CHAPTER 1

INTRODUCTION

There are two main reasons for investigating the primary cosmic radiation . The first is to obtain information about the astrophysical aspect and second is to obtain information about the nuclear interactions at extremely high energies. Accelerators can accelerate particles only upto energy $\sim 10^{13}$ eV. Above this energy cosmic radiation is the only source of obtaining high energy particles and properties of their interactions. For both aspects of study we need to know the primary composition , flux and energy spectra of the particles.

A branch of cosmic ray physics which is important both from the point of view of nuclear physics and astrophysics is the study of the Extensive Air Showers (EAS) discovered by Auger in 1938. Primary Cosmic Ray particles interact in the earth's atmosphere and give rise to a cascade of secondary particles known as Extensive Air Showers. Let's now discuss the formation of air showers in the atmosphere.

1.1. The phenomena of EAS :

A high energy cosmic ray particle arriving at the top of the atmosphere collides with a nucleon of an air nucleus , loses a fraction of its energy and passes through the atmosphere . The energy that is lost by the primary particle leads to the production of a large number of secondaries . The secondary particles are mostly charged and neutral pions ($\Pi^{\pm}$, Π^{0}) and a small fraction of kaons and nucleon-antinucleon pair . The neutral pions decay immediately into two gamma ray photons which create the electron-positron pair by the pair production process . The new electrons radiate more photons by bremsstrahlung process which again forms electron - positron pair and create the electromagnetic cascade . Some of the charged pions and kaons decay into muons and give rise to the muon component of air showers . The remaining pions , kaons and all other hadrons suffer further collisions and generate more secondaries . At each new step the number of secondary particles increases and their average energy decreases . However a stage is reached when the energy of the particles become so low that secondary particle production stops and thereafter the number of particles decreases due to ionization loss and decay. Due to multiple coulomb scattering the secondary particles arrive at the ground level spreading over large area .

Since most of the electrons are ultra-relativistic and pass through the atmosphere with a velocity greater than the velocity of light , they give rise to a considerable amount of Cerenkov radiation . The electrons also emit radio waves in the frequency range of 1 MHz to several hundred MHz. Thus ultimately at the sea-level the various components of EAS particles are the

(1) soft component (electrons , positrons and gamma rays)
(2) muon component
(3) hadron component (pions , kaons and nucleon-antinucleons) mainly
(4) Cerenkov radiation
(5) radio waves

Considering the scope of the present experiment only the electron-photon component and the muon component of EAS are discussed briefly in the following section.

1.2. Electron-photon component :

The electron photon component is the most abundant component of the shower and constitutes almost 90% of the shower particles. Because of multiple coulomb scattering the shower particles spread laterally to hundred of metres. The density of shower particles is maximum at the core of the shower and it falls off rapidly with the distance from the shower core. A photon electron cascade in EAS with radial symmetry is described laterally at a distance r from the EAS axis by expressing the shower particle density $\Delta(r)$ by

$$\Delta(r) = N_e/r_0^2 . f(r/r_0, s) \quad \text{------------------} \quad (1.1)$$

Where N_e is the total number of particles in EAS, s is a parameter called the shower age which determines the steepness of the lateral distribution function and r_0 is the Moliere unit of displacement . The value of r_0 in air is 9.5 g cm^{-2} and its geometrical length (m) depends on the level of observation .

The most extensively used electron lateral distribution function given by Greisen [1] is a modification of the form given by Nishimura -Kamata [2] which is referred to as NKG function . The form of the function is

$$\Delta(N_e,s,r) = N_e/r_0^2.c(s).(r/r_0)^{s-2}.(1+r/r_0)^{s-4.5} \quad \text{-------(1.2)}$$

where c(s) is the normalisation constant , r_0= 79m (Moliere unit of displacement at sea-level).

The age parameter s is closely linked to the longitudinal development of the shower . For photon originated showers of primary energy E_0 observed at a depth of t (radiation lengths) from the point of origin,s is given by

$$s= 3t / [t+2\ln(E_0/\varepsilon_0)] \quad \text{-------------------(1.3)}$$

ε_0 being the critical energy for electrons in air and is equal to 84 MeV. More accurately, s is a function of the lateral distance from the axis also.

Recently it has been shown that the NKG function does not give a good fit to the lateral distribution of electrons and the observed distribution is steeper than the NKG distribution. Several forms of the distribution function have been given by different authors (Hara et al [3] , Dedenko et al [4] , Linsley [5] , Kaneko et al [6] , Capdevielle et al [7] , Lagutin et al [8] , Hillas and lapikens [9]) to fit the observed distribution of electrons.

