OPTICAL EMISSION ASSOCIATED WITH UHE COSMIC RAYS

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This is to certify that Mr. Jyoti Prasad Phukan, M.Sc. has worked under my guidance and supervision since January 1998 for his thesis entitled “Optical Emission Associated with UHE Cosmic Rays” which is being submitted to the Gauhati University for the award of the Degree of Doctor of Philosophy. The thesis is based on original work done by Mr. Phukan. He has fulfilled all the requirements for submission of Ph.D. thesis as per regulations of the Gauhati University. He has also published a few original research papers in reputed Conference Proceedings, Journal and few are communicated for publication. He has also presented research papers at the 27th International Cosmic Ray Conference, Humburg, Germany, 2001 and 29th International Cosmic Ray Conference, Pune, India, 2005. This thesis or any part of this has not been submitted to any University for any other degree.

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DECLARATION

The thesis entitle “Optical Emission Associated with UHE Cosmic Rays” is an original work done by me and I am submitting this as a fulfillment of the requirements for the award of Degree of Doctor of Philosophy in Physics of Gauhati University. I hereby, declare that no portion of this work reported here has been submitted to Gauhati University or anywhere else by me or by any other person for the award of any degree.

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ABSTRACT

Instead of expensive particle detectors covering large area to investigate different parameters from UHE (Ultra High Energy > $10^{17}$eV) Cosmic Rays, a cheap and novel method, suitable for small laboratories for such studies was proposed by Prof. John Linsley. Based on Linsley’s concept of simultaneous measurement of arrival time and particle density, a miniarray of eight plastic scintillation counters was set up in the roof top of the Physics Department, Gauhati University, which detects giant air showers of primary energy $10^{17}$eV to $10^{18}$eV. An optical detector is installed at the center of the miniarray to detect the optical Čerenkov radiation in association with UHE Cosmic rays, with an aim to throw light on primary mass composition. Mass composition at UHE is yet an unsolved problem with conflicting results from different world groups. More data are therefore, necessary to solve this problem. Čerenkov pulse associated with an EAS, carries information about longitudinal shower development, which is directly related to the primary mass number. The composition inference at ultra high energies being indirect, involves detailed simulations using specific models. Simulation is a step by step procedure, where a real physical process is idealized as a sequence of choices governed by some probability functions. Computer generated pseudo-random numbers are used to simulate an air shower, by a process called Monte Carlo method. The present experimental work consisting of operation of the miniarray, recording of Čerenkov light, simulation, data reduction and analysis was carried out in the miniarray laboratory from 1998 to 2006. The entire work can be divided into the following steps,

(i) Design and fabrication of Optical Čerenkov detector consisting of 5 inch Photo Multiplier Tube (PMT) with associated circuits to record optical data in association with miniarray events by measuring particle densities($\rho$) and the arrival time spread of the shower particles ($\sigma$) using suitable coincidence technique. From these primary measurements, parameters viz, core distance ($r$), shower size ($N$) and primary energy ($E_p$) are derived as functions of measured parameters.

(ii) Calibration of Čerenkov detector using secondary cosmic rays and a tank of distilled water as detecting medium.
(iii) Analysis of measured optical pulse profile in correlation with shower parameters like core distance, shower size and primary energy.

(iv) Development of necessary shower simulation programs to analyse the experimental data and derive information about primary mass composition.

The detector unit consists of eight plastic scintillators (size 50 x 50 x 5 cm$^3$) each viewed by a 2 inch fast PMT (Type-EMI 9807B) and an optical detector consisting of a 5 inch fast PMT (Type- 9792KB ), which is installed at the center of the miniarray. The total carpet area of the detectors which are put in a hut at the roof of the Physics building is 2m$^2$. The output signals from all the detectors are pre-amplified and carried to the control room using coaxial cables for further amplification. The particle detector pulses are then discriminated into logic pulses, OR’ed together into a pulse train and branched into a Digital Storage Oscilloscope (DSO, Tektronix, TDS520A,500MHz, 500 M Sample/sec) and a trigger circuit. The amplified signal from the Čerenkov detector is directly fed to the channel-1 of the DSO, while particle detector pulse train and triggered pulses are fed to the channel-2 and AUX-1 respectively. On trigger, the optical pulse-form, the number of particle pulses and their relative time positions are stored in the scope and this is transferred to the computer via General Purpose Interface Bus(GPIB). The necessary software used for this purpose is written in C language.

Optical detector is calibrated using known flux of secondary Cosmic Ray muons and a distilled water tank optically coupled to the 5 inch PMT. Measured pulse height spectrum is compared with simulated photon number distribution to get the calibration curve. The calibration curve is used to convert the experimental optical pulse height to corresponding number of Čerenkov photons. Information about primary mass composition is derived from two sets of experimental measurements, viz,

(i) Čerenkov pulse height spectrum compared with simulation under different mass composition models.

(ii) Čerenkov Lateral distribution parameter deduced for different shower size bins, as a function of primary energy.

In the first case, $\chi^2$ per degree of freedom is found to be minimum for pure proton composition model. In the second case, recorded EAS events are grouped in narrow class intervals of shower size bins, and assuming grouped data to have the same average
primary energy, the corresponding optical flux density is fitted to a power law lateral distribution function using least square method. In deducing primary energy from shower size measurement of miniarray, a new relation as given by reanalysis of miniarray data using CORSIKA simulation program, has been incorporated. The measured power index is used to derive the depth of shower maximum ($X_m$), whose variation with primary energy shows proton enhancement beyond primary energy of $10^{17.7}$ eV.

According to recent measurements by various world groups, primary mass composition is mixed with iron enhancement around $10^{17}$ eV, becoming lighter at highest energies. Our result is in agreement with this observation, with composition changing from heavy galactic component to lighter extragalactic component.
CONTENTS

ABSTRACT i

CONTENTS iv

LIST OF FIGURES viii

LIST OF TABLES x

CHAPTER-I

INTRODUCTION:

1.1 Discovery of Cosmic Rays. 1
1.2 Origin of Cosmic Rays. 2
1.3 Composition and Energy Spectra of Cosmic Rays. 4
1.4 Cascade Development in the Atmosphere. 8
1.4.1 Electromagnetic Components. 11
1.4.2 Muon Components. 12
1.4.3 Hadron Components. 15
1.5 Lateral and Longitudinal Development of Charged Particles. 16
1.6 Electromagnetic Radiation from EAS. 20
1.6.1 Optical Emission (Čerenkov Radiation) from EAS. 20
1.6.2 Radio Emission from EAS. 25
1.6.3 Fluorescent Light. 26
1.7 Ultra High Energy (UHE) Cosmic Rays. 27
1.7.1 Primary Mass Composition at UHE. 28
1.8 Major Stations on Cosmic Ray Studies. 30
1.8.1 The AGASA Cosmic Ray Detector. 30
1.8.2 The Fly’s Eye Detector. 31
1.8.3 The Yakutsk Array. 31
1.8.4 The Pierre Auger Project. 32
1.8.5 The Space Air Watch Mission. 34
<table>
<thead>
<tr>
<th>1.9</th>
<th>The Present Work.</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9.1</td>
<td>Experimental studies</td>
<td>35</td>
</tr>
<tr>
<td>1.9.1(i)</td>
<td>Recording of Events.</td>
<td>35</td>
</tr>
<tr>
<td>1.9.1(ii)</td>
<td>Detector Calibration.</td>
<td>35</td>
</tr>
<tr>
<td>1.9.2</td>
<td>Monte Carlo Simulation of Recorded Events.</td>
<td>35</td>
</tr>
<tr>
<td>1.9.3</td>
<td>Data Analysis.</td>
<td>35</td>
</tr>
</tbody>
</table>

**CHAPTER-II**

**MOTIVATION AND THEORETICAL ESTIMATION:**

<table>
<thead>
<tr>
<th>2.1</th>
<th>Motivation</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>Detection Technique.</td>
<td>37</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Conventional.</td>
<td>37</td>
</tr>
<tr>
<td>2.2.2</td>
<td>MiniArray Technique.</td>
<td>37</td>
</tr>
<tr>
<td>2.3.1</td>
<td>The Shower Front.</td>
<td>39</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Theoretical Estimation from MiniArray Geometry.</td>
<td>41</td>
</tr>
<tr>
<td>2.4</td>
<td>Characteristics of Čerenkov Radiation.</td>
<td>42</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Lateral distribution of Čerenkov Radiation.</td>
<td>44</td>
</tr>
<tr>
<td>2.5</td>
<td>Primary Mass composition.</td>
<td>46</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Composition Models.</td>
<td>47</td>
</tr>
<tr>
<td>2.5.1(a)</td>
<td>Heavy to Light.</td>
<td>47</td>
</tr>
<tr>
<td>2.5.1(b)</td>
<td>Constant Mixed Composition.</td>
<td>47</td>
</tr>
<tr>
<td>2.5.1(c)</td>
<td>Pure Proton Composition.</td>
<td>47</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Some Important Parameters for the Determination of Mass Composition.</td>
<td>48</td>
</tr>
<tr>
<td>2.5.2(a)</td>
<td>Depth of Shower Maximum (X_m)</td>
<td>48</td>
</tr>
<tr>
<td>2.5.2(b)</td>
<td>Elongation Rate(ER)</td>
<td>50</td>
</tr>
<tr>
<td>2.5.2(c)</td>
<td>Estimation of Shower Size(N)</td>
<td>51</td>
</tr>
</tbody>
</table>

**CHAPTER-III**

**EXPERIMENTAL SETUP:**
3.1  Introduction.  
3.2  Detectors.  
3.2.1  Scintillation Detectors (Particle Detectors)  
3.2.2  Čerenkov Detector.  
3.2.2(a) Photomultiplier Tube (PMT).  
3.2.2(b) Pre-amplifier.  
3.3  Control Room Electronics.  
3.3.1  Eight Channel Discriminators.  
3.3.2  Trigger Unit.  
3.3.3  The Digital Storage Oscilloscope and GPIB Interface.  
3.3.4  Microprocessor and Microcomputer Interface.  
3.3.5  The Necessary Software used.  

CHAPTER-IV  
CALIBRATION AND TEST OF THE DETECTORS.  

4.1  Introduction.  
4.2  Calibration of the Čerenkov Detector.  
4.3  Method of Calibration.  
4.4  Results.  
4.5  Calibration of the Particle Detectors.  
4.6  Calibration of the Discriminator.  
4.7  Calibration of the Trigger Circuit.  
4.8  Adjustment of Delay among all Detectors.  
4.9  Reduction of Data Estimation of Noise.  
4.10  Operation of the experiment.  

CHAPTER-V  
SIMULATION OF ČERENKOV EVENTS ASSOCIATED WITH MINIARRAY.  

5.1  Monte Carlo Simulation.  
5.1.1 Pseudo-Random Numbers. 80
5.1.2 Transformation of Random Variables. 81
5.2 Simulation of Čerenkov Pulse Height Spectrum. 82
5.2.1 Simulation of Individual Shower Size(N). 82
5.2.2 Simulation of Individual Primary Mass. 82
5.2.3 Simulation of Depth of Shower maximum. 83
5.2.4 Estimation of Čerenkov Pulse Height. 83

CHAPTER-VI 85

ANALYSIS OF EXPERIMENTAL DATA, RESULTS AND DISCUSSION
6.1 Pulse Height Distribution. 85
6.2 Čerenkov Lateral Distribution. 89
6.3 Discussion. 94

CHAPTER-VII 96

CONCLUSION:
7.1 Concluding Remarks. 96

APENDIX

Appendix I 98
Appendix II 103
Appendix III 105
REFERENCES. 109
LIST OF FIGURES:

1.1. Integral all particles energy spectrum of the major components of high energy Cosmic Rays (the mass composition is uncertain in the shaded region.) 6

1.2. Low energy differential Energy Spectra. 7

1.3. The EAS Development with primary energy $\sim 10^{12}$eV or above. 9

1.4. (a)&(b). Propagation of secondary particles by gamma and proton initiated showers. 13

1.5. Lateral distribution of EAS electrons as suggested by various theories. 19

1.6. Čerenkov light as function of longitudinal development and emission of this light at three different atmospheric heights. 21

1.7. The resultant photon density at ground level as a function of core distance.
   (a) For single particle and (b) For EAS. 21

1.8: Huygens constructions to illustrate coherence. 23

1.9: A compilation of all $X_{\text{max}}$ measurements compared with models of energy variation of shower maximum from Shower Simulations. 29

1.10. Cosmic Ray energy Spectrum for $E > 10^{17}$eV. 33

2.1. A typical shower front of thickness $\sigma$ (nS) striking the ground. 40

2.2: Lateral distribution (power law) index $\delta$ vs. $X_{\text{m}}$, depth of cascade maximum. 43

2.3. Čerenkov Radiation from shower initiated by a particles of energy $10^{18}$eV at different core distances and the insert lower left shows the shape of the optical wave front. 45

2.4. Composition plot of $X_{\text{m}}$ vs. $E_p$. 50

3.1. Block Diagram of the Experimental Setup. 54

3.2. Fast Scintillation Detector. 55

3.3. Voltage Divider Network for 9807 Type PMT. 57

3.4. Voltage Divider Network for 9792KB Type PMT 58
3.5. Circuit diagram of fast scintillation pre-amplifier. 60
3.6. Circuit diagram of one Channel Discriminator with Pulse shaper. 61
3.7. Schematic Diagram of Trigger Circuit. 63
3.8. A typical output pulses of the discriminator corresponding to an event trigger. 64
3.9. A typical Čerenkov pulse triggered by miniarray and captured by DSO. 66
4.1. Experimental Setup for Calibration of Čerenkov Counter. 69
4.2. Geometry of the Experimental Setup. 70
4.3. Simulated and MCA Pulse Height Distribution. 72
4.4. Čerenkov Pulse Height Calibration Curve. 72
4.5. Statistical Fluctuation of Count Rate. 74
4.6. Single Particle Pulse Height Distribution. 74
4.7. Block Diagram of Testing of Trigger Circuit. 76
4.8. Linear characteristics of the trigger circuit. 76
4.9. A Spurious Event triggered by noise. 77
4.10. A Photographic view of the Experimental setup. 78
6.1. Čerenkov pulse height spectrum for pure proton composition model. 87
6.2. Čerenkov pulse height spectrum for pure iron composition model. 87
6.3. Čerenkov pulse height spectrum for constant-mixed composition model. 88
6.4. Čerenkov pulse height spectrum for heavy to light composition model. 88
6.5. Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 17.17 \) 91
6.6. Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 17.65 \) 91
6.7. Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 17.81 \) 92
6.8. Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 17.97 \) 92
6.9. Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 18.13 \) 93
6.10: Experimental Čerenkov lateral distribution with fitted curve for energy bin $\langle \log(E_p) \rangle = 18.29$

6.11: Plot of $\langle X_m \rangle$ vs average $\langle \log(E_p) \rangle$ for each bin compared with modified ER Theorem of Linsley.
LIST OF TABLES:

2.1. Measured $X_m$ and $\sigma X_m$ at Yakutsk and Fly’s Eye Array. 49
2.2. Measured $X_m$ and $\sigma X_m$ for P and Fe compositions. 49
6.1. Distribution of Čerenkov Pulse height and photon density. 86
6.2. Čerenkov lateral distribution parameter from binned data. 90
CHAPTER I

INTRODUCTION

1.1. DISCOVERY OF COSMIC RAYS:

The continuous and uncontrollable leakage of electric charge from a well insulated charged gold leaf electroscope is the mystery that remained unexplained almost from the time of Héneury Coulomb who had noticed in 1785, that a charged metal sphere suspended by an insulated silk thread did not retain its charge even though it was isolated.

