating particles of the EAS consist, mostly, of nucleons, \( \pi^- \) - mesons and muons. A part of the penetrating particles produce local showers, as was evident from experiments of Brown and Mckay (1949), Ise and Fretter (1949) and Chowdhuri (1950). The penetrating particles can then be divided into "the interacting" and "the non-interacting" components. The former consists of \( N \)-particles and later mostly of \( \mu^-\)-mesons.
The percentage of N-particles in the penetrating component of EAS was investigated in a number of early experiments. McCusker (1950) gave a 1:2 ratio for interacting to non-interacting particles. Greisen et al. (1950) found the intensity of N-component to be 60% that of non-interacting component near shower axis. Experimental results of Chowdhuri et al. (1952) gave a ratio of N-component to \( \mu \)-mesons as high as 88%, taking all low energy events into consideration, for showers of primary energy \( 10^{15} \) eV. The high energy N-component ( \( \geq 10 \) GeV) was found to be 29% as abundant as \( \mu \)-meson. Fujioka (1953) obtained the abundances of the N-component among penetrating particles at various core distances and found that the values varied from 0.64 at 5 m to 0.37 at 47 m.

Most of the above mentioned experiments, however, lacked in details, e.g. the energy of the detected particles, the size of the showers detected etc. and so a consistent picture could not be obtained from these experimental results.

I.5 N-Component of EAS:

The behaviour of nuclear active particles in EAS can be understood in terms of N-cascade of EAS. The studies of N-component of EAS, conducted by a number of workers, are mainly related to i) the lateral distribution
of the particles around EAS core, ii) the dependence of N-particle number $N_n$ on shower size $N_e$ and iii) the energy spectrum of the N-particles.

In energy range of 0.9 Gev - 3 Gev Danilova and Nikol'ski (1963) have obtained a lateral distribution which is well represented by

$$\rho_n (r) = \frac{A}{r_0} \exp \left( -\frac{r}{r_0} \right)$$

for $3 \times 10^4 \leq N_e \leq 10^7$ particles, with $r_0 = 70$ m for 2 Gev particles and 50 m for 3 Gev ones. Chatterjee et al. (1968a) give following form of lateral distribution of N-particles of energies between 50 Gev to 1600 Gev for showers of size $3,10^4 \leq N_e \leq 3 \times 10^6$ at 800 gm/cm$^2$.

$$\rho_n (N_e, r, E_n) = A \exp \left( -\frac{r}{r_0} \right)$$

$$A = 8.2 \left( \frac{N_e}{2.10^7} \right)^{0.097} E_n^{0.28}$$

$$r_0 = 13.3 \left( \frac{N_e}{2.10^7} \right)^{0.39-0.49E_n}^{0.28}$$

$0 \leq r \leq 15$ m

The integral energy spectrum obtained in various investigations agrees well with a power law having an index of -1.0. Chatterjee et al. (1968a) give an index
of -1.1 for the energy spectrum in the above mentioned energy range.

The ratio of the N-particles to the total number of particles in EAS decreases with increasing size. Danilova and Nikol'skii (1963) give following relation for particles of energy 0.2 Gev - 3 Gev at 3300 m elevation.

$$\frac{N_n}{N_e} = (1.2 \pm 0.4) \times 10^{-2} \left(\frac{N_e}{10^6}\right)^{-0.34 \pm 0.01}$$

for $3 \times 10^3 \leq N_e \leq 10^7$. A similar results is obtained by Chatterjee et al. (1963) for N- particles of energy $\geq 1$ Gev at 800 gm/cm$^2$ for sizes $10^5 \leq N_e \leq 10^7$

$$\frac{N_n}{N_e} = 2.1 \times 10^{-3} \left(\frac{N_e}{10^6}\right)^{-0.35 \pm 0.05}$$

At higher energies (50 Gev - 1600 Gev) Chatterjee et al. (1968a) give the following relation

$$N_n (\geq E_n, N_e) = 1.75 N_e^{0.78} E_n^{-1.1}$$

I.6 Muon Component of EAS:

The main emphasis in experiments to study EAS problems has slowly changed from the electron-photon component to muon component, as it has become clear that the latter component carries a large share of the
original energy. Various features of muons, associated with EAS, which have been studied are a) the lateral distribution of muons, b) their energy spectrum, c) variation of total number of muons with shower size, d) the fluctuation of muons at observation level and e) the phenomena of multiple penetrating particles and muon beams.

