CHAPTER I

INTRODUCTION

Ever since their discovery and identification as highly energetic particles coming from outer space and entering the earth's atmosphere 'Cosmic Rays' have been a subject of extensive scientific investigation. The prospects of gathering different information about the large-scale details of structure of the universe and the mechanism of particle interactions at high energies have initiated many experiments to investigate the properties of these radiations. However, direct observation of these particles become difficult at higher energies due to their decreasing flux, and hence many investigators have resorted to an alternative method of studying the cascade of secondary particles known as Extensive Air Shower (EAS) produced by the interaction of primary particles with the air nuclei. The different observable features of this EAS can be interpreted in terms of the nature of primary particle initiating the cascade and the characteristics of particle interaction at high energies by reconstructing the air shower development by theoretical simulation of events.

The present experiment whose results are being reported in this thesis was performed to investigate the electron and muon components of the EAS. The measurements of the present experiment are analysed in terms of the calculated results obtained and reported by different authors with theoretical simulations using different models of particle interaction at high energies. In this chapter, brief introductions of Cosmic Rays and the EAS along with the techniques of theoretical simulation of air shower events and the models of hadronic interactions, in general, are presented.

1.1 THE COSMIC RAYS

Summarizing the results of his balloon-borne experiment performed in August 1912, Victor F. Hess had reported - " The results of my observation are explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above." His assumption of existence of these 'radiation from above' to explain the variation of rate of ionisation with the altitude, was subsequently supported and verified by Kohlhorster. But, it was Milikan who, with his extensive experiment performed between '23 and '26 at different altitude and under water, convinced the whole scientific community that the radiation did exist and actually came from beyond the earth's atmosphere, and baptised it to bear the name of 'Cosmic Rays'. Clearly, the motivation in Milikan's mind to give such a name was that the only possible nature of Cosmic Rays (CR) which could be thought about at that time was of highly energetic gamma rays. He, in fact, went a bit further and tried to explain CR to be the energy released in the form of gamma rays during the synthesis of heavier elements from the primordial hydrogen spread throughout the universe. But somehow, the other experimental evidences especially that of Bothe and Kohlorster did not support Milikan's theory of CR to be the birth cry of atoms being continuously created in space. On the contrary, they indicated the possibility of CR being corpuscular in nature. This dispute about the fundamental nature of CR, however, did not last long and was rather convincingly settled by 1933 with the discovery of East-West and latitude effects in favor of the corpuscular theory. Hess was awarded Nobel Prize in physics for his discovery of CR in the year 1936.

So, it took almost 15 years to prove the existence of this initially assumed 'radiation from above' as 'Cosmic Rays', almost 21 years to understand its nature and 24 years to acknowledge its discoverer with the esteemed Noble Prize. However, this initial lackluster in the CR research got more than compensated by the hectic activities it initiated once its importance as the natural source of highly energetic particles much beyond than that can be produced in the laboratory was realised.

These highly energetic particles, the highest energy reported so far being 10^{20}eV, bombarding the earth's atmosphere continuously and from all directions turned out to be one of the most important messengers coming from the outer space which brought along the messages about the large scale details of the universe and distribution of the magnetic fields in the interstellar medium. They also proved themselves to be a very effective probe to investigate the interior of the sub-nuclear world. It is this later role of CR which has contributed a lot to understand the characteristics of high energy particle interactions and brought to light many new facts about the elementary particles with the series of discoveries of new particles. The first colored feather in the cap of CR came as early as 1932 in the form of discovery of positron by Andersson followed by a long list of new particles, some of them predicted earlier to fit the demands of theoretical studies and some of them totally new demanding to be fitted in the theoretical frame, and in the process pushing forward the frontiers of the knowledge of Physics deep inside the atomic nuclei.

However, the total monopoly of CR in the studies of high-energy interactions is slightly curtailed by the new generation of particle accelerators in the energy region below 10^{14} eV, but in the ultra high region of above 10^{14} eV it still enjoys the status of being the only source of information. But again, in this ultra high-energy region, the energy spectrum of the CR particles is observed to be very steep resulting into a low flux of the particles which makes the direct observation of these particles difficult. So, to study the interactions above 10^{15} eV or so one has to resort to an indirect way of studying Extensive Air Shower, a phenomenon first observed by Pierre Auger and his collaborators [1] in 1938 with coincidence of the detectors separated from each other.

1.2 EXTENSIVE AIR SHOWER

Extensive air shower (EAS) is the atmospheric cascade of particles produced by a single CR primary with energy large enough to produce a coherent, detectable flux of particles at an observational level deep in the atmosphere. The phenomenon of EAS can be described in broad terms like this- the primary CR particle, mostly hydrogen nuclei, interacts with a nucleon in the target air nucleus high in the atmosphere producing secondary hadrons like pions (both charged and neutral), kaons, nucleons and antinucleons. Neutral pions immediately decay into two photons, which in turn initiates what we call as the soft or the electromagnetic component of the cascade. The nucleons, antinucleons and some charged pions interact again to produce more hadrons and thus the hadronic core of the cascade is developed and sustained. Other charged pions and kaons decay to muons contributing to the development of the muon component of the cascade. The hadronic core continues to feed the electromagnetic and muon components as it penetrates into the atmosphere. Thus the number of particles in shower increases, spreads out over a large area around the axis (the original direction of incidence of the primary particle) of the shower and attains a maximum and then it decreases with atmospheric depth due to the loss of energy by secondary particles through various interactions with atmospheric atoms. So, as a result of the successive multiple generations of particles and their spreading out due to various scattering processes a large number of particles spread out to great distances from the shower core is observed at sea level.