In the twenty century H. Geital (1900), J. Elster (1900) and C. T. R. Willson (1901) performed experiment on ionization of air and observed some strange irreducible ionization current in the perfectly shielded electrometers and this opened the window of entirely new branch of Physics for the next generation of scientists. T. Wulf climbed the Eiffel Tower in Paris carrying ionization measuring device and noticed that the ionization decreased as he climbed to higher level. Gockel observed at higher heights using balloons and concluded that the ionization was not due to radioactivity of the Earth. But the credit goes to an Austrian Physicist Prof. Victor F. Hess for settling the issue unambiguously. On the historic day of August 7, 1912, Victor Hess along with an assistant went up in a balloon Gondola carrying three electrosopes and floated for several hours at altitudes ranging from 13,000 to 16,000 ft. and established that the radiation responsible for the mysterious ionization was coming from “above” and was possibly of extra-terrestrial origin. By series of observations by a verity of workers all over the world, the radiation not only from extra-terrestrial but also extra-solar. Millikan confirmed this radiation and named this penetrating radiation from depths of space in 1925 as “COSMIC RADIATION”. Prof. Victor Hess was awarded Nobel Prize for his discovery in the year 1936.

The studies of High Energy Cosmic Rays is an important tool in the branch of high energy Physics. The energy of cosmic ray distributes over a wide range from 1MeV to $10^{20}$ eV and possibly even beyond which is far from any artificial manmade accelerators. Such High Energy particles can be created only by astrophysical phenomenon which are investigated by many scientists.
1.2 ORIGIN OF COSMIC RAYS:

The Cosmic Rays must originate from a very powerful accelerator as the energy of the individual particles are very high. However, the flux of Cosmic Rays at low energy region change appreciably with solar activity. Most lower energy Cosmic Ray particles ($< 10^{17}$ eV) come from within our own Milky way Galaxy. This low energy component of Cosmic Ray must originate form the nearby objects in the interstellar space and are accelerated within the solar system. Many probably come from exploding stars, we call supernovae. Some Cosmic Ray particles pickup energy from moving magnetic fields of the Galaxy as they travel around it. The great Physicist Enrico Fermi first provided an explanation that strong moving magnetic fields produced in supernovae explosion provide the energy for acceleration. In Fermi’s Cosmic Accelerator, the protons “bounce” off moving magnetic clouds in space and finally gain energy. Particles are modulated by the Solar wind, the expanding magnetized plasma generated by the Sun, which decelerates and partially excluded the lower energy galactic Cosmic Rays from the inner Solar System[46]. Any source of Cosmic radiation would have to be a powerful particle accelerator to account for the tremendous energy of the individual Cosmic Rays. The most energetic of them have energies greater than $10^{20}$eV (that is 100 million times more than the energy expected to be imparted to particles in the Large Hadron Collider(LHC)being built in CERN, which would be operating by December 2007). The presence of heavy nuclei in relatively high abundance and their energies point to supernovae, the exploding stars releasing fantastic amounts of energy in space, as the major source of Cosmic Rays. There are some models on Galactic, meta galactic and extra galactic origin or Cosmic Rays, formulated depending on the location of the sources. Models of Cygnus X-3 assume that it is a binary star system in which one component is a dense neutron star. In one model the neutron star is a rapidly spinning Pulsar. The Pulsar accelerates protons to Cosmic Ray energies and ejects them in all directions. Some protons strike gas nuclei in the outer layer of the companion star, generating high energy gamma rays that continue along the proton trajectory. The gamma rays are detected on the earth during two phases of the Pulsar’s orbit. In the accretion model the neutron stars gravitational field draws matter off the companion star, and its magnetic field induces an increased electric field in the rotating disk of accreted matter. Protons are accelerated to Cosmic Ray energies along the electric field lines, some collide with gas nuclei in the accretion system and produce Gamma Rays. High energy Gamma Rays from Cygnus X-3 have
identified it as a source of Cosmic radiation at least 37,000 light years away [69]. Various astrophysical phenomenon have been suggested for the source of these energetic particles such as active galactic nuclei (AGN), Pulsars, explosive radio galaxies and high speed Jets of quasars. Cygnus X-3 is an important source of high energetic particles and Gamma Rays bombarding the Earth. Cygnus X-3 is the third brightest X-ray emitter in the constellation Cygnus which was first observed by X-ray astronomers in the year 1960. Cosmic Rays of energies beyond $10^{20}\text{eV}$ cannot be easily contained by weak magnetic field within the Galaxy, a fact that also suggests their extra galactic origin. The source must be near by our Galaxy (within 100 million light years or so), since collision with the lower energy microwave that pervades the Universe would reduce Cosmic Ray energies to below $10^{20}\text{eV}$ before they ever reached the earth, a phenomenon known as GZK cutoff [55,111]. The highest energies beyond GZK cut off [20] present a challenge to outstanding puzzle in astroparticle physics and cosmology [19]. The protons with energies above $5 \times 10^{19}\text{eV}$ could not reach Earth from a distance beyond 50-100 Mpc [98], because they scatter off the Cosmic microwave background photons with a resonant photon-production of pions, $p\gamma \rightarrow \Delta^* \rightarrow N\pi$. The mean free path for this reaction is only 6Mpc. The photons of comparable energies pair produce electron and positrons on the radio background and likewise, can not reach Earth from beyond 10-40Mpc [101]. This creates a problem because the closest astrophysical object that could produce such energetic particles, active galactic nuclei (AGN), are at least hundreds of mega parsecs away. Cosmologist–Scientists who study the structure and dynamics of the Universe offer another possible explanation for the mysterious source of highest energy cosmic Rays. Cosmologists postulate a Universe filled with relice left over from the Big-Bang hypothetical objects, called topological objects with names like “COSMIC STRINGS”, “DOMAIN WALL” and “MONOPOLES”. Although these strange objects figure prominently in the theories of the evolutions of the Universe, there is no experimental evidence.

The highest energy Cosmic Rays ever detected was observed in 15th Oct.1991, by the Fly’s Eye Cosmic Ray Detectors in Utah, USA [102]. The Utah researchers measured the energy of the Cosmic Ray event to be $(3.2 \pm 0.6) \times 10^{20}\text{eV}$ (1$\sigma$ errors). In 1993, AGASA array in Japan, recorded a very large air shower that was produced by a cosmic ray with an energy of about $(2 \times 10^{20}\text{eV})$. For the AGASA event measurement of the direction of the event predicts a radio galaxy NGC 315[21]. For the Fly’s Eye event there is the radio source 3C 134[109], the radio
structure of which resembles that of a powerful radio galaxy at a distance of about 30 Mpc, making it an acceptable candidate. Yakutsk in Russia (7.8 degrees form the Fly’s eye Group) also observed an air shower event with energy \((1.1\pm0.4) \times 10^{20}\) eV. Confirmation of the galactic origin idea has come from the Compton Gamma ray observatory observations of Megellanic clouds.

1.3 COMPOSITION AND ENERGY SPECTRA OF COSMIC RAYS:

From the various observations of Cosmic Rays, these rays are known to be high energy protons (over 90%), helium nuclei (about 9%), a small amount (about 1%) of heavier nuclei like Carbon, Oxygen etc to very heavy nuclei like Uranium and some times even heavier ones. Electrons and Positrons (about 1%) and Gamma Rays about (.01%) of the total flux are also found. A host of elementary particles like positrons, pi-mesons, Mu-mesons, K-mesons, hyperons, etc were discovered for the first time in Cosmic Rays. Cosmic Rays are being studied for the possible presence of exotic particles such as magnetic monopoles, Quarks, tachyons, etc. Intensity of the Cosmic Rays is nearly isotropic and is constant in time for millions of years as deduced from studies of radio active isotopes produced by Cosmic Rays in meteorites. The most interesting facts concerning the chemical composition of Cosmic Rays is that it closely resembles over most of the energy range observed, the composition of Galaxy as a whole, only Lithium, Beryllium and Boron are present at enhanced levels [26]. Their energies are observed to cover an enormous range extending to about \(10^{20}\) eV. The accelerators at CERN, Geneva can produce particles only up to an effective energy approximately \(10^{14}\) eV. Which is the highest energy of the particles produced by man made particle accelerators. Above this energy, cosmic rays are the only source of high energy particles for the study of high energy nuclear interaction characteristics.

At the very lowest energies (~ < \(10^{10}\) eV ) Cosmic Rays occasionally arrive from the Sun, largely via the giant solar flares[108]. The energy spectrum of some major components of Cosmic Rays is shown in fig.1.1.

The integral intensity decreases by a factor of 50 to 100 for each decade increase in energy. Studies of such vastly different fluxes at different energies require a wide range of experimental techniques. Direct measurements using satellite and balloon exposures currently exists only up to energies of \(10^{14}\) eV. Indirect measurements, with large area detectors are required for
investigating the low fluxes at higher energies. These include studies of Extensive Air Showers (EAS) and underground muons.

The intensity of primary nucleon in the energy range form several GeV to somewhat beyond 100 TeV is given approximately by,

\[ I_N(E) \equiv 1.8 E^{-\gamma} \text{nucleons cm}^{-2} \text{s}^{-1} \text{Sr}^{-1} \text{GeV}^{-1} \] \[46\]

Where \( E \) is the energy per nucleon (including the rest mass energy) and \( \gamma \) is the differential spectral index of the cosmic ray flux. About 79% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei. At low energies below \( 10^{14} \text{eV} \), where the flux is large enough to have been measured for individual particle type, it is observed that each nuclear species obeys a power law spectrum of the type \( dN/dE = KE^{-\gamma} \).

Figure 1.2 shows the low energy differential type for some dominant source nuclei Protons, Helium, Carbon and Iron. Except for the energy range \( 10^5 - 10^8 \text{ MeV per nucleon} \), where the fluxes are modulated by Solar magnetosphere, a single spectral index \( \gamma = 2.7 \) is valid for protons \[29,103\]. The spectrum of heavy nuclei in the same energy range is flatter and has the exponent close to \( \gamma = 2.5 - 2.6 \). In the low energy region \( E < 10^5 \text{ MeV/nucleon} \), spectra of both protons and heavier nuclei flatten. Cosmic Rays at energies \( E \approx 10^8 \text{ MeV per nucleus} \) contains considerably more heavy nuclei than at low energy (about several MeV/nucleon).

If the flatter index \( \gamma = 2.5 \) observed for iron were to continue indefinitely to higher energies, then iron nuclei would dominate the Cosmic Ray flux above the energy \( 10^{15} \text{eV} \). But the results from the JACEE experiment \[28\] involving a complex balloon borne detector have indicated no iron enhancement up to at least \( 5 \times 10^{13} \text{eV} \).

As discussed above, low energy Cosmic ray consist of mainly protons and light nuclei. Measurement taken in high altitude balloon, the JACEE Experiment shows that as Cosmic Ray energy increases the proportion of heavier nuclei also increases. This suggests that as the energy reaches the “knee” of the spectrum, around \( 10^{15} \text{eV} \), heavy nuclei becomes the dominant component. It is very difficult, however, for a satellite or balloon experiment like JACEE to study particles at these high energies. This is because the flux of the particles at these energies is very low, and the detector area that can be carried aboard a satellite is so small. A better alternative is to use a ground based detector to sample the energies from extensive air showers and infer the particle energies indirectly. The situation is complicated because there is a lot of
Fig. 1.1 Integral all particles energy spectrum of the major components of high energy Cosmic Rays (the mass composition is uncertain in the shaded region.)
Fig.(1.2) Low energy differential Energy Spectra.
fluctuation in the way a shower develops, but in general, a heavy nucleus will start to shower higher up in the atmosphere than a light nucleus.

Except for proton and helium, spectral measurement for high energy Cosmic Ray flux have not been made for individual species above a few hundred GeV/nucleon. Moreover, because of statistical limitations the all particle spectrum is generally given in integral form. Two obvious features in the all particle spectrum shown in fig.1.1, are steepening (knee) around $3 \times 10^{15}$ eV and flattening (ankle) around $10^{19}$ eV. The spectral change observed around $10^{15}$ eV can be explained either by change in the primary chemical composition or by change in the nuclear interaction characteristics, leading to a new physics. The steepening of the energy spectrum at the position of the “knee” has been most widely interpreted as probably reflecting an increased rate of leakage of high rigidity particles from the Galaxy. Alternatively the knee is produced in the source region due either to threshold for breakup of heavy nuclei or a threshold for photodisintegration. In all the models, a change of composition is expected at around the knee.

1.4 CASCADE DEVELOPMENT IN THE ATMOSPHERE.

Primary particles of energy $\geq 10^{13}$ eV, impinging at the top of the atmosphere are $\approx 92\%$ protons, $\approx 6\%$ alpha particles, and heavy nuclei and less than 1\% of electrons and gamma rays. These particles reaching the earth’s atmosphere, undergo a series of interactions, leading to the generation of a downward moving shower of particles. Atmospheric density with altitude essentially follows an exponential distribution and the mean free path for the Cosmic Ray protons and gamma ray photons are $80 \text{gm}.\text{cm}^{-2}$ and $\approx 38 \text{gm}.\text{cm}^{-2}$ respectively. During the collision, the primary particles lose about 50\% of their energy to a large number of secondary particles produced, which are mainly pions, kaons, nucleons and anti nucleon pairs and may be some exotic particles. The first interaction of the particles takes place rather deep in the atmosphere (typically at the altitude $<30$ km.). A gamma ray initiated pure electromagnetic cascade has different characteristics compared to those of proton initiated showers, with the later involving both electromagnetic and hadronic interactions. In both the cases, interactions give rise to a laterally extended showers of relativistic electrons and positrons ($e^\pm$), called the “shower cascade”. Gamma ray initiated showers would have predominately pair-production ($e^\pm$) process as the first interaction. The resulting ($e^\pm$) produces secondary gamma rays through
Fig.1.3: The EAS Development with primary energy $\sim 10^{12}$eV or above.
bremsstrahlung interaction, these photons become the seed particles for another generation of electron positron pairs, and so, eventually leading to the production of a fully developed showers of electron positron pairs and lower energy gamma rays, all traveling earthwards with ultra relativistic velocities. On the contrary, in the case of a cosmic ray proton, the first interaction is generally a nuclear interaction wherein a number of pions ($^0\pi$, $^+\pi$, $^-\pi$), kaons and other hadrons are produced, in addition to the e-m component, initiated by $^0\pi$ decay gamma rays. These showers are relatively richer in the muon component (decay product of charged pions ), where as a purely electromagnetic shower ( initiated by a gamma ray photons ) is more or less exclusively made of electromagnetic components ( $e^\pm$, gamma rays). Figure 1.3 shows the EAS development with primary particle energy $\sim 10^{12}$ eV or above and gives schematic representation of photons and nuclear cascade respectively while in their development phase in the earth’s atmosphere. All the particles being of high energy move with velocities close to the velocity of light and hence the whole shower moves down the atmosphere as a disk of few meter thickness. The charged secondaries $^\pm$ and $K^\pm$ mesons having relativistic energy and mean life time ($\sim 10^{-8}$ sec) participating in the chain of nuclear interactions form the nuclear active component. On the other hand neutral pions($^0\pi$) and kaons ($K^0$) have very small life time ( $\sim 10^{-15}$ sec and $10^{-10}$ sec respectively ) and they decay as,

$$^0\pi \rightarrow \nu_\mu + \pi^\pm$$

$$K^0 \rightarrow \mu^+ + \nu_\mu$$

The muons are highly penetrating particles because of their long life time($\sim 2 \times 10^{-6}$ sec) and small interaction cross-section. Only few of them decay into,

$$^+ e^+ + e^- + \bar{\nu}_\mu$$

$$^- e^- + \bar{\nu}_e$$

The particles in a shower can be divided into three components, viz., (a) the electromagnetic or simply the electron component, consisting of electron-positron and gamma rays (b) the hadronic or nuclear active particle(NAP) component , consisting of all the strongly interacting particles i.e. hadrons and (c) the muon component consisting of $^\pm$ arising from meson decays.

1.4.1 ELECTROMAGNETIC COMPONENTS:
(a) Electromagnetic cascade:

Neutral pions produced in hadron-hadron collisions decays immediately into two high energy gamma photons almost in no time (\( \sim 0.83 \times 10^{-16} \) Sec.)

\[ \Pi^0 \rightarrow \gamma + \gamma \]

The electromagnetic cascade is the result of a series of electromagnetic interactions of electrons and photons with the atmospheric nuclei. These increasing number of electrons and photons develop, as they travel down the atmosphere through a process called PHOTON-ELECTRON cascade.