Various investigations on the muons associated with EAS may be classified into three different categories.

i) Experiments in which muons of energy greater than a given energy $E_\mu$ are selected through detectors shielded by appropriate amount of absorber and the detectors examined in coincidence with EAS. These experiments may be termed as "absorption experiments".

ii) Experiments using magnetic spectrographs with a muon detector in coincidence with EAS.

iii) The experiments studying the e-m bursts produced by muons associated with EAS.

Pioneering work in this field was done by Barret et al. (1952) who studied the muon intensities at a depth of ~1600 m.w.e underground, corresponding to $E_\mu = 560$ Gev, in association with air showers at the surface. The most extensive measurements in this regard
are those of Bennett and Greisen (1961) and Earnshaw et al. (1967, 1968). A number of experiments at energies $E_\mu \sim 40$ Gev, have been done by Russian group using absorption, underground for selecting muons. Following paragraphs summarise the present information available on muons in EAS:

a) The Lateral Distribution of Muons:

Fig.1.1 to Fig 1.4 show lateral distribution of muons of energy $\gtrsim 1$ Gev, $\gtrsim 10$ Gev, $\gtrsim 40$ Gev and $\gtrsim 100$ Gev as obtained by various workers, mentioned therein, and normalised to showers of size $10^6$ particles. Measurements show that the muons, in EAS, have a broader-distribution than electrons. Also the distribution becomes steeper for higher energy muons. Nikol'skii (1962) has fitted following formula to the lateral distribution obtained by Vavilov et al (1957), Khernov (1961) and Fukui et al (1960) for muons of energy $\gtrsim 440$ Mev in showers of size $7.7 \times 10^5$ particles.

$$p(r) = A(N,E_\mu) (r+2)^{-0.7} \exp (-r/r_0(E_\mu))$$

with $r_0(\gtrsim 440$ Mev) $=330$ m, $r_0(\gtrsim 1$ Bev) $=220$ m and $r_0(\gtrsim 5$ Bev) $=100$ m.

Greisen (1960), on the basis of the available experimental results, has given the following formula for the lateral distribution of muons of various energies.
FIG. 1.2 LATERAL DISTRIBUTION OF MUONS ENERGY @ 60 GeV IN SHOWERS OF SIZE $10^6$ PARTICLES

FIG. 1.1 RADIAL DISTRIBUTION OF MUONS IN SHOWERS OF SIZE $10^6$ PARTICLES
LATERAL DISTRIBUTION FOR MUONS (ENERGY > 100 GeV) IN SHOWERS OF SIZE $10^6$ PARTICLES

**FIG. 1.4**

LATERAL DISTRIBUTION FOR MUONS (ENERGY > 40 GeV) IN SHOWERS OF SIZE $10^5$ PARTICLES

**FIG. 1.3**
\[ f(r, N, E_{\mu}) = A(N, \geq E_{\mu}) r^{-0.75} (1 + \frac{r}{520})^{-2.5} \]

\[ 20 \leq r \leq 500 \text{ m} \quad \& \quad 1 \leq E \leq 20 \text{ Gev}. \]

The experimental results of Earnshaw et al (1968) for the threshold energies up to 100 Gev are in agreement with the above formula. Barrett et al. give a mean lateral distance of 9.7 m for muons of energy \( \geq 560 \) Gev whereas Sivaprasad (1970) has obtained a mean distance of \((12 \pm 2)\) m for muons of energy \( \geq 220 \) Gev.

Hara et al. (1970) have obtained the lateral distribution of muons above 5 GeV. The distribution goes as \( r^{-2.6 \pm 2.5} \) for \( 200 \leq r \leq 800 \) m. For the size range \( 10^4 - 10^8 \) particles Staubert et al (1970) measured the lateral distribution of muons with energies \( \geq 2 \) Gev. The lateral distribution was found to go as \( r^{-0.85 \pm 0.02} \) and was found to be independent of the shower size within limits of error.

b) Size dependence of muon number:

Measurements done as early as 1949 by Cocconi et al. have shown that the relative number of muons decreases with increasing shower size. Results of majority of experiments, summarised by Greisen (1960) are in agreement with a dependence of the type

\[ N \propto N_e^{-0.75} \]

for threshold energies \( \leq 40 \) Gev.
However, the results of Barrett et al. (1952)
give a dependence of the type

\[ N (\geq 560 \text{ Gev}) \propto N_e^{0.45 \pm 0.13} \]

which indicates that the increase in number of muons
of higher energies is much flatter. Recent measurements
by Hara et al. (1970) for muons with energies \( \geq 5 \text{ Gev} \)
give a size dependence of the type \( N_e^{0.85 \pm 0.10} \) whereas
the experiments of Vernov et al. (1970) and Staubert
et al. (1970) yield a size dependence of the type
\( N_e^{0.78} \). However, Catz et al. (1970) have demonstrated,
for muons with energies \( \geq 1 \text{ Gev} \), a characteristic osci-
llation in the value of \( \alpha = \partial \ln N_\mu / \partial \ln N_e \) in the
size range \( 10^5 - 10^6 \). The authors indicate a possible
change in the primary composition on the basis of this
oscillation in \( \alpha \). However, there are also significant
errors on the values of \( \alpha \).

Sivaprasad (1970) has obtained a size dependence
for muons of energies \( \geq 220 \text{ Gev} \) and \( \geq 640 \text{ Gev} \) in showers
of size \( 10^5 - 10^6 \) particles. The relationship is a
power law with power index \( (0.41 \pm 0.14) \). The earlier
results of TIFR group (Chatterjee et al. (1965) and
Chatterjee et al. (1968b) were in error and the modified
results have been presented by Sivaprasad (1970) and
summarised by Sreekantan (1971).
c) **Energy Spectrum of Muons in EAS:**

On the basis of various experimental results, Greisen (1960) gives an energy spectrum of the type

\[ N_\mu (\geq E_\mu, N) = 1.7 \times 10^5 \left( \frac{N}{10^6} \right)^{0.75} \left( \frac{2}{E_\mu + 2} \right)^{1.37} \]

The spectral index obtained by Sivaprasad (1970) for \( E_\mu \geq 220 \text{ Gev} \) is \((1.35 \pm 0.15)\) which is similar to that obtained by Greisen (1960) but the absolute values of muon numbers at \( E_\mu \geq 220 \text{ Gev} \) and \( E_\mu \geq 640 \text{ Gev} \) are much smaller than expected on the basis of the above formula. Results of Earnshaw et al (1968) give an energy spectrum of the type very much similar to that obtained by Greisen in the range \( 1 \leq E_\mu \leq 100 \text{ Gev} \) and \( 10^5 \leq N \leq 10^8 \) particles.

There are no experimental results on energies between 100 Gev and 200 Gev at present. The present experiment deals with muons of energy \( \geq 150 \text{ Gev} \) and the details of the energy spectrum will be discussed in later chapter.

d) **The Fluctuations in muon number at observation level.**

Studies of fluctuations in the number of muons in showers of a given size as well as fluctuations in the shower size for showers having a given muon number have
been done by Moscow state university group (Vernov et al 1968, Vernov et al 1970). It is seen that for showers of a given size $N_e$ the dispersions $D N_\mu / N_\mu$ do not change within the range of error and within the whole range of $N_e$ studied viz. $10^5 \leq N_e \leq 10^7$. The relation between $\overline{N}_\mu$, the average number of muons, and $N_e$ at fixed $N_e$ and the relation between $N_\mu$ and $\overline{N}_e$ at fixed $N_\mu$ are described by a power law with the same exponent $\alpha = 0.78$. However, the proportion of muons in the showers with fixed $N_\mu$ is greater by a factor of $(1.51 \pm 0.18)$ than for the showers with fixed $N_e$. Firkowski et al (1970) have also investigated the fluctuations in EAS development on the basis of the ratio $N_\mu / N_e$ for two muon energy thresholds (0.5 Gev and 5 Gev). From the investigation of the electron and muon component of EAS Khristiansen et al. (1970) have shown that the dependence of the average number of muons $\overline{N}_\mu$ on the size $N_e$ can be approximated by a single power law in a large interval of $N_e$. The dispersions of the distributions of $N_\mu / N_e$ for the showers with fixed $N_e$ have large values in the interval of $N_e = 10^5 \div 10^7$. From these studies the authors conclude that protons make up a considerable part of the primary cosmic radiation at energies of $10^{15} - 10^{17}$ eV.
From the very narrow distribution of the number of muons observed in large EAS Linsley and Scarci (1962), Suga et al (1970) and others have concluded that the primary cosmic ray particles above $10^{17}$ eV are mainly protons.

e) **Multiple Penetrating Particles and Muon Beams:**

The phenomenon of multiple penetrating particles (mpp) has been of considerable interest in studies of EAS. Barret et al. (1952) were the first to report such events in which more than one parallel particles separated by distances $\sim 1\text{m}$ were incident on the underground detector simultaneously. Since then a number of workers have reported this type of events both in experiments associated with EAS as well as in experiments not associated with EAS. Barton (1968) has compiled along with his data, the data obtained by others and has calculated the rate of variation of multiple penetrating particles with depth. The observed rate of variation is slower than expected on the basis of number spectrum of the showers. This presumably means that the average energy of the muon, observed as a part of parallel particles, is higher than that of a single muon.