The electron density distribution as a function of core distance calculated by Hillas and Lapikens [9] is represented by the following formula

$$\Delta(r) = N_e/r_0^2.c(s).[(r/r_0)^{a1+a2(s-1)}.(1+r/r_0)^{b1+b2(s-1)}] \quad \text{----------(1.4)}$$

where the parameters chosen for the best fit of the experimental results are

r_0=24m, a1= -0.53, a2=1.54, b1= -3.39, b2=0

Capdevielle et al [7] assumed that the shower age parameter in the fitting function should be the «effective age» for radial development of shower and defined it as

$$s(r) = \alpha.\log\beta(r/r_0) + s_l \ , \text{for } r \leqslant 150\text{m} \quad \text{------------------(1.5)}$$

where s_l is the longitudinal age parameter at the level of observation and α,β,s_l are constants at sea-level for a given shower size. With this modification the radial density distribution of electrons according to Capdevielle et al can be expressed as

$$\Delta(r) = N_e/r_0^2.[\ c(s).(\ r/r_0\ )^{s(r)-2}.\ (\ 1+r/r_0\ )^{s(r)-4.5}\ ] \quad \text{-----------(1.6)}$$

The shower size (N_e), age parameter (s) and the shower core (X_0,Y_0) are determined by fitting a chosen function to the density of shower particles at various points. The shower size is a measure of the total energy of the primary particle. The relation between the average shower size and primary energy (E_0) can be expressed as

$$E_0 \sim N_e^{\beta} \quad \text{---------------------(1.7)}$$

where β is a constant .
The value of β is 0.86 (Trzupek et al [10]) for showers in the size range $3\text{x}10^3$-10^5 particles initiated by primary proton .Thus the shower size spectrum represents the energy spectrum.

1.3. <u>Muon component :</u>

Muons, having no strong interaction, reach the observation level from the point of their production. Hence they loose energy only by ionisation and disappear only by decay. The ionisation loss in the atmosphere is comparetively small and the mean life of muons is comparetively long. Therefore, neither process is very effective in eliminating muons before they reach sea-level. This accounts for the fact that the number of muons after reaching a maximum in the upper atmosphere decreases slowly with increasing atmospheric depth. As a consequence muons become the dominant component of the cosmic radiation near the sea-level. Muons constitute about 10% of the total number of particles in EAS and spread out to much wider area than the electromagnetic component.

The muons of different energies in EAS have been studied using magnetic spectrographs associated with air shower array by different cosmic ray groups such as Durhum Group, Kiel Group, Moscow Group. The lateral distribution of low and high energy muons can be represented by the equation of the form

$$\rho_\mu(r) \sim r^{-\alpha}.e^{-r/ro} \qquad \text{------------------(1.8)}$$

where α is a fitting parameter. The values of α obtained from the present experiment lie in between 0.3 to 0.9 for muon energies 2.5 to 100 GeV and shower size 3.15 x10^4 to 1.79 x10^6 particles.The total number of muons N_μ in a shower can be obtained by integrating the lateral distribution function (eqn. 1.8).The average number of muons N_μ per shower can be represented by the relation

$$N_\mu \sim N_e^{\alpha} \qquad \text{--------------- (1.9)}$$

The present experimental data show that the value of α is about 0.6

The detection of muon component is sensitive to both cosmic ray primary composition and high energy nuclear interaction processes. At near sea-level atmospheric depths , an average shower size of 10^4 particles correspond to a primary energy of ~ 10^{14} eV if the primary is a proton, and to an energy of ~ 3x10^{14} eV if the primary is an iron nucleus . The air showers , of average energy ~ 10^{14} eV, when analysed in terms of lateral distribution and total size of muons of all energies would reveal differences with respect to these characteristics depending on the mass of the particle initiating the shower . For example , in an EAS of size ~10^4 particles , initiated by an iron nucleus primary of energy ~3x10^{14} eV , the total size of muons and the lateral structure of both low and high energy muons will be different from those in the shower produced by a proton primary of energy ~10^{14} eV . These differences in characteristics are largely independent of the high-energy nuclear model characteristics and that have been used to simulate, under necessary experimental conditions , the EAS data on various EAS components.

It should be mentioned here that the information available so far on primary composition in the energy range 10^{13}-10^{15} eV has been inadequate and it has been suggested by Cowsik et al [11] and Yodh [12] that the relative abundance with respect to iron group nuclei becomes very high at $\sim 10^{14}$ eV.

Let's now see how the total number of muons (N_μ) and the lateral distribution of muons in EAS are affected by the presence of heavy nucleus in the Primary Cosmic Ray .