Photons interact with matter through the following three processes.

(i) **Photoelectric Effect**.

(ii) **Compton Effect**.

(iii) **Pair Production**.

Photoelectric is the process by which a photon losses its energy completely sending parts of its energy in liberating an electron from the atom and the rest is given to the liberated electron as kinetic energy. This process is important only at very low energies.

The Compton effect is the process by which the photon interacts with a free electron or at energies high enough for the orbital electrons to be considered free. In this process photon transfers part of its energy and momentum to the free electrons immediately at rest and emerges with reduced energy. i.e. in Compton process \( \gamma \rightarrow \gamma + e^- \)

Pair production is the process by which a photon interacts with the Coulomb field of the nucleus. In this interaction, the photon disappears and an electron-positron pair is created. The progression of secondary particles by gamma and proton initiated showers is shown in the figure 1.4(a) & (b) This process can occur only at energies higher than the sum of the rest masses of electron and positron (\( \sim 1.02 \) MeV), The positron annihilates producing more gamma photons. \( e^+ + e^- \rightarrow \gamma + \gamma \).

Again electrons interact with matter through the following process,

(a) Ionization and

(b) Bremsstrahlung.

The energy lost by an electron or a positron due to ionization in a medium produces more electrons. On the other hand, electron produce more gamma photons by Bremsstrahlung. In this process a high energy electron emits a photons when it interacts with the electromagnetic field of
the nucleus in the medium. i.e.

\[ e^+ + e^- \]

These processes are repeated producing electron-photon cascade and the overlap of the individual electron photon cascades of all the gamma rays produced above a particular level of observation constitute the electromagnetic component at that level. The electrons here include both the electrons and positrons.

A fraction of the charged pions on the other hand decays into muons and neutrinos as,

\[ + + + \]
\[ - - + \bar{\nu}_\mu \]

some of these muons decay by giving electrons, positrons while others reach the ground level.

\[ + e^+ + e^- + \bar{\nu}_\mu \]
\[ + e^- + \bar{\nu}_e + \]

Muons are also produced as a result of decaying of W and Z bosons.

\[ W^\pm \rightarrow \pm + \]
\[ Z^0 \rightarrow + + - \]

A part of the charged pions collide with air nuclei giving rise to secondary showers. The process of electron-photon multiplication continues down the atmosphere till they reach the maximum after which absorption takes place.

**1.4.2: MUON COMPONENT:**

The muon component arises from the decay of pions and kaons. They may result from the decay of charged particles through direct production process or from the decay of W and Z bosons. This component constitute about 10% of the total number of particles in the shower. Muons are nearly stable and have a small cross section for interaction, they penetrate about 12-14 km through underground. Hence, muons are called the “penetrating component” of the Cosmic Rays. As they are charged particles they are relatively easy to detect and reach the observation level straight from the point of their production. Only a few of them decay into electrons( or positrons) and neutrons during flight. High energy muons and also low energy muons at large distances from the core are produced at very high altitudes and hence carry
Fig. 1.4 (a) & (b): Propagation of secondary particles by gamma and proton initiated showers.
important information about highest energy interactions in the cascade as well as the nature of the primary particle. They also carry genetic information from various stages of longitudinal development of Extensive Air showers. The average production height of the muons in a given shower increase with the energy of the muons Therefore, by choosing the higher energy muons one can probe that region of the longitudinal development of the shower where interactions of energy higher than available at accelerators, take place. Moreover, the total number of muons in a shower depends upon the energy per nucleon of the initiating primary rather than its total energy.[1]

The density of the muons around the core depends on their energy. The higher the muons energy, the steeper the distribution. Based on some early investigation, Greisen [57] suggested a function to describe the lateral distribution or spread of muons of energy > 1 GeV at sea level[94],

\[
\rho_\mu(N_e, r) = 18 \left( \frac{N_e}{10^5} \right)^{\frac{3}{4}} r^{\frac{3}{4}} \left( 1 + \frac{r}{320} \right)^{-2.5} \text{m}^{-2} \quad \text{(1.1)}
\]

Where \( \rho_\mu(N_e, r) \) is the density of muons of energy > 1 GeV at a core distance \( r \) in showers of size \( N_e \). At energies ( \( E \geq 220 \text{ GeV} \) ) an exponential distribution function is found to represent the average lateral distribution of muons rather well[95] and this function can be expressed as,

\[
\Delta_\mu(R_\mu) = \frac{N_\mu}{2 \pi R_0^2} e^{\frac{-r_\mu}{R_0}} \text{m}^{-2} \quad \text{(1.2)}
\]

\( \Delta_\mu(R_\mu) \) is the density of muons at a distance \( R_\mu \) (in meters) from the shower core, \( N_\mu \) is the total number of muons in the shower and \( R_0 \) is a constant for a given altitude and threshold energy of muons. Capdevielle et al [30] propose that, primary energy can be estimated from the electron abundance by a simple formula,

\[
E_0 = \left[ a \ln \left( \frac{N_\mu}{N_e} \right) + b \right] N_e \quad \text{(1.3)}
\]

Where \( a = 0.404 , b = 3.932 \) for \( \frac{N_\mu}{N_e} < 0.666\% \)

\( a = 1.534 , b = 9.6 \) , for \( \frac{N_\mu}{N_e} \geq 0.666\% \)
The density of muons at large distance from the core is small but the muons are relatively more numerous. In fact, at sea level while 50% of all the particles in a shower are found inside a circle of radius ~ 70m, 50% of the muons are in a circle of radius ~300m. Thus the muons number, $N_\mu$ is a good index of primary energy, which can be written as,

$$E_p = 10^6 \left( \frac{N_\mu}{2 \times 10^4} \right)^{1.1} eV \quad \text{(1.4)}$$

The energy spectrum of muons can be represented by a power law, as in the case of hadrons. Muons lose energy by ionization and by radioactive process, bremsstrahlung, direct production of $e^+e^-$ pairs and photo nuclear interactions [47]. It is flat at low energies because of increasing loses due to ionization and decay with decreasing muon energy, and becomes steeper at higher energies. The relation between the number of muons of energy $> E_\mu$ and the shower size can be expressed as,

$$N_\mu (E_\mu) \propto N_e^{\alpha_\mu(E_\mu)} \quad \text{(1.5)}$$

The value of $\alpha_\mu$ is 0.8-0.9 at $E_\mu \sim 200$ GeV. This feature makes the muon component sensitive to the primary mass number. In the interaction mean free path, the number of muons at energy $> E_\mu$ in a shower given by,

$$N_\mu (A) \propto A \left( \frac{N_e}{A} \right)^{\alpha_\mu} \propto A^{1-\alpha_\mu} \quad \text{(1.6)}$$

Thus showers generated by heavy primaries have larger number of muons. The higher the energy of the muons, the more sensitive they are to primary mass number.

### 1.4.3: HADRON COMPONENT:

The hadron component which is also called the Nuclear Active Particle (NAP) components includes nucleons, anti-nucleons, charged pions and kaons. This is the least abundant component of the shower constitutes about 1% of the EAS population, but carry
substantial amount of energy of the primary particle and forms the backbone of the shower. Due to the confinement of the hadron components within 10 to 20 meters from the shower core, it is very difficult to study this component both at near the core as well as at further away from the core. At near the core, interference from the EM component is very large, while at far distance from the core, the density of hadrons is very small because of steep lateral distribution and small total number. Thus, a mountain altitude is more favourable site for the study of HE hadrons.

A detailed study of hadron component associated with air showers of different sizes has been done by various experimental groups [105, 68, 82]. These observations show that the hadron energy spectrum has a power law form with an exponent varying between $-1.2$ & $-2.0$ and its lateral distribution has an exponential form which flattens as the shower size increases. The agreement between various experiments is poor and is attributed to different sensitivities, energy and spatial resolutions and errors in energy estimation. The number of HE hadrons above any fixed energy in a shower varies almost linearly with shower size. The charged / neutral ratio $\left(\frac{C}{N}\right)$ and the time structure of hadrons as well as nucleon-anti nucleon pair production process in high energy interactions are studied well. For the production of kaons and nucleon-anti nucleons pairs, the ratio of $\left(\frac{C}{N}\right)$ [94] can be expressed as,

$$\frac{C}{N} = \frac{n_{s^+} + n_{K^+} + 0.5 n_{N\bar{N}} + 0.5}{0.5 n_{N\bar{N}} + n_{K^+\bar{K}^+} + 0.5} \quad \text{(1.7)}$$

The $\left(\frac{C}{N}\right)$ ratio for pions, kaons and nucleons is $\propto 1.5$ (since $k_s$'s are short lived and not many of them survive) and 1 respectively. By comparing the total number of hadrons and $\left(\frac{C}{N}\right)$ ratio with Monte Carlo simulations, the production cross-sections of different types of particles can be obtained.

1.5: LATERAL AND LONGITUDINAL DEVELOPMENT OF CHARGED PARTICLES:

Initially EAS was attributed to the arrival of a HE electron or photon on the top of the atmosphere and it was not until a more detailed study of its longitudinal and lateral development was made that the nucleonic origin of the EAS established. Because of the multiple Coulomb scattering the shower particles spread laterally to hundreds of meters. The density of the shower
particles at any level of observation is maximum at the core (the central axis) of the shower and it falls off rapidly with the distance from the shower axis. As the shower propagates down the atmosphere, the hadron and the electromagnetic components increases in size, reach a maximum and then decrease while the muon component does not suffer significant attenuation after reaching maximum because muons lose energy only by ionization and a small fraction of them are lost by decay. This complex nuclear Electromagnetic cascade is called Extensive Air Showers (EAS). An age parameter, s, is defined such that s = 1 at the shower maximum. Value of s < 1 corresponds to young showers, i.e. the shower which has not reached its maximum development, and s > 1 corresponds to old shower [108].

The e.m component is the most abundant component in air shower. The total number of charged particles in a shower is called the shower size (N) of that particular shower.

As the shower develops, it also spreads laterally, i.e. perpendicular to the direction of the incident primary particles, due to the multiple Coulomb scattering. The mean square scattering angle, due to multiple Coulomb scattering of an electron of energy E in traversing a small thickness “t” of the matter given by,[94]

\[ < \theta^2 > = (E_\gamma/E)^2 \frac{t}{(1.8)} \]

Where “t” is measured in radiation lengths and \( E_\gamma = m_e c^2 \left( \frac{4}{s} \right)^{1/2} = 21.2 \) MeV.

The longitudinal and lateral development of electron photon cascade initiated by photon and electron has been studied out by different authors [16, 99]. Numerical results obtained by Kamata and Nishimura [67] can be well approximated by a function, known as Nishimura-Kamata-Greisen (NKG) function, as suggested by Greisen [56],

\[ \Delta(N_e, s, r) = \frac{N_e}{2\pi r_0^2} \frac{\Gamma(4.5)}{\Gamma(s) \Gamma(4.5 - 2s)} \left( \frac{r}{r_0} \right)^{(s-2)} \left( 1 + \frac{r}{r_0} \right)^{(s-4.5)} \]

Where \( \Delta(N_e, r) \) gives the density of the particles per meter square at a distance r in a plane perpendicular to the shower axis in a shower with total number of particles (shower size) \( N_e \), is the gamma function, s is the age parameter and \( r_0 = \frac{E_s X_s}{\epsilon_0} \) is the Moliere unit of length or “scattering length” and ‘ ‘ is the density of air at the observation level. Later, it has been shown that the NKG function does not give a good fit to the lateral distribution of electrons in the shower [6, 38, 49, 61].

For a photon initiated shower observed at a depth “t” (radiation length) from the point of
origin, ‘s’ shower age is given by,

\[ S = \frac{3t}{t + 2 \ln \left( \frac{E_p}{E_0} \right)} \]  \hspace{1cm} (1.10)

Here, \( E_p \) is the primary energy, \( E_0 \) is the critical energy for electrons in air which is equal to 84 MeV. It is found that ‘s’ is not constant across the lateral structure of the shower but decreases with the distance from the shower axis. The possible errors introduced in the estimation of shower size and age parameter due to use of NKG function in fitting the lateral distribution is discussed in detailed by Capdevielle and Gawin [30].

By sampling the density of the shower at various points and fitting the above lateral distribution function to these densities, \( N \), \( s \) and co-ordinates of the shower core \( (r) \) i.e.( \( x_0, y_0 \)) are usually determined. The total size \( N \) is a measure of the total energy of the primary particles. The relation between the average shower size and the primary energy can be expressed as [1]

\[ N \sim E_0^\beta \]  \hspace{1cm} (1.11)

Where \( E_0 \) is the primary energy and \( \beta \) is a constant. Thus the shower size spectrum represents the primary energy spectrum. Fluctuation in development from shower to shower is large, even for shower of the same energy and primary mass. Thus the shower size \( N_c \) and the primary energy \( E_0 \) are only related in an average sense, and even this relation depends on depth in the atmosphere. One estimate of the relation [83], for the vertical shower with \( 10^{14} < E < 10^{17} \text{eV} \) at 920 gm cm\(^{-2} \) (965m above s.l.)

\[ E_0 \sim 3.9 \times 10^6 \text{GeV} \left( \frac{N_c}{10^6} \right)^{0.9} \]  \hspace{1cm} (1.12)

The lateral distribution function (LDF) for shower initiated by 100GeV gamma photons proposed by Hillas and Lapikens is in the form,

\[ f_{HL} = C(S) \left[ \frac{r}{0.25r_0} \right]^{a_1 + a_2(x-1)} \left[ 1 + \frac{r}{0.25r_0} \right]^{-b_1 + b_2(x-1)} \]  \hspace{1cm} (1.13)

where \( a_1 = -0.76, a_2 = 1.3, b_1 = -3.23, b_2 = 0 \) and Moliere unit was reduced by a factor 0.25 of the usual 80m at sea level. Capdevielle et al in the year of 1983 [31] proposed a formula for radial electron density distribution.
Fig.: 1.5: Lateral distribution of EAS electrons as suggested by various theories.
\[
\Delta_e(r) = C(S) \frac{N}{m^2 r_0^2} \left( \frac{r}{m r_0} \right)^{s-2} \left( \frac{r}{m r_0} + 1 \right)^{t-4} \left( 1 + d \frac{r}{m r_0} \right)^{2.7-s}
\]

where \( d = 0.026 \) and \( m = 0.5 \)

\[
C(S) = 0.3265 \exp \left[ -0.5 \left( \frac{s - 1.125}{0.499} \right)^2 \right] \text{ for } s \leq 1.4
\]

\[
C(S) = 0.2854 S^2 - 1.385 S + 1.66 \text{ for } S > 1.4
\]

The equation (1.14) can be written in the form,

\[
\Delta_{cap}(r) = \frac{N}{m^2 r_0^2} f_{cap} \left( \frac{r}{m r_0} \right)
\]

This equation is a good approximation for lateral distribution function of electrons. Luorui et al in 1993 [79] reported a simple exponential function with the factor \((r+1)\) instead of \( r \) in the denominator to avoid the divergence at \( r=0 \), for the determination of density of shower particles as,

\[
\rho = \frac{N \exp \left( -\frac{r}{r_0} \right)}{2\pi r_0(r+1)}
\]

1.6: ELECTROMAGNETIC RADIATION FROM EAS:

Electromagnetic Radiation in the form of Čerenkov radiation, Fluorescent radiation and Radio emission are emitted when the shower front of relativistic charged particles pass through the atmosphere.

1.6.1: Optical emission (Čerenkov Radiation) from EAS:

Ultra relativistic charged particles like shower electrons and muons, while traveling in the downward direction in the atmosphere produce a Čerenkov light flash in the
Fig.: 1.6: Čerenkov light as function of longitudinal development and emission of this light at three different atmospheric heights.