A class of phenomenon essentially similar to mpp but involving rather a larger number of muons has been consistently reported by Moscow State University Air
Shower group in their experiments at rather shallower depths \( \sim 40 \text{ m.w.e.} \). Vernov et al. (1960, 1962, 1963, 1965), Vernov (1967) and Vernov et al. (1969). This phenomenon has been named by these workers as muon beams. Higashi et al. (1957, 1960, 1962) were the first to observe this phenomenon in cloud chamber pictures at a depth of 30 m.w.e. Vernov et al. (1960) reported the observation of muon beams in Air Showers at sea level. Higashi et al. (1962) and Hasegawa et al. (1963) suggest that the muon beams are the results of Poisson fluctuations on muon trajectories in the composition of EAS. In contrast Vernov et al. (1962) have shown that muon beams observed by Moscow State University group could not be ascribed to these fluctuations.

Details of the muon beams are given by Vernov et al. (1967). The mean energy of the muons in beams turns out to be \( 10^{13} \text{ ev.} \) Vavilov (1962) gives an independent estimate of \( 10^{12} \text{ ev} \) for the energy. Blake et al. (1971) have looked for the muon bundles in EAS. The results are, however, inconclusive. Wdowczy and Wolfendale (1971) suggest that such muon beams (bundles) might arise from the coherent production of pions.

1.7 Objectives of EAS Studies:

The studies of EAS are mainly related to the studies of very high energy primary cosmic ray particles
( $\geq 10^{12}$ eV) as the observation of EAS provides a unique method of detecting such particles. The primaries of aforementioned energies are rare and hence direct methods involving their detection at the top of the atmosphere are impracticable. As the coherent particles in the EAS initiated by such primaries are spread over a very large area ($\sim 1$ Km$^2$) the effective detection area for primaries by means of EAS can be made very large.

There are two principal aspects of the EAS studies. One of them relates to the study of nuclear interactions at very high energies ( $\geq 10^{12}$ eV). The study of various components of EAS, which are secondaries and later generation products of these interactions, provides an indirect means of studying these interactions.

The other aspect is related to the astrophysical information which can be derived from the EAS studies. The energy spectrum of very high energy primary cosmic rays can be obtained only through the EAS observations. Existence or otherwise of any directional anisotropies in the arrival directions of EAS and hence in the directions of the primaries has an important bearing on the origin and source of these high energy particles and on the region through which they propagate.
High Energy Interactions:

The EAS studies, particularly those related to the high energy muons and N-component, provide indirect information about the nuclear interactions at high energies ($\geq 10^{12}$ eV). A characteristic feature of the nuclear interactions at these energies is the phenomenon of multiple production of the particles. Fermi (1950) advanced a theory of multiple particle production in which the nucleons are assumed to interact and deposit their energies in C.M. system in a volume surrounding the two nucleons. Particles are supposed to be produced in this volume in which thermal equilibrium is attained. The theory predicts a quarter power law for the multiplicity. Some of the features expected on the basis of this theory are in contradiction with the experimental observations.

i) The theory predicts totally inelastic collisions, whereas experimentally it is known that the incident nucleon retains a large fraction of its energy after the interaction.

ii) An increase in the transverse momenta of the created particles with increasing energy of the primary particle is implied by the theory whereas experiments show a near constancy of the transverse momenta.
iii) The experiments indicate an anisotropic emission of the created particles in the CM-system whereas an isotropic emission is expected from the theory. Further the theory evokes a high temperature for the system of interacting nucleons and hence the emission of particles heavier than pions should be as much probable as that of pions. This is not observed experimentally.