According to the different properties exhibited by the secondaries they are classified into different components. A brief account of the principle components of the EAS is given here.

1.2.1 THE ELECTROMAGNETIC COMPONENT

This component consists mainly of electrons and photons, and electrons being the most populous particles in EAS their number fix the so-called size of the shower (Ne). The development of this component of the cascade depends primarily upon the momentum distribution of the secondary neutral pions produced in the p-air and pion-air interactions. The number of particles in this component grows, attains a maximum and decreases rapidly as the energy of the shower is degraded.

The total number of electrons in an individual shower is determined by measuring their densities at different points of shower front. Fitting these density information to one of the functional forms assumed to represent the distribution of particles in the shower, the location of the shower core (X_0, Y_0) and the shower age (s), a parameter which is related to the growth and decay of the shower, are determined.

A brief review of the different electron distribution functions suggested and used by different investigators is presented in section 2.1 of Chapter II. And, the measurements representing the distribution of electrons obtained in the present experiment are presented in section 4.2 of Chapter IV of this thesis.

1.2.2 THE MUON COMPONENT

This component of the EAS. comprising of the secondary muons, in contrast to the electromagnetic component, grows and maximizes but decays very slowly as the muons do not interact strongly and have very small cross sections for radiation and direct pair production. They carry the generic information from various stages of longitudinal development of EAS. Particularly, the high-energy muons due to their origin at the early stages of the development of the shower carry information from the highest energy interactions in the cascade development. The muon content of the shower is an indication of the energy degradation and the sharing of energy between charged and neutral pions in the cascade. The ratio of muon number to electron number is thus an indicator of overall shower development, which is also observed to be sensitive to the primary composition.

A number of experiments have been performed and are still being performed to study the muon component of the EAS at different levels of observation. A brief survey of these experiments and their results is presented in section 2.2 of Chapter II and the results of measurements of this component obtained in the present experiment are presented in section 4.3 & 4.4 of Chapter IV of this thesis.

1.2.3 THE HADRON COMPONENT

This component of the EAS consists of nucleons, antinucleons, charged pions and kaons. These particles are produced in the interaction of primary particles and the secondary hadrons with the air nuclei and hence carry direct information about the high-energy interactions. Since they are produced with very small angular divergence most of them are concentrated within a small distance from the shower core and have very steep lateral distribution. Though less in number they carry a substantial amount of energy and through the production of neutral pions and its subsequent decay into photons multiply the electromagnetic component of the EAS cascade. Similarly, some of the charged pions and kaons decay into muons contributing to the growth of muon component. In this way, the energy retained by the hadron component slowly but continuously flow into the other components as the shower develops in the atmosphere.

Different aspects of this component of EAS have been studied and are still being studied by different groups of investigators [2-5].

1.2.4 THE OTHER COMPONENTS

In addition to these above three components, the other features associated with the EAS, which are also being investigated, are the Cerenkov light, the radio waves and the atmospheric scintillation light.

The Cerenkov lights, which were first detected by Galbraith and Jelley [6] as flashes of light in the night sky, are radiated by electrons and positrons of the air shower having energies above a certain value depending on the refractive index of the medium. These linearly polarized lights spreading over a large area are good indicators of the longitudinal development of the shower. Moreover, the total number of Cerenkov photons in the shower is proportional to electron and positron track length integrals and hence gives a good estimate of primary energy.

The radio waves are emitted by electric dipoles created due to the macroscopic displacements of electric charges caused by the geomagnetic deflections during the development of the air showers. Jelly and his collaborators [7] first detected radio waves with the frequency of 60 MHz in large EAS in 1965. Different investigators studied these waves, which are also good indicators of the longitudinal development of the shower and the composition of the primary CR. The lateral distribution of field strength in the distance range of 30 to 300m from the shower core and frequency spectra covering frequencies of 0.1 MHz to 100 MHz have been measured and reported by different authors [8-10].

In an EAS initiated by primary particles with very high energy (>10^{18} eV), fluorescent lights are produced due to excitation of the molecules, mainly Nitrogen, of the atmosphere. The emitted radiation having wavelength between 300 to 430 nanometer is very isotropic and spreads over a large area. The study of this radiation gives a good account about the longitudinal development of the air shower and also the primary energy spectrum, which of course, needs a long time of observation. The experimental installation at Dugway, Utah named as 'Fly's Eye' developed by Cassiday and his coworkers [11] is a typical example of the detecting system that is necessary for studying this atmospheric scintillation lights.