Fig.: 1.7.: The resultant photon density at ground level as a function of core distance.
(a) For single particle and (b) For EAS.
atmosphere [Fig.1.6]. In general, Čerenkov radiation is produced in the ultra violet and visible region with \( \sim 2^2 \) wavelength dependence, when such a particle traverses a dielectric medium (refractive index = \( n \)) with a velocity greater than that of light in that medium (\( c/n \)). This radiation has been given the name Čerenkov radiation having been discovered by the Russian Scientist P.A. Čerenkov in the year of 1934. This Čerenkov light is emitted at an angle \( \theta_c \) with respect to the direction of motion of the particle. These Čerenkov photons, mostly in the visible region, reached the observation level with very little absorption in a clear sky and linearly polarized light are spread out over a large area. Galbraith and Jelly in 1953 [49] first recorded experimentally the Čerenkov light flash correlated with EAS [Fig.1.7].

A conical wave front of Čerenkov radiation is emitted by the medium with a specific cone semi-angle \( \theta_c \) with respect to particle track. The angle of emission of Čerenkov light is given by,

\[
\theta_c = \cos^{-1} \left( \frac{1}{\beta n} \right) \tag{1.17}
\]

where \( \beta = \frac{v}{c} \), \( v \) being the particle velocity. The particles above \( \frac{1}{n} \) only can emit Čerenkov light. The conditions for emission of Čerenkov radiation can be explained by means of Huygens’ construction shown in fig 1.8. Spherical wavelets spread out at a speed of \( u = c/n \) from the centers of disturbances created by the particle along its path, where, \( c \) is the velocity of light in vacuum and \( \cdot n \) is the refractive index of the medium. The particle moving with a velocity \( v \) will cover a distance \( AB = vt \) in time ‘t’ second. By this time EM radiation, which is emitted from the point A will spread out into a spherical envelop of radius \( AC = ut = \frac{ct}{n} \)

Constructive interference of the wavelets from the successive points of disturbances will form a co-axial wave-front along the tangent BC. From the above figure we can write,

\[
\cos = \frac{AC}{AB} = \frac{1}{\beta n} \text{ where } \beta = \frac{v}{c}
\]

Since \( \cos \leq 1 \) \( \therefore \frac{1}{\beta n} \leq 1 \text{ or } n \geq 1 \Rightarrow v \geq u \)

Since the phase velocity of electromagnetic radiation in a medium of refractive index ‘\( n \)’, \( v = c/n \) is always less than the velocity of light in vacuum (\( c \)). Therefore, \( \cdot \)}
'n' must always be greater than 1. But, for highly relativistic particles \( n \approx 1 \) and the angle of emission is maximum given by \( \theta_{\text{max}} = \cos^{-1}\left(\frac{1}{n}\right) \). The value of 'n' is 1.000292 for air at sea level at N.T.P. and \( \theta_{\text{max}} = 1.3^\circ \). Since the refractive index in air is close to 1, it is convenient to write \( n = n + 1 \). The refractive index variation with atmospheric depth and temperature in air can be written as [62],

\[
\eta = 0.000292 \left( \frac{x}{1030} \right) \left( \frac{273.2}{T} \right) \]

\[\text{(1.18)}\]

Where \( T = 204 + 0.091x \) is the temperature at depth 'x' (gcm\(^2\)) in K. In this approximation, \( \theta_{\text{max}} = (2\eta)^{1/2} \) rad, with these values the threshold energy for electrons at sea level is 21 MeV. The number of Čerenkov photons between wave lengths \( \lambda_1 \) and \( \lambda_2 \) per cm of path length \( \frac{dN}{dl} \), emitted by a particle in air is given by,

\[
\frac{dN}{dl} = 2\pi\alpha \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \sin^2 \theta \]

\[\text{(1.19)}\]

where \( \alpha = \frac{1}{137} \) is the fine structure constant. For highly relativistic particles the above formula
can be written with the approximation \( \sin \approx \) as,
\[
\frac{dN}{dl} = 4\pi \alpha \eta \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right).
\]

The number of photons emitted per cm of air at sea level between wavelengths 3500Å and 5000Å is 0.23, which corresponds to 230 per gm.cm\(^{-2}\). Most of the electrons in an EAS are relativistic and therefore emit Čerenkov radiation. Because of the weak absorption of light in the atmosphere, most of it reaches the observation level. The number of Čerenkov photons in the shower is therefore proportional to the track length integral above the observation level and is a good measure of primary energy. Fluctuation in the amount of light for showers of a given primary are much less than those in shower size, thus making it a more accurate primary estimator. The Čerenkov burst, at ground level, lasts typically for about \( \sim 5-10 \) nS for these cascade [18]. On the other hand this radiation occurs only in a dielectric medium having refractive index greater than one and the velocity of this charged particles are greater than the phase velocity of light in that medium. Due to the relativistic speed of the cosmic ray particles, they have good contribution in the production of Čerenkov radiation in the atmosphere. But, due to the low flux of primary cosmic rays, the contributed amount of Čerenkov radiation is not satisfactory for its detection by normal photometric method, being very low \( \sim 10^{-4}\) of the total night sky light. The charged particles from EAS reach the ground level with relativistic velocities. Thus total contribution from all the secondary charged particles is detectable as a large momentary pulse of light. In this production of Čerenkov radiation electron takes major part but other components of EAS are less effective for this occurrence. This intensity of Čerenkov light at ground level due to relativistic charged particles can be calculated by using the following formula,
\[
\frac{dW}{dl} = 8\pi^2 \varepsilon^2 \eta \int \frac{d\lambda}{\lambda^3} \tag{1.20}
\]

where \( \eta = n - 1 = 0.00029 \), \( Z \) is atomic number. For a single charged particle the amount of radiation in the region \( \lambda = 4000\text{Å} \) to \( 7000\text{Å} \) is
\[
\frac{dW}{dl} = 3.8 \times 10^{-4} \eta \text{erg.cm}^{-1} \approx 0.7 \text{eV.cm}^{-1}
\]
Again \( \eta \) is proportional to density of air and varies approximately with height above ground level, \( \eta = 2.9 \times 10^{-4} e^{-h'/r} \), where \( r = 2.1 \) km is the relaxation length for the pressure variation in the atmosphere and \( h' \) is in km ( a.s.l.). Thus the emission also falls off with depth of the
atmosphere as, \( \frac{dW}{dt} = 1.1 \times 10^{-12} e^{-\frac{h}{1.7} \text{erg.cm}^{-1}} = 0.7e^{-\frac{h}{1.7} \text{eV.cm}^{-1}} \).

An important feature of Čerenkov light, in contrast with other EAS components, is that it carries vital information about the longitudinal development of the shower. Calculations show that the lateral distribution as well as the temporal structure of Čerenkov pulse at large distances from the core depend on the position of the shower maximum. This dependence is independent of the model of nuclear interactions and primary mass\[96\]. Čerenkov lateral distribution can be approximated as, \[93\]

\[
\Phi(r) \propto (r + a)^{-\delta}
\]

Where \( \delta = b + cX_m \), \( X_m \) is the depth of shower maxima in gm/cm\(^2\) and \( a, b, c \) are constants.

### 1.6.2: Radio Emission from Extensive Air Showers:

The large (giant) Cosmic Ray Air Showers can generate detectable pulses of electromagnetic radiation at radio frequencies. This was first established experimentally by Jelley and his collaboration at Harwell in 1965\[64\]. Although Blackett and Lovell in 1940 \[23\] first predicted about the possible transfer of energy in to the radio frequency spectrum from the shower particles from EAS. Several other research groups also observed radio pulses \[7, 11, 27\].

Theoretical explanation of the production of radio pulses was first given by Askaryan\[10\]. According to him normal Čerenkov radiation from individual shower particles was enhanced due to the phase coherence at lower radio frequencies. Theoretical treatments \[66\] by various groups, suggest that the principal mechanism should be the lateral or transverse motion of shower particles by the earth’s magnetic fields. The polarization to be expected from this geomagnetic mechanism is perpendicular both to the shower axis and to the magnetic field lines. As the shower passes through the earth’s atmosphere, the positive and negative charges (mainly positrons and electrons) in the shower front are separated mainly due to geomagnetic deflections which creates an electric dipole and finally gives radio pulses.

However, the upper cutoff frequency of 75MHz which should exist as predicted by charge excess mechanism is contradicted by detection of radio pulses at much higher frequencies by various workers. Further, experiments on East-West and North-South polarization of the electric field also put weight towards dominance of geomagnetic mechanism of radio pulses.
Dutta and Pathak [41] have drawn conclusion that, the geomagnetic mechanism is the main source of radio emission in the high frequency region (> 80 MHz) but transition radiation mechanism may be expected as a possible source for low and very low frequency region. In case of shower, when the excess negative charge hits the ground, the phenomenon of transition radiation occurs. A shower of $10^{20}$eV may produce $10^{10}$ charged particles, each a source of an electric field, and there is the possibility that the overall charge distribution may give rise to a significant emission of radio frequency energy. Recently Dova et al [40] applied Monte Carlo technique to study the limitations of the various existing models on radio emission from air showers. They discussed the possibility of its applications as a new window on EAS measurements giving statistically independent information on primary mass composition.

Radio emission from EAS has been studied by various groups with the hope that it will shed light on the longitudinal development of the shower and the primary composition as well. The depths of the shower maxima were found to be correlated with the lateral distribution of radio emission. Radio frequency spectrum and lateral distribution of field strengths have been studied in showers initiated by primaries of energy $>10^{16}$eV. However, this radio method of detection must take into consideration the emission of radio wave from geo-magnetic field particularly during thunderstorms [8,9]. Reliable data can be collected only during fair weather condition and electrically undisturbed periods. Hence the contribution from the component of EAS in understanding the primary composition is meagre.

1.6.3: Fluorescent Light:

High energetic charged particles passing through the atmosphere, ionize and excite the air molecules. The excited nitrogen molecules emit fluorescent light. Most of the fluorescent light comes from 2P band system of molecular nitrogen(~ 80%) and 1N band system of the $N_{2}^+$ molecular ion(~20%). The emitted radiation is highly isotropic, it can be detected at large distances from the axis and thus can be distinguished from the Čerenkov light which is emitted in the forward direction and therefore confined mostly to small distances. The fluorescent light yield is inversely proportional and the ionization loss per unit path length is directly proportional to the atmospheric density and so the light yield per unit path length( in meters) is nearly constant, independent of altitude. For primary energy above $10^{18}$ eV, the possibility of detection of EAS by means of nitrogen fluorescent light is very promising[58]. The longitudinal
development of the EAS and the primary energy spectrum could be studied with greater detail, through the observation involving the detection of optical fluorescent photons in the atmosphere and is restricted to only 5-10% of the time. Fly’s Eye experiments of Utah, USA [33] recorded the atmospheric scintillation light associated with giant EAS. Hi Res.- the High Resolution Fly’s Eye Cosmic Ray detector is composed of optical fluorescent telescopes built in two different sites in the Utah desert to be used as a stereo fluorescent detector. In India, atmospheric fluorescent light from large air shower was detected at Gulmarg using a simple system[17]. Auger Project fluorescent Group, OWL-Air Watch (Orbiting wide angle Light collectors) and Telescope Array (for Čerenkov and fluorescent light) are world projects detecting fluorescent light from giant air showers.

1.7: ULTRA HIGH ENERGY (UHE) COSMIC RAYS:

The cosmic rays of energy above $10^{17}$eV are referred to as Ultra High Energy (UHE) Cosmic Rays. Systematic investigations of Cosmic Rays at Ultra High energies started in the late fifties and early sixties after the construction of large facilities for measuring EAS at Volcano Ranch (USA) and the Moscow (Moscow State University). Since the flux of Cosmic Rays falls rapidly as the cosmic ray energy increases. At about $\sim 10^{9}$eV, the particle rate is about 10,000 per square meter per second. At $10^{12}$eV the rate is only 1(one) particle per square meter per second. The rate starts to decrease even more rapidly around $3 \times 10^{15}$eV (this so called “knee” of the cosmic ray spectrum). At these energies, there are only a few particles per square meter per year. The highest energy particles, above $10^{19}$eV, arrive only at a rate of about one particle per square kilometer per year. There is also an “ankle” in the spectrum around $10^{19}$eV, where the rate is found to be some what higher than expected. The cosmic ray particles with energy window $10^{17}-10^{18}$eV are found to have a steep energy spectrum. By modernization of the equipment at Volcano Ranch and building of large stations at Chacaltaya mountain in Bolivia and Tokyo, near Sydney (Australia), and specially at Haverah Park (England) and in Yakutsk (USSR) made it possible to obtain detailed information on the spectrum of the cosmic rays of Ultra High Energy ($E \geq 10^{17}$eV) and their anisotropy[2, 39, 71, 34].

In the sixties it becomes generally accepted that particles with $E \geq 10^{17}$eV are of extragalactic origin, in view of the difficulty to confine particles of such energies by the galactic magnetic fields. for a prton with an energy of $10^{17}$eV the radius of curvature in a typical
magnetic field of H \sim 3 \text{G} \text{ is } r_H=10^{20} \text{cm} \sim 30 \text{pc}[52].

Primary Cosmic Ray protons of energy above $5 \times 10^{19} \text{eV}$ interact with the microwave cosmic ray background radiation causing an abrupt degradation of the spectrum, a phenomenon known as the Greisen-Zatspin-Kuz'min (GZK) cut off [55,111]. It was predicted that part of the spectrum for $E \geq 3 \times 10^{18} \text{eV}$ would be flat as a result of the interaction. Cosmic rays with the microwave background electromagnetic radiation. In the galactic model the flat part of the spectrum is explained by the particles propagating almost along straight lines with the galactic magnetic field. It is pointed out that this necessarily leads to an anisotropy connected with the distribution of the sources in the disc.

However, several cosmic ray events with primary energy $>10^{20} \text{eV}$ have been observed by Giant EAS Arrays like High Resolution Fly’s Eye (HiRes.) of USA, Akeno Giant Air Shower Array (AGASA), Japan and Yakutsk array of Russia. The energy spectrum has the form $kE^{-\gamma}$ with the index $\gamma = 3.0$ of the differential spectrum as shown in the figure 1.10 obtained by the experiments operating at these experiments [88]. Yakutsk reported a power index of $3.03 \pm 0.04$ between $10^{17.5} \text{eV}$ and $10^{18.1} \text{eV}$. Above $2 \times 10^{18} \text{eV}$ the energy spectrum steepness with $\sim 3.0$, before recovering a lower slope. Yakutsk reported a value of $\sim 2.78 \pm 0.2$ for $E > 10^{18.9}$. In the same energy range AGASA Group obtained $\sim 2.5 \pm 0.3$. This behaviour of the of the energy spectrum is expected at the transition from the galactic to an extra galactic dominance of the Cosmic ray origin. The data from the various experimental setups in the region above $5 \times 10^{19} \text{eV}$ are very contradictory.

1.7.1: Primary Mass Composition at UHE.

Shower experiments sample different features of the development of particle cascade produced by cosmic rays in the atmosphere. The shower particle swarm moves close to the speed of light and arrives at the observation level as a curved pancake of relativistic particles. The arrival time of individual shower particles is related with the distance from the shower axis and their number density at a particular core distance is related to the shower size (total number of shower particles). The maximum of the shower cascade can be determined by direct observation
of the longitudinal development of the cascade using either fluorescent light or Cerenkov radiation. Composition inference is indirect and involves detailed simulations which require a knowledge of physics of high energy particle interaction and characteristics of shower detectors.
The mass dependence can be inferred from the position of shower maximum in the atmosphere, or from the muon content of the shower. Muons once they are produced through decay of pions or kaons etc. do not interact and measuring their total number can provide an estimator of the mass $A$, because heavy nuclei interact higher up in the atmosphere where decay of unstable particles can be more important relative to their interactions.

The dependence of atomic mass is generally proportional to $\log A$, a quantity which varies between 0 for proton initiated showers and 4.2 for iron initiated shower. In a superposition model the dependence of position of shower max is related to energy and atomic mass as:

$$X_{\text{MAX}}^A = X_0 + X_1 \left( \log_{10}(E) - \log_{10}(A) \right)$$

a linear dependence of $X_{\text{max}}$ on $\log(E)$ with a different magnitude for $X_{\text{max}}$ for different atomic species of cosmic rays. Figure 1.9 is a compilation of most of the measurements of depth of shower maximum as a function of energy as compared with expectations from simulations for different primaries- gamma primaries, proton primaries and iron primaries.[51]

The figure shows that composition of cosmic rays is mixed and is changing with energy. It is possible that the mix of cosmic ray nuclei at highest energies becomes lighter and around 100 PeV, it is enriched in iron. The enrichment in the knee region is probably consistent with rigidity cutoff of cosmic rays produced and accelerated in supernova explosions. However, this conclusion is particle physics interaction model dependent. There are many other air shower experiments currently operating which measure the spectra of cosmic rays and their masses by ground based air shower experiments.