The main objection to Fermi's theory came from Landau (1953) who argued that because of the high temperature of the system the coupling between the particles inside the interaction volume must be very strong and the concept of independent particles existing in the interaction volume is not valid. He, therefore, envisaged a non-equilibrium behaviour of the system in the initial stage which could be described in terms of relativistic hydrodynamics. An expansion of the system in forward - backward direction in the CM-system takes place accompanied by reduction in the temperature. The multiplicity law in Landau's theory is similar to that obtained by Fermi. However, as the emission of the particles takes place when the system has cooled to a sufficiently low temperature the last two difficulties (mentioned above) in Fermi's theory, which arise because of the high temperature of the system, can be overcome.
However, the experimental results have repeatedly shown that only a part of its energy is given by the incident particle to the interaction and the angular distribution of the secondaries becomes more and more peaked as the energy of the incident particles increases, implying an increase in the longitudinal momentum with the energy. On the basis of these results two-fire-ball models have been proposed (Ciok et al. 1958; K. Niu (1958), Cocconi 1958a). In such a model it is assumed that as a result of interaction, two fire-balls are produced moving in forward and backward directions, in the CM-system, together with two survival particles. Particles are produced isotropically in the rest system of the fire-ball.

Cocconi, Koester and Perkins (1961) have proposed a numerical model, on the lines of the fire-ball model and based on the data at machine - energies (≈ 30 Gev). The model envisages a quarter power law for multiplicity, and exponential distributions for the energy and momenta of the produced particles and is in good agreement with the data at the accelerator energies (≈ 30 Gev).

Experiments have indicated the presence of a group of particles, among the secondaries of high - energy interactions, which carry higher energies than majority of the secondaries. To explain this, models envisaging
an excitation of the surviving particle to a resonance state have been proposed (Kraushar and Mark 1954; Takagi 1952, Peters 1962, Zatsepin 1962). Such models are known as Isobar models and involve the production of particles in two separate groups. The first group contains particles resulting from the evaporation of a fire-ball, the process being known as the "pionization". The second group corresponds to the nucleons in the fire-ball model. It is assumed that each of the nucleons comes out in an isobar state of $\pi N$ system which subsequently decays into several pions, emitted isotropically in the rest system of the respective isobar.

Pal and Peters (1964) have put forward a phenomenological model having the essential features of an Isobar model. It is assumed that $\sim 20\%$ of the energy of incident nucleon is given for pionization and the incident nucleon emerges, with $\sim 80\%$ energy, in an isobar state with a high probability. The excited nucleon subsequently decays into pions. The multiplicity law in this model is

$$n_t = S n_{10} + n_{f} \varepsilon_{p}^{1/2}$$

where the first term gives the average number of decay mesons from Isobar state and 2nd term is the contribution of the fire-ball process.
The various models and theories, described above explain some of the experimental observations at comparatively lower energies, especially at machine energies. The success of a given model depends upon the number of experimental facts which can be accounted for by the model. The applicability of these models at ultra high energies ($\gtrsim 10^{12}$ ev) is yet to be investigated. Experimental observations at these energies are still very meagre.

I.9 Importance of the muon component of EAS:

Muon component, especially the high energy muons, of EAS has a unique importance in probing the high energy interactions occurring near the origin of EAS. Because of near inertness, these particles are able to maintain (approximately) their initial directions, as well as other characteristics while traversing the atmosphere. These muons originate more or less near the origin of the EAS because of the reduction in their production probabilities at larger depths due to i) the degradation of N-Cascade energy and ii) the increase in the density of the atmosphere, with increasing depth. A detailed study of these muons, therefore, reflects features of the first few collisions at the top of the atmosphere. In recent years there has been an increasing emphasis on the study of this component.
The high energy muon component can be studied by operating detectors at underground levels in association with the air shower arrays at surface. The surface array provides information about the energy of the primary particle. A simple consideration shows that the percentage of association of muons with EAS is related to the total number of these muons in EAS. Also variation of the percentage of association with depth of the observation of the muons gives information about the energy spectrum of the muons in EAS. The information obtained thus can be used to derive various characteristics of the high energy collisions e.g. multiplicity, inelasticity, transverse momenta of secondaries etc. This becomes feasible because the number of collisions involved are few and hence the cascade calculations, using known models, are easy to perform.

Keeping these possibilities in view an experiment has been carried out to study some of the characteristics of the muons of energy $\geq 150$ Gev in association with EAS. We have also used one neon flash-tube hodoscope to get information about the multiple production and angular distribution of these high energy muons as well as about their interactions with the matter.