A shower initiated by a heavy nucleus of mass number A with energy E_0 is equivalent to the superposition of A number of showers initiated by a proton of energy E_0/A . The total number of muons N_μ in a shower initiated by primary proton is experimentally known to be

$$N_\mu = K.N_e^\alpha \quad , \alpha<1 \qquad \text{-----------} (1.10)$$

Now if the effect of fluctuation is not taken into account the shower size is roughly proportional to the primary energy. Then the total number of muons (N_μ') in a shower initiated by a heavy nucleus of mass number A is roughly given by

$$N_\mu' = K.A.(N_e/A)^\alpha$$
$$= K.A^{1-\alpha}.N_e^\alpha$$
$$\text{so, } N_\mu' > N_\mu$$

Hence the total number of muons in a shower initiated by a heavy primary is larger than the corresponding one of the proton primary.As a result the N_μ-N_e curve for heavy primary will be shifted upward compared to the N_μ-N_e curve for proton primary.

Because of lower energy per nucleon , the showers of a given size initiated by heavy primaries at a given altitude are older than showers initiated by primary protons . Also the production height of muons is always higher for heavy primary induced showers than that of proton showers . Since the total number of muons and muon production height are higher , the lateral distribution of muons for showers initiated by heavy primaries will be flatter compared to proton initiated showers.

Therefore, the total number of muons and muon lateral distribution in an EAS at sea-level , if the primary is heavy nucleus will be different from those in a proton initiated shower. An Extensive Air Shower experiment in which the lateral distribution of muons and variation of total number of muons with shower size can be measured accurately can indicate the nature of the primary particle.

The lateral distribution of muons and the variation of total number of muons with shower size have been studied by the air shower experiment at the NBU campus to interpret the nature of the primary in the energy range 10^{14}-10^{16} eV.

1.4. Results on composition of Primary Cosmic Rays:

The study of EAS is highly complicated since most of the observed parameters are highly dependent on high energy interaction characteristics as well as primary mass composition both of which are unknown. Thus conclusions from one depends on the assumptions regarding the other.

From EAS measurements it is seen that the Primary Cosmic Ray energy spectrum steepens in the energy range 10^{14}-10^{16} eV, known as the knee energy region. At the 1959 Conference in Moscow the MSU group reported a steepening of the sea-level size spectrum for $N_e > 8x10^5$. A group working at Norikura (2770m. a.s.l.) reported a steepening from integral exponent 1.55 to 2.04 occuring for N_e between $3x10^5$ and $5x10^5$ (Kameda et al 1960). The steepening of the energy spectrum has been most widely interpreted as probably reflecting an increased rate of leakage of high rigidity particles from the galaxy. Peters [13] suggested in 1961 that due to magnetic field in the galaxy the galactic cosmic rays will be cut off at constant rigidity.Alternatively it is suggested that the knee is produced in the source region due to either a threshold for break up of preferentially accelerated heavy nuclei (Zatsepin et al [14] .) or to the threshold for photodisintegration (Hillas [15]). It has also been suggested that the knee is formed due to cosmic rays from a different class of sources perhaps pulsars (Karakula et al [16]). In all these models a change of primary mass composition is expected at around the knee.

There is a lot of controversy regarding the primary mass composition . The primary mass composition below 10^{14}eV has been measured by balloon borne detectors , like emulsion stacks, scintillation detectors, cerenkov counters flown to the top of the atmosphere (Balasubrahmanyan and Ormes [17] ; Juliusson [18] ; Ormes et al [19] ; Lezniak and Webber [20]). Chemical composition of Primary Cosmic Rays have been estimated from the fractal analysis of the charged particle distribution near the core of individual EAS by Kempa et al [21] .From the fractal analysis they concluded that (1) Neither before the knee ($10^5<N_e\leqslant 5x10^5$) nor after the knee ($5x10^5<N_e\leqslant 5x10^6$) heavy primaries dominate in the primary spectrum . (2) After the knee the fraction of heavy primaries decreases to a value of 14%±4% while the fraction of protons increases to 67%±13%.

At energies above 10^{14} eV an indirect estimation of the primary mass composition has been made from EAS measurements. Composition of Primary Cosmic Rays has been derived indirectly by various groups from the study of various parameters in Extensive Air Showers : i.e. from the study of delayed hadrons, fluctuation of muons, high energy muons and their correlations with other parameters of EAS and the depth of shower maximum from atmospheric cerenkov radiation observations.Unfortunately the various experiments indicate compositions which are at variance with each other. Delayed hadron and shower maximum measurements favour an iron rich composition at $\sim 10^{15}$ eV. Whereas the observations based on muons are consistent with the normal mixed composition. Some of the results are summarised below:

From the variation of central density of EAS electrons with size and its fluctuation Sydney group (Mc.Cusker et al [22]) concluded that around 10^{15} eV the primary mass composition is mixed which becomes progressively richer in heavy nuclei upto 10^{17} eV.