The following section gives brief report of major cosmic ray stations around the world.

1.8: MAJOR STATIONS ON COSMIC RAY STUDIES:

1.8.1: The AGASA Cosmic Ray Detector:

Akeno Giant Air Shower Array in Tokyo, Japan is a 100 km$^2$ world largest ground array of scintillation and muon detectors. It consist of 111( one hundred eleven) particle detectors, each detector occupies a small hut of 2.2m$^2$ in area with a separation of approximately 1km. 27 muon detectors of varying area, which are shielded proportional counter arrays and having a threshold of 0.5 GeV for muon detection form part of the array. The communication in two-way between detectors and the central station for data transmission is carried out through optical fiber cable.
1.8.2: The Fly’s Eye Detector:

The Fly’s eye Detectors, Fly’s Eye-I and Fly’s Eye-II, were set up by the University of Utah, USA group on the top of the little Granite Mountain, Dugway, Utah about 160 km from Salt Lake city (40°N, 113°W, atmospheric depth 860g-cm²). The separation between Fly’s Eye-I and Fly’s Eye-II is 3.3 km. Fly’s Eye-I is a cluster of 67 spherical mirror and Fly’s Eye-II has 36 spherical mirror units each mirror being 62 inch in diameter having 12 or 14 Photomultipliers packed hexagonally at the focus. It detects giant air showers by the optical fluorescent light. There are 880 ‘eye’in the Fly’s Eye-I, in the Fly’s Eye-II, there are 120’eye’ only. Fly’s eye-I started operating in 1981, Fly’s Eye-II became operational in 1986. The Fly’s Eye-II views half the night sky in the direction of Fly’s Eye-I.

High Resolution Fly’s Eye (Hi-Res.) is an improved version of the Fly’s Eye. It is under collaboration with University of Utah, University of Illinois and the University of Adelaide, Australia which is constructed in the same region of the Five Mile Hill. The resolution of Hi-Res is 1° while the resolution of Fly’s Eye is 5.5°. This is achieved by keeping a 6x16 array of hexagonal photomultiplier tubes in the image position of 3.8m² mirrors. There are in all 152 units oriented to over the entire night sky. The 152 units are distributed among three independent sites. By measuring how much light come from each stage of the air shower, one can infer not only energy of the cosmic ray particle, but also whether it is more likely a simple proton or a heavier nucleus.

1.8.3: The Yakutsk Array:

The Yakutsk array in USSR, uses scintillation counters, Čerenkov light detectors and muon detectors to simultaneously measure the lateral distribution function. The Yakutsk array began in the year of 1973. At that time 35 stations, taking part in the selection of events, occupied an area about 20km². The number of such stations are increased. Now a days 49 such stations are located in the circle of 2 km radius. In each of them there are 2 scintillation detectors(2m²). In the central circle of a radius equal to 250m more 9 such detectors are mounted at different points. In the very beginning the Yakutsk array had been created as a complex air shower detector. The Čerenkov light measurement from EAS with $E_p \geq 10^{17}$eV are provided only at Yakutsk array. As a light detector, one or more photomultiplier tubes( a
diameter of photocathode equal to 15 cm) are used. At present they are mounted at 19 stations in the circle of 1 km radius, 12 additional detectors are mounted at the very centre. Yakutsk array provides 5 underground points for measurement of the muon flux with threshold energy 1 GeV. The total area of scintillation detectors in each point is about 20 km$^2$. Furthermore, there is muon detectors of area 180 m$^2$ and muon threshold 0.5 GeV. Yakutsk recorded an air shower event with an energy of $(1.1 \pm 0.4) \times 10^{20}$ eV\cite{43}.

1.8.4: The Pierre Auger Project:

An international group of 100 physicists and engineers based at Fermi National Accelerator Laboratory 30 miles west of Chicago, has began to design the detector for the Pierre Auger Cosmic Ray Observatory to study the highest energy cosmic rays observed on earth. Named after the French physicist Pierre Auger, who in 1938 first detected the air showers produced by the high energy cosmic rays, this project is aiming at a high statistics study of cosmic rays with energies exceeding $10^{19}$ eV (around and above the so called GZK spectral cut off). The Pierre Auger Observatory (PAO) is a broadly based international effort to explain the upper end of the cosmic ray energy spectrum.

The cosmic ray of energy of the order of $10^{20}$ eV is quite rarer. The rate is extremely low. One expects approximately one cosmic ray arriving on an area of one km$^2$ per century. In order to collect a significant statistics, the Pierre Auger Observatory covers an area of 3000 km$^2$. The cosmic rays particles are measured by two independent detector systems. This hybrid detectors located at two sites in the North and South hemispheres (in US and Argentina). The reason for this two components to the detector is to be able to see the whole sky. The surface detector is a giant array of 1600 water Čerenkov tanks, placed over the area with 1.5 km spacing.

The fluorescent detector is a telescope system which reconstruct the cosmic ray shower from the fluorescent light emitted by the atmospheric nitrogen excited by the particles of the cosmic ray shower. The combination of two complementary detection technique-water Čerenkov tanks arrays over-looked by atmospheric fluorescent detectors.
Surface arrays measure the lateral distribution of particles in air showers when they strike the ground. Fluorescent detectors view the longitudinal development of showers as they move downward through the atmosphere. These two complimentary techniques form a uniquely
powerful instrument to study the nature of extreme energy cosmic rays. The southern hemisphere detector is especially interesting since very few detectors took data in the past in this part of the world from where the direction of the centre of our Galaxy is visible.

The detector is designed [24,102] to be fully efficient for showers with energies of $10^{\text{EeV}}$ and above. They will make the link with the part of the energy spectrum well explored by a few other detectors, especially AGASA, Fly’s Eye and Hi-Res.

The relative synchronization of the station has been done using signals emitted by GPS (Global Positioning System) satellites and the stations is powered with solar panels. A survey team spent more than a year to study and visit many proposed sites and finally the collaboration selected two of them. The southern site is in Malargue (Argentina) and the Northern site is in the state of Colorado in USA.

The Pierre Auger Observatory records more than 20 events with energy above $10^{20}\text{eV}$.

1.8.5: The Space Air Watch Mission:

A permanent earth-observing optical system on the international space station Alpha (ISSA) is proposed. The idea of a permanent ISSA optical observatory has evolved from the concept of studies of cosmic ray air shower observatory in space. The fluorescence due to Cosmic Rays of Extreme Energy (EECR) showering the atmosphere could be observed with a high power optical observatory having much wider field of view and an overwhelmingly abundant statistics ($N \geq 10,000$) [72]. In particular, the proposed space air watch method is capable of detecting and identifying giant Air showers from space and fluxes of protons, nuclei, gamma rays and neutrinos could be distinguished and measured. This optical system is proposed to be a permanent facility aboard of the ISSA for observing the Earth in optical and near optical wave lengths [73] from a single point of a Low-Earth orbit at altitudes between 400 and 1000 km.

Another proposed dual satellite mission is the OWL “Orbiting array of Wide-angle Light collectors, a pair of Earth ‘Eye’ to study Air Showers initiated by $> 10^{20}\text{eV}$ quanta,” proposed to NASA.

1.9: PRESENT WORK:

Present investigation consist of two parts: design and fabrication of electronic circuits for recording of particle and optical detector pulses using computer based data acquisition system,
and Monte Carlo Simulation of detected events for data analysis.

1.9.1. Experimental Studies:

(i) Recording of events:

A miniarray of eight plastic scintillation counters each consisting of 2 inch fast PMT (Type 9807) and 50x50x5 cm³ BICRON plastic scintillators, is operating at the roof top of Physics Department, Gauhati University [15]. In the present work, an optical channel consisting of 5 inch PMT (Type 9792KB) is placed at the centre of the miniarray [90]. Each optical pulse is used to trigger a Digital Storage Oscilloscope (DSO), one channel of which is fed with OR’ed pulses from the eight plastic detectors of the miniarray. Events are recorded as waveform in the DSO and data are transferred to the computer via General Purpose Interface Bus (GPIB). Details of the experimental setup is described in chapter III.

(ii) Detector Calibration:

The optical detector (5 inch PMT) is calibrated using secondary muons of known flux and water tank containing distilled water at the base of which the PMT is placed symmetrically with good optical contact. The output from preamplifier and amplifier connected by coaxial cable (RG 58U) is analysed using MCA. The resulting pulse height spectrum is compared with simulation results to draw the calibration curve. Details of calibration experiment is presented in chapter IV.

1.9.2: Monte Carlo Simulation of recorded events:

Čerenkov pulse height distribution has been simulated using Monte Carlo method for different primary mass composition models and results are compared with experimental data. The technique of simulation is presented in chapter V.

1.9.3: Data Analysis:

(i) Experimental pulse height distribution is compared with simulated pulse height spectrum deduced under four different primary mass composition models using $\chi^2$ analysis. Results give minimum $\chi^2$ value for pure proton composition.

(ii) Čerenkov lateral distribution is studied by grouping recorded data into a
number of shower size bins. Results show proton enhancement beyond $10^{17.7}$ eV.

The next chapter describes the motivation and theoretical estimation of experimental as well as simulation works.

CHAPTER – II
MOTIVATION AND THEORETICAL ESTIMATION:

2.1: MOTIVATION:

In the UHE, the primary mass composition can not be measured directly and there is a controversy regarding mass composition, as reported by various world groups. The composition is changing from lighter (proton) to heavier within energy range $10^{17}$ to $10^{18}$ eV as reported by Fly’s Eye, Utah, USA [22], on the other hand, AGASA (Akeno Giant Air Shower Array), Japan [60] has found unchanging composition.

To resolve the problem, more experimental data are necessary in this energy interval. Further, it is well known that the optical emission, i.e. Čerenkov light is a very sensitive parameter for measuring primary mass composition. It is therefore proposed to carry out simultaneous measurement of optical pulse associated with miniarray triggered events, giving core distance and shower size. Effort is made to infer mass composition from experimental pulse height distribution compared with Monte Carlo simulation result under different composition models, as well as from Cerenkov Lateral Distribution parameter fitted to different groups of recorded events in narrow shower size bins.

2.2: DETECTION THCHNIQUE:

2.2.1: Conventional:

Extensive Air Shower (EAS) is conventionally detected using ground based particle detector array covering large area and using coincidence technique. By measuring the particle density at the predetermined detector positions and by fitting with a known lateral distribution function for the charged particles, like NKG, it is possible to estimate the core position, shower size and age parameter. Age parameter is an indication of shower development and the shower size is used to estimate the primary energy.

2.2.2: Mini-Array Technique:

The detection of UHE Cosmic Rays at energies $> 10^{17}$ eV, about hundreds of particle detectors are required conventionally, covering km$^2$ of area. Prof. John Linsley gave an unconventional, cheap and novel method to detect giant EAS by measuring arrival time spread i.e. thickness of the shower front and the secondary particle density. The method is applied in the
detection of UHE Cosmic ray shower in the Department of Physics, Gauhati University, Assam, INDIA.

The Linsley’s effect is the increase in spread of arrival time distribution in a particle sample from the given shower with increasing distance from the shower center [74,75]. The measured time spread of the particles striking localized detector system gives an estimate of the distance (r) to the shower axis. The number of particles gives the measure of the local particle density (ρ). The shower size (N) is estimated from the assumed lateral distribution function and primary energy (E) is derived from the same. The Gauhati University Miniarray is installed at the roof top of the Physics Building, Gauhati University( 26°10”N, 91°45”E and altitude 51.8 m). This array consists of eight plastic scintillators( each of area 50 x 50 cm² ; thickness 5cm) viewed by fast PMT’s) (type: Thron EMI,9807B) covering total carpet area of 2m². Fig.3.1 (chapter-III) shows the arrangement of the detector system. The optical Čerenkov detector, a 5 inch diameter PMT (Type 9792KB) is installed at the miniarray for recording optical pulses in association with EAS events recorded by the miniarray [89]. The signals from the eight detectors and from the Čerenkov detector are amplified and then carried to the control room via co-axial cable( Type-RG58U). In the control room, all the eight signal are discriminated to provide corresponding logic signals. The discriminated output is then individually shaped into narrow pulses of 20nS width and OR’ed together to give a serial pulse train. This serial pulse train is then branched in to two channels, one going to the Digital Storage Oscilloscope(Tektronix, TDS 520A,500 M Sample/sec) and the other to the trigger unit. The trigger circuit senses the incoming pulse train and generates the necessary trigger pulse. Once triggered, the number of detector pulses and their relative time positions are stored in the scope. The triggered pulses from the scintillation detectors, associated Čerenkov pulses from the optical detector and trigger pulses are recorded by the DSO through the channel-1, channel-2 and AUX-1 respectively. The pulse wave form is recorded by the scope and transferred to the PC via GPIB interface. The microprocessor also monitors the status of the detectors at a pre-determined interval and handles the recording and transfer of data of each event to the PC via RS232 interface. During the recording period the DSO is in the real time single acquisition mode and wave forms are available in the wave form memory of the DSO.

2.3.1: THE SHOWER FRONT:
The shower particles spread over a large area, mainly due to angular distribution of \( \pm \), \( k^\pm \), \( k^0 \) at the time of their production, initial transverse momentum of the particles, multiple Coulomb scattering, angle of emission of \( e^+ \) and \( e^- \) during pair production. The electromagnetic component(EM) suffer maximum lateral spread followed by muons. However, lateral spread of muons in EAS is somewhat energy dependent. For high primary energy (\( \sim 10^{19} \text{eV} \)) and low muon energy threshold (\( \sim 1 \text{GeV} \)) muons spread over wider distance than that of high muon energy threshold (~10GeV). Although muons comprise only some few percent of the total charged particle flux at small core distances, at large core distance (~1000m), muon are the dominant shower component [106]. The wider lateral spread of muons can be explained either by considering higher pion transverse momenta or muons produced higher in the atmosphere [107]. Lateral spread of nuclear active particles(NAP) is very small due to their extremely high energy. Hadron component having energy ~10^{12}eV or above are usually found within 2m of the shower axis, while particles of energy ~10^{11} eV or less suffer maximum spread up to 30m.

The angle of scattering of electrons is by far the most important cause for the lateral spread of EM component, since at any level, there will be electrons which being slowed down to very low energies scatter heavily.

For scattering process the mean square angle of scattering \( < z^2 > \), of a relativistic, particle of energy \( E_0 \) (MeV) varies with the thickness “t” of the medium.(in unit of radiation length \( X_0 \)) as

\[
< z^2 > = \left( \frac{E}{E_0} \right)^2 \left( \frac{t}{X_0} \right), \quad \text{Where } E_s = m_0 c^2 \sqrt{(4\pi/137)} = 21 \text{ MeV.}
\]

\[
< z > = \frac{21}{E_0} \sqrt{\frac{t}{X_0}} \quad \text{for } 1 \quad \text{--------------------------------(2.1)}
\]

The above relation shows that the r.m.s. scattering angle is inversely proportional to \( E_0 \), that is the highest energy particles are least scattered and are found nearest to the core. To explain lateral spread, it is usual to define unit of length, the characteristics or scattering length, \( R_1 \) as the
Fig. 2.1.: A typical shower front of thickness $\sigma$ (nS) striking the ground.

The product of one radiation length and the r.m.s deflection $\langle \phi \rangle$ of a particle of total energy $E_c$ (the critical energy for electron in air) traversing one radiation length i.e. $R_1 = \langle \phi \rangle X_0 [50]$. Therefore, using equation for $\langle \phi \rangle$ given above, we have, $R_1 = \frac{21}{E_c} X_0$, $E_c = 84$ MeV and $X_0 = 37.8$ g/cm$^2$, so that, $R_1 = 9.45$ g/cm$^2$ or, $R_1 = 79$ meter in air at sea level. This value
characterizes the minimum lateral spread of the EAS at sea level over an area ($R_1^2$)~ $10^4$ m$^2$. It was pointed out in [50, 81] that due to initial transverse momentum of the particles and mainly due to Coulomb scattering, the huge number of secondary particles spread over a large area at the observation level extending in some cases to tens of square kilometers.