1.3 THEORETICAL SIMULATIONS OF EAS

The Cosmic Ray EAS is a unique source of information about the characteristics of hadron interactions at high energies over a large energy range and much beyond the energy region of accelerators. Practically, all known high energy nuclear interactions occur within it but unfortunately this treasure house of knowledge is veiled by a lot of complexities. Due to the large spatial extension of EAS the amount of information that is simultaneously accessible in each air shower event is comparatively small. The majority of data obtained will represent a particular stage of cascade development depending upon the location of the detectors at a particular level of observation, the arrival direction of the shower and also the energy and mass of the primary particles initiating the cascade. The last two parameters, which play vital roles in the development of the cascade, are inaccessible to direct measurements. So, only reconstruction of the shower based on observations made at relatively great atmospheric depths enable us to unfold the early history of the development of air shower in the atmosphere and the processes involved therein. Hence, for the evaluation and interpretation of the experimental data an indirect approach by means of computer simulation of the air showers is employed.

In the simulation of air shower events, different observable features of shower particles like their energy spectra, their radial distribution etc. are calculated with the help of some theoretical models of particle interaction. These calculated data, representing the distributions of the secondary particles at different points of a shower front and at different levels of observation, can then be compared with experimentally measured data to test the validity of the theoretical models adopted.

Two basic approaches are possible for air shower simulation viz. Analytical and Monte Carlo simulation.

1.3.1 THE ANALYTICAL SIMULATION

In this type of simulation, an equation is formulated to express the functional relationship of the different shower observable or parameters with primary energy, primary mass and the level of observation. Such an equation has to incorporate both the particle production and all other processes that may affect the propagation of particles in a shower. This method of simulation, in spite of being simple and having the advantage of less computational effort has severe limitations. It is practically impossible to work out equations that describe all the processes involved to a sufficient degree of accuracy. A number of approximations have to be made in any such analytical method and that tends to make the calculations rather model insensitive and hence loses dependability.

1.3.2 THE MONTE CARLO SIMULATION

This method of simulation is most frequently used these days to investigate the relationship between experimental data and interaction models on a much more refined level. Here, each particle of the cascade is individually generated and allowed to propagate in highly realistic way considering all the possible phenomena it might undergo during propagation. Each of the generated particles is followed up to the level of detection keeping records of all the details of interactions.

The only disadvantage of Monte Carlo (MC) simulation is the long computing time needed to complete the procedure. The computing time needed for a complete simulation is approximately proportional to the primary energy and also depends on the lower energy threshold. So, in MC simulation of EAS, the speed of the calculation is balanced against the precision and the amount of output information. Different methods are used to minimize the computing time such as setting the lower threshold energy of interaction as high as possible and neglecting the interactions below this threshold, or following all the particles only above some demarcation energy by detailed MC simulation and then using some analytical equations to simulate the rest part of the shower. This later technique of simulation is known as hybrid MC simulation. A typical example of this type of simulation can be seen in ref. [12-13].

1.4 MODELS FOR AIR SHOWER SIMULATIONS

The main guiding principle behind any MC simulation of EAS is the model adopted for describing the development of air showers. All the models used for the simulation of air shower events consist, in general, of two principal parts - the high-energy interaction and the propagation part. The propagation part of the model, so-called superstructure of the calculation, takes care of all the known processes that effect the propagation of the primary and all subsequent secondaries. Mostly, well known effects like decay or annihilation of particles, the competition of these processes with other interactions, ionization losses of charged particles, Coulomb scattering of muons etc. are included in this part and hence basic features of this part remains more or less same for different MC simulations. So, it is the high-energy interaction and the particle production part of the model that plays the dominant role in any simulation of the air shower events.

Considering the interaction of high-energy Cosmic Ray particles with air nuclei as proton-proton (p-p), proton-nucleus (p-A) and nucleus-nucleus (A-A) collisions, different models of high-energy interaction have been developed in recent days. Since, these high-energy collisions give rise to the multiple production of the particles, the characteristics of these interactions can be described in terms of the different parameters of collision kinematics such as- interaction cross-section (σ), inelasticity (K), multiplicity (n), the transverse (p_t) and longitudinal (p_l) components of the momentum of secondaries etc. Taking information from the accelerator experiments, which are limited to the energy region of ~TeV, about the behavior of these parameters, a model is proposed to predict their corresponding changes in the higher energy region. Any such model proposed to represent the characteristics of high-energy particle interactions has to describe equally well the results of the accelerator experiments and at the same time, predict different energy behavior at higher energy region. Based on these models, the development of air shower events in the atmosphere is simulated and the different characteristics of the EAS are calculated.

A number of models like Statistical model and its modified form- the Thermodynamic model of Fermi [14], Hydrodynamic model of Landau [15], the CKP model [16,17], Isobar and fire-ball models [18-20] etc., were proposed and used in the past. With the upcoming of new generation of the accelerators and the results provided by them, many other models have been proposed in recent days and are being used by different investigators for the simulation of EAS.

A brief survey of the different models used by various authors and their results are presented in section 2.3 of Chapter II. And, a comparative study between the measurements of the present experiment representing the distribution of electrons and muons in EAS with those calculated theoretically by different authors using various models like scaling, scale-breaking and quark gluon string (QGS) models is presented in section 4.6 of Chapter IV of this thesis.

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