By measuring the same parameters the Kiel group (Samorski et al [23]) suggested that the primaries are either proton or mixed but not all heavy primaries in the energy interval 10^{15}-10^{16} eV.

From the variation in the number of very high energy muons ($E_{\mu} \geqslant 220$ GeV) with the shower size together with the expected behaviour of showers generated by pure proton and heavy primaries by Monte Carlo simulation, KGF(Kolar Gold Field, India) group favoured for a mixed composition with a gradual enrichment of heavy primaries in the energy range $10^{14.7}$-$10^{15.7}$ eV (Sivaprasad [24]). Afterwards the same group (Acharya [25]) concluded that the mixed composition is consistent up to $10^{15.7}$ eV.In the primary energy interval $10^{15.7}$-10^{16} eV the primary composition changes from mixed to proton dominant. At energies greater than 10^{16} eV the primaries are dominant in protons.

Some of the recent and main observations other than those as discussed above are given in table 1.

Table 1. Composition of Primary Cosmic Rays from EAS observations

Authors	EAS-particles studied	Conclusion
Andam et al. [26]	Depth of maximum development of shower from atmospheric cerenkov light	Rate of change of primary mass with energy in the range 10^{15}-10^{18}eV is constant
Linsley and Watson [27]	Depth of maximum development of shower from atmospheric cerenkov light	Predominantly heavy at 10^{15} eV and changes to lighter at 3×10^{16} eV
Walker and Watson [28]	Rise time of pulses from water cerenkov detectors	Mass composition is nearly constant between 10^{17}-10^{19} eV

Yodh et al. [29]	Delayed hadrons	Heavier nuclei is dominant in the primary energy range 10^{14}-10^{16} eV
Stamenov et al [30]	Muon and electron flux fluctuation distribution in EAS	The mass composition of the primary cosmic radiation in the energy interval 10^{15}-10^{16} eV is mixed and does not substantially change with energy.The relative contributions of primary protons is not smaller than (39±4)% and for iron nuclei group (15±5)%
Nikolsky et al. [31]	Fluctuations of muons	The primary composition is constant and mixed (40% proton, 15% Fe)
Muraki [32]	Variation of muon size with shower size	In the primary energy range $2x10^{16}$- $2x10^{17}$eV the iron component does not become dominant
Dawson [33]	Lateral distribution of cerenkov light in EAS	Cosmic ray primary composition is rich in iron over the energy range $3x10^{15}$-$5x10^{16}$ eV
Cho et al [34]	High energy muons in EAS above 200 GeV	Primary composition of cosmic rays in the energy range till $10^{14.5}$ eV is proton dominant

Blake et al. [35]	Muon component in EAS	Primary mass changes from heavier to lighter in the primary energy range $0.6x10^{15}$-$5x10^{15}$ eV

1.5. Present investigation:

The present experiment has been carried out to study the low and high energy particles (electrons and muons) in EAS at the knee energy region (10^{14}-10^{16} eV) by using the NBU air shower array. The air shower array consisting of 19 electron density detectors , 8 fast timing detectors , two shielded magnet spectrographs (with a spacing of 4m, maximum detectable momentum 500 GeV/c , each of area 1m x 1m and cut off at an energy 2.5 GeV) and a neon flash tube chamber is designed to detect electrons and muons of various energies simultaneously.

All the particle detectors in the array working simultaneously under the four fold coincidence measure particle density and particle momentum in individual EAS and the data are processed by a 486-DX2 computer to provide the shower parameters i.e. the EAS axis co-ordinates, EAS age, EAS size (measured in number of particles). From these estimations we obtain the radial distribution of particle density as well as the energy distributions of particles in EAS.

There is a great deal of controversy regarding primary composition obtained by various groups. A number of observations indicate the presence of heavy nuclei in the primary energy range 10^{14}-10^{16} eV while some other observations show the lighter composition of the primary cosmic rays in the same energy range. In the present work , the characteristics of the radial density distribution of muons in terms of measured shower parameters and the variation of total number of muons with shower size have been studied and compared with different

Monte Carlo simulation results to draw conclusion about the average nuclear mass of the primaries of EAS.