Total numbers of charged particles in a shower at sea level, called shower size $N$ is related to the primary energy by a power law,

$$E = aN^b \quad \text{(2.2)}$$

Where constants $a$ and $b$ are estimated by different workers.

Particles of the shower are delayed with respect to one another either due to their path length difference as a result of scattering or due to their difference in velocities etc.

Also since almost all the particles are relativistic and difference in the geometrical path traversed by them being small, all the particles are confined to a disc, which is known as shower front. So the picture of the shower front is some what like a sparsely populated disc of mostly electrons and positrons plunging down through the atmosphere and arriving at the ground level covering wide area and thickness 1 to 2 meter and figure 2.1 shows the structure of the shower front. The relation between shower disk thickness $\sigma$ (nS) and core distance $r$ (m) has been derived by Capdevielle et al [32] from their simulation with CORSIKA for near vertical shower as given by,

$$\sigma(r) = B\left(1 + \frac{r}{c}\right)^\beta \quad \text{(2.3)}$$

Where values of the constants, $B=2.6$, $c=25$ and $\beta=1.4$ and are derived from the experimental data.

2.3.2: Theoretical Estimation from Miniarray Geometry:

Linsley’s method of detection of giant EAS due to UHE Cosmic Rays is based on measurement of thickness of shower front ‘$\sigma$’ (in nS) and particle density at a closely packed particle detector array, sampling a small portion of the shower front at large core distance.

The particle density distribution for large shower and medium core distance (100m $< r <$ 1000m) has been parameterized by using our simulated miniarray data for proton and iron initiated showers separately is as follows:

$$\rho(N, r) = eNr^{-n} \quad \text{(2.4)}$$
Where $\varepsilon = 0.00053$, $N$= shower size and $n=1.5$ for proton primary as deduced by reanalysis of miniarray data using CORSIKA simulation [54].

The differential and integral shower size spectrum[15] are respectively,

$$ j(N)= -\gamma D N^{-(\gamma+1)} \quad \text{-------------------(2.5,a)} $$

$$ J(N) = D N^{-\gamma} \quad \text{-------------------(2.5,b)} $$

Where the constants have values $D=318$ & $\gamma = 1.7$.

From the above relations we can derive the frequencies of Linsley’s events as functions of minimum time spread ($\sigma_1$)and threshold density ($\rho_1$) and shower size $N'$ as,

$$ F(>\sigma_1, >\rho_1) = \int_{N_{\text{min}}}^{A(N)} j(N)dN \quad \text{----------(2.6)} $$

$$ F_L(N) = \int_{N}^{A(N)} j(N) \quad \text{----------(2.7)} $$

Where $A(N) = \pi \left( r_{\text{max}}^2 - r_{\text{min}}^2 \right)$ \text{----------(2.8)}

$A(N)$ is acceptance area, an annular ring whose inner radius is determined by the minimum time spread ($\sigma_1$) and outer radius is determined by density threshold ($\rho_1$) = 1.5m$^2$ selected. These $r_{\text{min}}$ and $r_{\text{max}}$ are given by equations(2.3) and (2.4) as,

$$ r_{\text{min}} = \left\{ \left( \frac{\sigma_1}{B} \right) \left( \frac{\gamma}{\beta} \right)^{-1} \right\} C \quad \text{----------(2.9)} $$

$$ r_{\text{max}} = \left( \frac{\varepsilon N}{\rho_1} \right)^{\frac{1}{\gamma}} \quad \text{----------(2.10)} $$

The minimum detectable shower size is given by the condition, $A(N_{\text{min}}) = 0$
Fig. 2.2: Lateral distribution (power law) index $\delta$ vs. $X_m$, depth of cascade maximum [93]

Which gives

$$N_{\text{min}} = \left( \frac{\rho_1}{\epsilon} \right) \left[ C \left( \frac{\sigma_1}{B} \right)^{\frac{1}{\beta}} - 1 \right]^n$$

--------(2.11)

2.4: CHARACTERISTICS OF ČERENKOV RADIATION:

Since the charged shower particles generate Čerenkov photons at every stage of the shower development by exceeding the critical energy, the accumulated Čerenkov light is concentrated in a small forward cone and the intensity of the light is much stronger than the fluorescent light along the shower direction. A significant part of the Čerenkov light can be scattered out through
Rayleigh and Mie scattering during the whole shower development history. This Čerenkov radiation also follows some basic properties i.e. the radiation is responsible not for the recombination or excitation associated with the ionization by the particles. It is also not responsible for bremsstrahlung radiation. Only medium through which the particles pass is responsible for Čerenkov radiation. This radiation has very low energy compared to that of particles, hence quantum effect is negligible for this radiation.

### 2.4.1: LATERAL DISTRIBUTION FUNCTION (LDF):

Čerenkov radiation emitted by each individual charged particle in an EAS is spread over wide area due to lateral spread of the shower particles. The number of photons emitted by each shower particle depends on the total path covered in the atmosphere. Hence, lateral distribution of Čerenkov photons is closely related to the longitudinal shower development.

Protheroe and Turver [93] carried out detailed Monte Carlo simulation in order to identify Čerenkov light parameters sensitive to the longitudinal shower development. They found from their simulated data that the lateral distribution of photons integrated over all angles, could be fitted by a power law of the form,

\[ \Phi(r) = C(r + 50)^{-\delta} \]

where, the Čerenkov lateral distribution shape parameter ‘\( \delta \)' (the power law index) is sensitive to the depth of shower maximum( \( X_m \)), independent of the interaction model, primary energy and mass number. It is to be noted that the sensitivity of ‘\( \delta \)' to the depth of cascade maximum is 0.2 per 100 gm.cm\(^{-2}\), independent of zenith angle. The relation between \( \delta \) and \( X_m \) at sea level is given by (figure 2.2, [93])

\[ \delta = 0.001 \langle X_m \rangle + 1.6 \]
Several other groups have also studied the Lateral Distribution of Čerenkov pulse response to get a clear idea about the longitudinal development of EAS. In 1979, Thornton et al [104], Aliev et al in 1985 [5] and Gao Xiao-yu et al in 1991 [48] fitted their experimental data to an exponential function of the form,

$$\Phi(r) = D \exp \left[-\left(\frac{br}{10^4}\right)\right]$$

(2.14)

where ‘D’ is a constant ‘b’ is a lateral distribution parameter and ‘r’ is the core distance. It has been observed that the exponential form is better for R ≤ 250m power law for R ≥ 250m.
Fig. 2.3 shows Čerenkov radiation from shower initiated by particles of energy $10^{18}\text{eV}$ at different core distances which indicates some useful properties of the Čerenkov radiation from a very energetic shower.

2.5: PRIMARY MASS COMPOSITION:

The composition of primary cosmic rays at energies up to $10^{14}\text{eV}$ can be measured directly but the primary composition of cosmic rays at energies $>10^{14}\text{eV}$ can at present, be estimated only indirectly from measurements of air shower parameters and hadron and gamma ray families in emulsion chambers deep in the atmosphere. All these estimates are based on the assumption of the superposition model for nucleus-nucleus interactions. At high energies information about the nature of the primary cosmic rays can be obtained by studying EAS that developed in the atmosphere. Since the shower generated by heavy nuclei is systematically different from that of lighter ones, the composition inferred from measurement of a given shower parameter depends on the normalization and shape assumed for the primary energy spectrum and vice-versa. The mass composition of primary cosmic rays below the energy $10^{12}\text{eV}$ are measured directly by using balloons and satellites, reveals 41% protons and 7.5% iron group[1]. An extrapolation of the measured iron spectrum leads to dominance of iron above $10^{14}\text{eV}$. But this view is in conflict with the JACEE experiment[100]which shows that iron doesn’t dominate by $10^{14}\text{eV}$. The composition of primary cosmic rays at higher energies ($\geq 10^{13}\text{eV}$) has been derived by various groups from the study of different parameters of EAS, e.g., 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 Čerenkov observations. Unfortunately, various experiments indicate compositions which are at variance with each other. Observation of steeping of the primary energy spectrum around the so called “knee” ($3\times10^{15}\text{eV}$) leads to the suggestion that there might be a change of primary composition due to rigidity cutoff. If such a cutoff exits, then one would expect nuclei with high Z values to be retained to higher total energy than protons so that heavy nuclei predominate at energies higher than the cutoff[44].

The mass composition of the Cosmic Rays with energy greater than $10^{17}\text{eV}$ is yet an unsolved problem, as indicated by results of different groups of workers all over the globe. The Fly’s Eye Groups, USA reported from the study of energy dependence of depth of shower maximum above $10^{17}\text{eV}$[22] that the mass composition around $(1-3)\times10^{17}\text{eV}$ is mainly heavy and
becomes gradually lighter above $3 \times 10^{17}$ eV.

On the other hand, at Akeno Giant Air Shower Array (AGASSA, Japan), composition study has been made from the analysis of muon component for showers with energies greater than $10^{16}$ eV[60] and no significant change in mass composition was found. The AGASSA result doesn’t support the model proposed by Fly’s Eye groups and indicate constant mixed composition to extend up to the highest energies. It is therefore, important to have enough experimental data in this energy range which could predict mass composition.

2.5.1: COMPOSITION MODELS:

Based on diverse observation of variation of mass composition with primary energy, the following models are studied [92].

(a) Heavy to light:

As proposed by Fly’s eye Groups, assuming that the two main components proton and iron nuclei determine the dependence of $X_m$ on the primary energy[20]

$$\text{Iron Flux Proton flux} = \left( \frac{E_p}{10^{18.5} \text{ eV}} \right)^{-0.887} \quad \text{------------------------}(2.15)$$

(for $10^{17.5} < E_p < 10^{19.5}$)

This shows that the heavy composition varies from 88.5% at $10^{17.5}$ eV to 73.5% at $10^{18}$ eV. At $10^{17}$ eV, KASCADE experiments of Karlsruhe, Germany[53] obtained form analysis of shower development fluctuation, about 80% heavy contribution. These results are incorporated in the present simulation.

(b) Constant mixed composition:

AGASA reports an unchanging mixed composition above $10^{16}$ eV. The heavy contribution is estimated at about 50% around this energy[53].

(c) Pure Proton Composition:

Studies of high energy muons show that above $10^{15}$ eV primary composition is mainly proton.

2.5.2: SOME IMPORTANT PARAMETERS FOR THE DETERMINATION OF MASS COMPOSITION:

There has long been controversy over the question of primary mass composition and interaction characteristics of Cosmic Rays with energies above $10^{16}$ eV. At such high energies,
EAS is the only probe to examine these two aspects. However, the secondary particles being many generations removed from the primary, dilute the information carried by primary Cosmic Ray considerably. The composition could, therefore, be obtained only qualitatively, such as predominately protons, mixed of predominately heavy nuclei.

Intensity of Cerenkov radiation from EAS is proportional to the track length integral of the individual electrons. Hence, their lateral distribution and pulse shape reflects the longitudinal development of the shower; in particular the steepness of the lateral distribution function is found to be proportional to the height of maximum development. The height of maximum is again different for different primary mass and energy. Thus, the lateral distribution parameter of Cerenkov radiation throws light on the primary mass composition. This composition at higher primary energies (\(E_p > 10^{14}\) eV) can be estimated from the measurement of different air shower parameters,

(a) Depth of shower maximum (\(X_m\))
(b) Elongation Rate (ER)
(c) Estimation of shower size (N)

2.5.2.(a): Depth of Shower maximum (\(X_m\)):

It may be mentioned that the depth of shower maximum (\(X_m\)) is a parameter sensitive to the primary mass and energy. This depth of shower maximum for showers of a given primary energy depends both on the behaviour of high energy interaction and primary mass number. Theoretical study on \(X_m\) [37] clearly confirm that the composition of initiating particle is the major factor affecting the \(X_m\) and it is possible to interpret the experimental data in terms of composition. The \(<X_m>\) and \(\sigma X_m\) are function of primary energy and mass composition, according to modified elongation rate theorem of Linsley [96],

\[
<X_m>^P = 76.5 \log E_p - 577 \quad \text{(for Proton)}
\]
\[
<X_m>^{Fe} = 76.5 \log E_p - 712 \quad \text{(for Iron)} \quad \text{(2.16, a &b)}
\]

A comparative study has been made by Dykonov et al in 1991[42] between the Cerenkov light observation data at the Yakutsk Array and Fly’s Eye Array to get a relative picture on ‘\(X_m\)’ and its fluctuation (\(\sigma X_m\)). On the basis of Quark Gluon Model an analysis about the primary mass composition is reported below,
2.1. Measured $X_m$ and $\sigma X_m$ at Yakutsk and Fly’s Eye Array.

| $E_0$ (EeV) |  | $X_m$ (gm/cm$^2$) |  | $\sigma X_m$ (gm/cm$^2$) |
|-------------|------------------|------------------|------------------|
|         | Yakutsk | Fly’s Eye | Yakutsk | Fly’s Eye | Yakutsk | Fly’s Eye |
| 0.16 | 0.14 | 649±27 | 648±20 | 100±5.5 | 84±4.8 |
| 0.28 | 0.23 | 675±24 | 647±20 | 87±4.2 | 76±3.5 |
| 0.45 | 0.42 | 695±26 | 665±20 | 84±3.5 | 75±3.1 |
| 0.81 | 0.75 | 716±24 | 672±20 | 77±3.6 | 86±3.7 |
| 1.45 | 1.30 | 730±25 | 704±20 | 76±5.4 | 76±4.0 |
| 3.47 | 2.20 | 755±26 | 729±20 | 86±5.5 | 81±5.7 |

2.2. Calculated $X_m$ and $\sigma X_m$ for P and Fe compositions.

<table>
<thead>
<tr>
<th>$E_0$ (EeV)</th>
<th>Particle</th>
<th>$X_m$ (gm/cm$^2$)</th>
<th>FXm (gm/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>P</td>
<td>684</td>
<td>50.4</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>578</td>
<td>9.3</td>
</tr>
<tr>
<td>5.0</td>
<td>P</td>
<td>746</td>
<td>46.0</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>640</td>
<td>8.2</td>
</tr>
</tbody>
</table>
2.5.2.(b): Elongation Rate (ER):

An important parameter to study the characteristics of an Extensive Air Shower (EAS) and also the primary mass composition is the Elongation Rate (ER). By ER is meant the rate of change of depth of shower maximum with primary energy. It may be mentioned that ER can be estimated indirectly from the measurements of Čerenkov pulse parameters. This ER can be expressed mathematically as,

$$\text{ER} = \frac{\delta X_m}{\delta \ln E_p} = a \left( 1 - \frac{\delta \ln A}{\delta \ln E_p} \right)$$ \hspace{1cm} (2.17)

This above equation can be obtained from the relation of ‘X_m’ as a function of primary energy ‘E_p’ and mass (A) as expressed by Rao(1988)[97].

$$X_m = a \log \left( \frac{E_p}{A} \right) + b \hspace{1cm} (2.18)$$

The expected variation of ‘X_m’ with ‘E_p’ on the basis of modified ER theorem of Linsley is shown in fig.2.4 The solid and dash lines are for A=1 and 56 respectively. Here, ER, the slope of the curve is constant for both A=1 and A=56 over the energy range. A change in slope would therefore, indicate a change in primary composition.

2.5.2.(c): Estimation of Shower size (N):

From the miniarray reanalysis using CORSIKA simulation code, the following relation for shower size N is derived as a function of primary energy for primary proton and iron compositions, [15, 54,]
\[ E = aN^b \] \hspace{1cm} \text{(2.19)}

Where \( a=2.217 \times 10^{11}, \ b=0.798 \) for proton primary and \( a = 6.194 \times 10^{11}, \ b=0.898 \) for iron primary.

CHAPTER -III

EXPERIMENTAL SETUP

3.1 INTRODUCTION:

A new experimental setup has been developed in the miniarray Research Laboratory, UHE Cosmic Ray Research, Gauhati University Guwahati, Assam, INDIA. based on a method as suggested by Prof. John Linsley, for the detection of EAS, This unconventional, cheap and novel technique has been successfully used to study the UHE(\( \geq 10^{15} \text{eV} \)) Cosmic Rays by measuring arrival time spread i.e. thickness of the shower front \( \sigma(nS) \) and the particle density \( (\rho) \) of the secondary particles from EAS produced by primary particles in the atmosphere[14].Studies of
optical pulses produced by UHE cosmic rays is done using optical detectors run along with the miniarray. The experimental setup consists of fast timing particle detectors, optical detectors, necessary electronics and microprocessor based data acquisition system and computer interface. Fig.3.1 shows the block diagram of the experimental setup and the data acquisition system. This experimental setup is performed by recording the time spread up to 2.5 \( \mu \text{S} \) with an accuracy of 10nS.

To detect the UHE Cosmic Rays an array of eight plastic scintillation detector is setup inside a hut at the roof top of the Physics Building covering a carpet area of 2m\(^2\). A Photomultiplier (PMT)( Type 9792KB,13 cm diameter) is installed at the centre of the mini array to record optical pulses in association with the detection of UHE cosmic Rays as recorded by the mini array. All the amplified pulses are carried to the Data Acquisition System(DAS) in to the control room.

3.2: DETECTORS:

In the present experiment particle detectors as well as optical detector are used,

(1) Particle detectors of the miniarray.

(2) Optical detector.

3.2.1 : THE PARTICLE DETECTORS:

Each detector unit consists of one fast photomultiplier tube(EMI-9807B),a plastic scintillator block of size 50x50x5 cm\(^3\) having a photomultiplier base, a pre-amplifier unit and a light tight enclosure along with a PMT unit as shown in the fig.3.2. The PMT’s are extremely sensitive light detectors which was first developed by Curran and Baker in 1944, provides a current output proportional to intensity of incident light. They detect light at the photocathode which emits electrons by the photoelectric effect. These photo electrons emitted by the photocathode are electro statically accelerated and focused into the dynode which produces number of secondary electrons, i.e. each electron liberates a number of secondary electrons which are, in turn, accelerated and focused on to the next dynode. The process is repeated at each subsequent dynode and the secondary electrons from the last dynode are collected at the anode. A organic scintillator of polyvinyltolune crystal are used as a scintillation counter. During the passage of a charged particle through the scintillation block, internal states of the atoms are disrupted and light is emitted usually in a kind of domain effect yielding enough light, i.e. atoms are excited but then de-excited and they emit light which falls on the photo cathode. Most of the
excitation energy quickly transform into heat and about 20% is stored by fluorescence centre of meta stable energy levels and eventually reappears in the form of light. Scintillators have many desirable general characteristics namely- linearity to energy, fast time response, pulse shape discrimination and variety in materials (organic and inorganic types) etc. The light emission from scintillators can be characterised by the expression,

\[ N = A \exp\left( -\frac{t}{\tau_f} \right) + B \exp\left( -\frac{t}{\tau_s} \right) \]

Where \( \tau_f \) and \( \tau_s \) are the fast and slow components and \( A, B \) are given by a functional form [35],

\[ A = N_0 f(\sigma, t) \]

The shape of \( f(\sigma, t) \) has a Gaussian shape. The ratio of the fast and slow components depends on the scintillator material and the type of radiation interacting on it.

Resolution of the scintillator is 20% with decay time of 4nS, light output 50% that of anthracene and maximum wavelength of emission 4340Å. A fraction of the light emitted is lost by the re-absorption in the phosphor or trapping within the boundaries of the phosphor by total internal reflection. The remaining portion of light is then collected by photocathode of the photomultiplier tube. Photomultiplier Tube are used to quantify low light levels, sent continuously or occurring in short-duration bursts. It has large collection area, high gain, linear
Fig.:3.1: Block Diagram of the Experimental Setup.
behaviour, fast time response and the ability to detect single photons give the photomultiplier distinct advantages over other types of light detectors. The PMT used in the miniarray is a round face end window type with a semitransparent bi-alkali photocathode having maximum sensitivity in the blue region of the spectrum. The dark current is low, (1nA- 1400V) and the maximum overall gain is 7.1x10^6 with the rise time of 2nS. Fig.3.3 and fig.3.4 show the voltage divider networks for the electron multiplication. The chain current is 0.45mA and the chain consist of 12 stages. The anode is biased with a positive high voltage and cathode is grounded. The
photomultiplier tubes are operated at an anode potential of +1800V supplied from a variable high voltage unit (ECIL,HV 4800E). A momentary negative pulse is produced across the anode load resistance due to the sudden potential drop produced by the instantaneous current pulse which is then coupled to the pre-amplifier unit. The unequal anode potential requirements for the different PMT’s are adjusted by using potentiometer in series with the branching network, generally 10 to 15 kilo-ohm resistances are used for this purpose. Fig.3.5 shows the circuit diagram of the fast scintillation pre-amplifier. This pre-amplifier unit is a double stage differential amplifier designed around µA733 video amplifier operated at ±6.5V D.C. supply derived from the low voltage unit. The rise time of the amplifier is 2nS with an overall bandwidth of 200MHz and the gain of the amplifier of each stage is 10. The amplifier has a power amplification stage consisting of two N-P-N transistors 2N 2222A coupled to the amplifier unit through a capacitor 0.01µF. The power amplification stage is used to compensate for power loss of the output pulse in the cable when it is transmitted to the control room for further processing.

3.2.2: ERENKOV DETECTOR:

The Čerenkov detector system comprises the following,

(a) A photomultiplier tube( EMI 9792KB) with an appropriate dynode chain.

(b) Pre-amplifier.

(a) Photomultiplier Tube:

A photomultiplier tube( type EMI 9792KB) of 130mm diameter photocathode with an overall gain of 0.7x10^6 is kept vertically pointing towards the sky. The unit is protected from sunlight as well as star light by keeping it in a light tight box. During the recording period the top cover of the box is opened to expose the PMT. The atmosphere in this case taken as medium for production of Čerenkov radiation. Fig.3.4 shows the voltage divider network of Čerenkov detector for electron multiplication. The chain consists of 9(nine) stages with a chain current
Fig.: 3.3: Voltage Divider Network for 9807 Type PMT.
of 0.5 mA. The cathode is grounded and the anode is biased by a positive high voltage. This PMT is operated at an anode potential of 1400V supplied from a high voltage unit (ECIL,HV 4800E). The chain resistance were of high stability type with a tolerance of 1% and they are soldered directly to the base socket.
The requirements of the voltage divider networks are fast rise time and decay times with as little ringing as possible in order to reduce the double firing of the discriminators. To reduce the ringing due to mis-match, a low value variable resistor is connected in series at the input of the pulse amplifier and adjusted for best results.

(b) Pre-amplifier:

To reduce noise, the detector pulses are amplified by a fast suitable amplifier connected near the PMT. Fig 3.5 shows the circuit diagram of the fast scintillation pre-amplifier. This pre-amplifier unit is a double stage differential amplifier designed by using a monolithic differential input, differential output, wide band video amplifier. This linear integrated circuit µA 733 operated at ±6.5V D.C supply derived from the low voltage unit. The rise time of the amplifier is 2nS with an overall band width of 200MHz and the gain of the amplifier of each stage is 10. The amplifier has a power amplification stage consisting of two N-P-N transistors 2N 2222A coupled to the amplifier unit through a capacitor 0.1 µF. The emitter follower outputs provide low output impedance, and enable the device to drive capacitive loads. The power amplification stage is used to compensate for power loss of the output pulse in the cable when it is transmitted to the control room for further processing.

3.4.: CONTROL ROOM ELECTRONICS:

The detector pulses from the scintillation detector and optical pulses from the Čerenkov counter are initially amplified at the detector station and transmitted to the control room through 50Ω coaxial cable(RG 58U) and following units are used to process in the control room.

3.4.1: EIGHT CHANNEL DISCRIMINATOR:

A modified multi channel discriminator board is designed and fabricated using high speed voltage comparators for the present experimental set up. The reference voltage is produced precision reference source RF01 and LM 301 and this stable
Fig. 3.5: Circuit diagram of fast scintillation pre-amplifier
Fig. 3.6: Circuit diagram of one Channel Discriminator with Pulse shaper.

reference voltage works as the source of discriminator level at the input of the comparator. The pulses from the detector are fed into the inverting input terminal of the high speed comparator
U2(LM 361) and the bias is set by the ten turn preset. As the incoming pulse crosses the
discriminator bias in the comparator input, the unit produces the logic pulse. The circuit diagram
of one channel of the discriminator with pulse shaper is shown in the figure (3.6).

The output of the discriminator is shaped into two separate pulse widths by using IC 3 and
IC 4 (Mono stable Multivibrator). One of them is of 20nS which is used for recording of air
shower events. The another one has pulse width 700nS. This pulse is generally used for counting
purpose at a pre-determined intervals, controlled by the microprocessor 8086.

To obtain stable operation and proper pulse shapes, a good high frequency technique is
necessary. The circuit pattern was printed on both sides of double side PCB and suitable spacing
is maintained at ground potential throughout the circuit. Components were soldered like surface
mount device. Figure 3.8 shows the typical output pulses of the discriminator corresponding to
an event trigger captured by the Digital Storage Oscilloscope. CH-1 shows the discriminator
output while the CH-2 gives the trigger pulse.

3.4.2.: TRIGGER UNIT:

For recording optical pulse in association with UHE Cosmic Ray events, the wave forms
are captured under some prerequisite criteria. These criteria’s are,

(a) The particle detector pulses are triggered by the Čerenkov pulse and must be
    present within the time window 2 µS.
(b) The hardware trigger requiring particle in the range two or above within the 2 µS
time window.
(c) The minimum arrival time spread between the particles must be 100nS. The
    trigger unit is shown in fig.3.7.

The trigger circuit design on an idea by [85] and shown in the figure 3.7 performs the
function required under (b). The output pulse train from the OR gate charge the
capacitor C5(220pF) through the diode D1(IN 914) for a time period determined by the timing
pulse at the CMOS Gate, U4 (4016-Quadruple Analog Switch). The timing pulse is generated
by applying the pulse train to U3(74121)which is at present set to 2µS by preset P2. The gate
pulse discharges the capacitor at the end of 2µS
Fig.3.8: Schematic Diagram of Trigger Circuit.
Fig.3.8: A typical output pulses of the discriminator corresponding to an event trigger.

period. The voltage at the capacitor varies as the number of pulses received in the 2µS duration. This voltage across C5 is fed to a high speed voltage comparator U8(LM 361) and the trigger pulse is generated by the U5(74S74- Dual Edge Triggered Flip-Flop) and U6(74LS11- Triple 3-Input Positive–And Gate). The 2µS Gate pulse is inverted and brought to the CLK2 input of the
flip-flop and both the outputs are combined by U6 to ensure that the trigger pulse is generated at the end of 2 \( \mu \) S period.

**3.4.3.: THE DIGITAL STORAGE OSCILLOSCOPE AND GPIB INTERFACE.:**

A Digital Storage Oscilloscope (DSO, Tektronix, TDS, 520A, 500MHz, 500MSample/Sec.) is connected through the General Purpose Interface Bus Adapter (NI Spy, National Instrumentation) for recording the optical Čerenkov pulse in association with the UHE Cosmic Ray events. The optical as well as particle detector wave forms are recorded by the DSO and written to files in the computer hard disk. We are recording the optical pulses within 2\( \mu \)S time window in association with events as satisfies the pre-requisite criteria. This is done by setting the DSO in the real time single acquisition mode. When the event trigger occurs with optical pulse, the DSO stops the acquisition and wave forms are available in the wave form memory of the DSO and are then transferred to the computer hard disk for permanent storage. An optical pulse in association with particle events recorded by the DSO is shown in the **fig.3.9.**

**3.4.4.: MICROPROCESSOR AND MICROCOMPUTER INTERFACE.**

A Microcomputer based on 8086 microprocessor with a clock speed of 5MHz is used for operation of the detector setup. The unit provides 128KB of battery RAM, Programmable I/O ports(8255), Priority Int. Controller (8259A), Real Time Clock(RTC), Programmable Timer Counter(8253), Keyboard and Monitor Interface. Additionally it provides one RS232C interface using USART 8251. Primary function of the microprocessor is to monitor the operation of the detectors by recording the count rates at predetermined intervals. For this the 8253 receives the Multiplexer(MUX) output pulses from each of the channels through its clock input. The total time of counting is monitored by using 1second timer output of the RTC. This is used as IR02 input of the 8259 and a procedure terminates counting when set time elapses. The microprocessor reads the counts(BCD),stores them in RAM and sends them to the computer for disk storage via RS232 interface.
Fig.3.9: A typical ėrenkov pulse triggered by miniarray trigger is captured by DSO.

3.4.5.: THE NECESSARY SOFTWARE USED:

The collection rate of the ėrenkov pulses in association with the particle events by the mini array is quite low and the period of recording of optical pulse is also very limited. So it is necessary to run the detector system on a continuous basis over whole night with moonless, cloudless sky condition to collect sufficient data. For this purpose a software is developed which performs the followings,

(i) Optical pulse and particle detector pulses received within the 2μS time window is recorded by capturing the waveforms displayed in the two channels of the DSO, channel one being used for optical and channel two for particle pulses.
(ii) The capture process is initiated once the trigger pulse is received in the auxiliary channel that stops the waveforms in the DSO waveform memory.

(iii) The computer software polls both the serial communication port (COM1) and the GPIB port, receives the waveform data and saves these in the computer hard disk whenever an event occurs.

(iv) When there is no event a counting sequence of the particle detector pulses is started, the number of counts and RTC time is transmitted to the computer for each channel sequentially.

(v) The counter data received are also saved in the computer hard disk as a separate file. The programmes for the microprocessor are developed in assembly language. The programme for handling the RS 232 communication, GPIB and file handling is written in C. The flowchart for the entire software is given in the appendix-III.

The test and calibration of all the detectors and fast electronics circuits will be reported in the next chapter.

CHAPTER –IV

TEST AND CALIBRATION OF THE DETECTORS:

4.1.: INTRODUCTION:

Visible ėrenkov radiation is produced when a charged particle moves through a medium with velocity greater than the phase velocity of light in the medium. The ultra relativistic particles in an EAS while traveling down the atmosphere produce ėrenkov Light flash, which can be detected using a PMT in a moonless night. This optical ėrenkov emission
associated with Ultra High Energy (UHE) Cosmic Rays are being detected using ėrenkov detector consisting of a 5 inch Photo multiplier tube (PMT) (Type-9792KB), microprocessor based DAS in G.U Cosmic Ray Research Laboratory[91]. This detector is calibrated using ėrenkov photons produced in a tank of distilled water through which secondary Cosmic Rays (mainly muons) of known average flux pass. ėrenkov pulses are recorded by Data Acquisition System (DAS) and the recorded pulse height spectrum is compared with simulated spectrum taking into account the detector geometry and absorption in water.

4.2: CALIBRATION OF THE ėRENKOV DETECTOR:

For calibration, we use a water tank of radius 20cm and height 32cm. The tank is filled with distilled water up to a height of 20cm and its outer surface is coated black to make it light tight. The experimental set up for calibration of ėrenkov detector is shown in fig.4.1. A photomultiplier tube(9792KB) is kept vertically in contact with the light window at the bottom of the water tank. A thin transparent plastic sheet acts as a water tight seal between the PMT and the tank. The anode pulses are fed to the emitter follower placed very close to the PMT. This arrangement including emitter follower circuit is finally placed inside a light tight enclosure. The entire tank and other attached units are covered by black polythene. The output of the emitter follower is carried via co-axial cable to the polarity inverter and inverted pulses are fed to the Multi Channel Analyser (MCA, Type –NETS-3M/U )for recording. ėrenkov events are due mostly to secondary cosmic ray muons of average intensity 180 m^{-2}s^{-1}. Events are recorded for 5 hours with average count rate of 17 per minute.
Fig. 4.1. Experimental Setup for Calibration of Čerenkov Counter.
4.3. METHOD OF CALIBRATION:

The PMT (of radius $r_o$) is placed at the centre of the base of the water tank of radius $r_1$ and water height $z_1$. These parameters are related by,
\[ r_1 = r_0 + z_1 \tan \theta_c \quad \text{------------------------ (1)} \]

where \( \theta_c \) is the Čerenkov angle. For vertical muons of average energy 2GeV, \( \theta_c = 41^\circ \) (in water). Points of incidence of vertical muons are chosen at random over the cross-section of the water tank, taking the origin at the centre of the water surface. The geometrical view of the experimental set up is shown in fig.4.2.

The effective path length \( (z) \) in water and the area \( A \) over which Čerenkov photons are distributed are calculated from the geometrical consideration. The number of photons emitted by the effective path length \( z \) is estimated from the number of photons emitted per cm (~200).[87] Assuming these photons to be distributed uniformly over area \( A \), the actual number of photons collected by the PMT is estimated from the fractional area of overlap by the photocathode area. The absorption of photons in distilled water is also taken into account. One thousand events are simulated using Monte-Carlo method and frequency distribution of the number of photons collected in each case is plotted using suitable class intervals. fig.4.3.

4.4: RESULTS:

The experimental pulse height distribution and the simulated frequency distribution are shown in fig.4.3. The shape of the two distributions are remarkably similar except for the lowest photon numbers[91]. The position of MCA peaks are correlated with the simulated spectrum and the detector is calibrated for the number of photons.

The peak positions are correlated and the corresponding photons numbers \( Q \) are plotted against pulse height \( H \) as shown in fig.4.4 along with least square fitting curve. The equation for this calibration is,

\[ Q = A.H. + B \]

Where \( A=1.3144 \) and \( B=0.023 \) The error in the measurement of photon number \( Q \) for different 5 (five) points are \( \pm 40.8, \pm 40.89, \pm 20.41, \pm 31.18 \) and \( \pm 42.49 \).
Fig. 4.3: Simulated and MCA Pulse Height Distribution

Fig. 4.4: Ėrenkov Pulse Height Calibration Curve.
This results may be used to derive lateral distribution of Čerenkov photons recorded in association with the particle component of UHE Cosmic ray EAS. It may be mentioned that in the Monte- Carlo simulation, the incident muons are assumed to be vertical and absorption of Čerenkov photons by the thin plastic layer separating photocathode from distilled water is neglected.

4.5.: CALIBRATION OF THE PARTICLE DETECTORS.: 

The total flux of the secondary cosmic ray particles is, \( F = 1.8 \times 10^2 \, \text{m}^{-2} \text{s}^{-1} \) (for hard component \( 1.3 \times 10^2 \, \text{m}^{-2} \text{s}^{-1} \) and for soft component \( 0.5 \times 10^2 \, \text{m}^{-2} \text{s}^{-1} \)) and thus the number of charged particles crossing the scintillator block of area 0.25m\(^2\) is 45/sec. Therefore the single particle rate for one channel of the detector array can be considered as 45Hz. The calibration of the detector for omni directional single particle pulse height is done by using a single channel analyzer(ECIL,SC 604B) and a counter. The histograms for the distribution in the counts per 10 seconds is shown in fig.4.5. The dashed line in the figure shows the Gaussian distribution for the mean value 568.44 and standard deviation 9.87. The rate is calculated as \( 56.84 \pm 0.987 \text{Hz} \). The error is less than predicted by the theoretical Gaussian distribution with the same mean(\( =23.8 \)).

The individual discriminator biases are set below the single particle peak obtained from pulse height distribution of the individual peak position. The distribution of one of the mini array detector is shown in fig.4.6. The discriminator biases are increased in step of 5mV with a window of 0.01mV for recording the distribution. From the figure it is seen that the single particle peak for the detector is observed around 73mV of discriminator bias.

4.6.: CALIBRATION OF THE DISCRIMINATOR.

For the calibration of the discriminator board, a standard pulse generator and a timer counter are used. The individual channels of the discriminator boards is tested with the help of standard pulse and timer counter. This test pulses are fed to the discriminator input. The bias of the discriminator channel is adjusted to produce a definite count rate. This rate is measured over a long period of time and doesn’t show any appreciable change. It is found that the drift is also negligible.
Fig.: 4.5: Statistical Fluctuation of Count Rate

Fig.: 4.6: Single Particle Pulse Height Distribution.
4.7.: CALIBRATION OF TRIGGER CIRCUIT.

The block diagram of testing of trigger circuit is shown in fig. 4.7. The expected event trigger rate for the Miniarray experiment is of the order of 10 per day \((10^{17} < E < 10^{20}\text{eV})\). The chance coincidence rate for the 3 particles with individual count rate of \(\sim 50\text{Hz}\) is calculated to be 0.067 per day. The integrated pulse width trigger circuit for the experimental setup is tested by a signal generator and the DSO. A square wave pulse train from the signal generator is applied to the input of the trigger unit. The pulse train during \(2\mu\text{s}\) time period charges the capacitor \(C_5\) of the trigger unit through the diode \(D_1\). The voltage across the capacitor varies with the number of pulses in the pulse train. The voltage across \(C_5\) is recorded for various number of pulses at the input obtained by adjusting the frequency of input pulses. The recorded voltage is plotted against the corresponding number of pulses at the input. A good linearity is found as shown in fig. 4.8.

4.8.: ADJUSTMENT OF DELAY AMONG ALL THE DETECTORS:

For proper recording of events the relative time delay introduced by the recording electronics between each of the channels of the particle detector and Čerenkov detector must be adjusted to zero. Initially this is done by using two number of green LED pulses inside the detectors fed by a common pulse source taking two detectors at a time. The current in the LED’s are adjusted to provide clear pulses of sufficient height above the normal detector pulses. These are recorded in the DSO by adjusting the trigger level. Now appropriate cable lengths are added to the channels so that relative time delay is reduced to zero.

Later, to keep a check on these delays we take help of local showers which hit the array. The pulses from this local showers are displayed simultaneously for two channels in the DSO with logic trigger through Channel-1 and channel-2 respectively. This displays any two detector pulses when they have coincidence. Any delay between the pulses can be checked. The length of the cable from Čerenkov detector is same with the particle detector cable to avoid the delay from the particle detectors.

4.9.: REDUCTION OF DATA AND ESTIMATION OF NOISE:

The data of mini array which includes the particle as well as Čerenkov data are
Fig. 4.7: Block Diagram of Testing of Trigger Circuit.

Fig. 4.8: Linear characteristics of the trigger circuit.
Fig. 4.9: A spurious event triggered by noise.
Fig. 4.10 : A Photographic view of the Experimental setup
reduced under some prerequisite criteria. Those events which have particle densities $\rho < 1.5/m^2$ and having the time spread of the sample $\sigma < 100nS$ are not taken into consideration and are rejected in analysis. The DSO events were reduced by careful visual inspection. Fast timing characteristics of the PMT pulses are very important for recording the arrival time spread of the shower events. The measurement over a long period shows that the average noise level of the mini array detector channel after amplification is 45mV and for the Čerenkov detector, it is 50mV and the single particle pulse height for the mini array is about 75mV. Measured Čerenkov pulse heights range from 100mV to 950mV.

One of the problem in recording the air shower events and optical pulses is due to the spurious trigger by the line noise. These spurious triggers are due to the fluctuation of the mains supply voltage. Such event is eliminated by visual inspection of the oscilloscope trace. Such a spurious event triggered by noise and captured by the DSO is shown in fig.4.9.

4.10: OPERATION OF THE EXPERIMENT:

A photographic view of the Experimental set up is shown in the fig.4.10. All the detectors are kept under running condition during day as well as night time except optical Čerenkov detector which is run at night time. The Čerenkov detector is operated during night time with moonless, cloudless sky. For smooth operation, a procedure is maintained for starting and running the experiment. At the start, the low tension supply is put through after which the high tension to PMT’s is applied, increasing the voltage in gradual steps. The detectors are kept on for a period of half an hour before data recording is started for ensuring stability. The data acquisition programme in the $\mu$P is started and the count rates are observed for normal operation. The data acquisition software for the GPIB hardware card GPIB-PCI(NI 488.2$^{TM}$) is started and the actual data collection begins. The operation continues until it is stopped manually. A logbook is maintained for keeping the relevant information about the operation of the experiment.

The next chapter of this thesis describes the Monte Carlo simulation and analysis of data.
CHAPTER – V

SIMULATION OF ERENKOV EVENTS ASSOCIATED WITH MINIARRAY:

5.1 : MONTE CARLO SIMULATION:

The term ‘Monte Carlo’ was introduced by Von Nuemann and Ulam during World War II as a code word for the secret work at Los Alamos, and was suggested by the gambling casinos at the city of Monte Carlo in Monaco. This method was then applied to problems related to the atomic bomb. The work involved direct simulation of behaviour concerned with random neutron diffusion in fissionable material. Later, this method was used to different areas including sampling of random varieties from probability distributions. Here, a real physical process can be idealized as a sequence of choices. These choices are determined by some probability functions and then one can establish a model which simulates the process. Because, sampling from a particular distribution involves random numbers, it is called Monte Carlo Simulation.

Although this method was known for a long time, however, until the advent of electronic computers, this method could not be used on any significant scale. Computer is used to generate a sequence of random numbers, called pseudo-random numbers, which are used to simulate the random observations. Thus, Monte Carlo method is an accelerated simulation of random phenomena by computer.

5.1.1 : Pseudo-Random Numbers:

In a computer random numbers are calculated using some specified formula, simulating a random variable \( R_n \). These are called pseudo-random numbers, as they are not truly random in nature, being generated by systematic arithmetic process. The whole series of numbers is uniquely determined by the starting value called the seed. However, it does not affect the process of simulation if its distribution is uniform and period is large.

The most common algorithm for generating pseudo-random numbers is called mixed congruential method or power residue method. Here,

\[
R_{n+1} = (mR_n + a) \mod (N) \tag{5.1}
\]
Where \( R_n \) is the \( n \)th random number, \( m \) is the multiplier, \( N \) is very large positive integer and \( 'a' \) is another integer. The \((n+1)\)th element is obtained as a reminder when \((mR_n + a)\) is divided by \( N \). For a given values of \( m \), \( N \) and first number (seed) \( R_1 \), a sequence of numbers fairly evenly distributed over the range \((0, N)\) is obtained. A proper choice of constants can give random sequence with period as large as desirable. When divided by \( N \), we get a random sequence in the range \((0,1)\), which is a standard and is used to derive any other probability distribution function.

5.1.2: Transformation of Random Variables:

Simulation of a real process requires random numbers following a particular distribution law. These can be derived by transforming or mapping the standard random variable [uniformly distributed over \((0,1)\)] on to the parameter space of non uniform distribution. For drawing a set of discrete random variables \( x_1, x_2, \ldots, x_n \) with corresponding probabilities \( p(x_1), p(x_2), \ldots, p(x_n) \), so that

\[
\sum_{i=1}^{n} p(x_i) = 1 \tag{5.2}
\]

the following steps are followed:

(i) A uniform random number \((R_n)\) between 0 and 1 is drawn using a suitable subroutine by power residue method.

(ii) If \( 0 < R_n < p(x_1) \), then \( x \) chosen as \( x_1 \), if \( p(x_1) < R_n < p(x_1) + p(x_2) \), then \( x \) is chosen as \( x_2 \), and so on.

For drawing a continuous random variable \( \nu \) in the interval \((a,b)\), the corresponding probability density function \( f(x) \) is first normalized in the given interval.

\[
N_r \int_{a}^{b} f(x)dx = 1 \tag{5.3}
\]

Where \( N_r \) is the normalization constant. The value of \( \nu \) can be obtained from the cumulative distribution,

\[
F(\nu) = N_r \int_{a}^{\nu} f(x)dx = R \tag{5.4}
\]
It follows that \( F(a) = 0 \) and \( F(b) = 1 \) and \( F'(x) = f(x) > 1 \). From equation (5.4) it is clear that all values of \( \nu \) can be obtained by the inverse transformation of the function \( F(\nu) \) i.e.,

\[
\nu = F^{-1}(R) \tag{5.5}
\]

This method is therefore called inverse transform method.

5.2.: SIMULATION OF ČERENKOV PULSE HEIGHT SPECTRUM:

UHE Cosmic Ray events detected by the rooftop miniarray are simulated by selecting at random core locations within the acceptance area of the miniarray, choosing \( N \) as primary parameter simulated from differential shower size spectrum \( j(N) \propto N^{-(\gamma+1)} \). For each event, depth of shower maximum \( X_m \) is also simulated as main parameter using Gaussian distribution with an exponential tail. Primary energy \( E_o \), Čerenkov LDF parameter \( \delta \) and fluctuation of \( X_m(\sigma_{X_m}) \) are derived as functions of the main parameter.

5.2.1. Simulation of individual shower size (N):

To generate shower size randomly in the range \( 10^7 \) to \( 10^9 \), the differential size spectrum [Equation 2.5(a)] is first normalized in the interval \( 10^7 \)- \( 10^9 \) and then using a random number \( R \) between 0 and 1, the following equation is solved (inverse transform method),

\[
R = \int_{10^7}^{N} AN^{-(\gamma+1)} dN' \tag{5.6}
\]

Where \( A = \text{Normalization constant.} \)

Using this simulated parameter \( N \), primary energy is simulated as secondary parameter using the relation (2.19).

5.2.2. Simulation of individual primary mass:

Three composition models mentioned in chapter II along with pure iron composition models are considered and using simulated primary energy, proton and iron fractions are evaluated first. Let, \( P_{pc} \) and \( F_{pc} \) are percentage of proton and iron as expected theoretically for a particular model, then fraction of protons on the average is,
\[ FPR = \frac{P_{pc}}{P_{pc} + F_{pc}} \]  \hspace{1cm} (5.7)

A random number is generated and it is checked whether it is less than FPR. If it is less, then the primary composition is taken as proton, otherwise iron.

### 5.2.3. Simulation of depth of shower maximum:

The depth of shower maximum `X_m` distribution is assumed to be Gaussian for \( X_m < <X_m> \) and exponential beyond \( <X_m> \left[ \alpha \exp \left( -\frac{X_m}{\Lambda_i} \right) \right] \). The index \( \Lambda_i \) is related to \( \lambda_{p-air} \) through the model dependent co-efficient ‘k’.

\[ \Lambda_i = k \lambda_{p-air} \]  \hspace{1cm} (5.8)

Where \( k=1.2 \) from the result of Quark Gluon String Model [45]. \( \Lambda_i \) is expressed as a function of fluctuation in the depth of maximum \( X_m \), using the relation for proton primary[77].

\[ \sigma_i = 1.4 \lambda_{p-air} \]  \hspace{1cm} (5.9)

After normalization, \( X_m \) distribution assumed the form,

\[ p(X_m) = \frac{1}{\sigma X_m \sqrt{2\pi}} \exp \left\{ -\frac{(X_m - <X_m>)^2}{2\sigma^2 X_m^2} \right\} \text{for} X_m \leq <X_m> \hspace{1cm} (5.10) \]

\[ = \frac{1}{\sigma X_m \sqrt{2\pi}} \exp \left\{ -\frac{(X_m - <X_m>)^2}{0.8571\sigma X_m} \right\} \text{for} X_m > <X_m> \hspace{1cm} (5.11) \]

\( X_m \) values are simulated using the above distribution, with parameters \( <X_m> \) and \( X_m \) derived as function primary energy [25].

Using the modified Elongation Rate Theorem of Linsley,

\[ <X_m>^p = 76.5 \log E_p - 577 \hspace{1cm} \text{(for proton)} \]

\[ <X_m>^{Fe} = 76.5 \log E_p - 712 \hspace{1cm} \text{(for iron)} \] \hspace{1cm} (5.12a & b)

\( \sigma_X \) is fitted from various experiments for protons [84]

\[ \sigma_{X_m}^P = 250 - 10 \log E_p \hspace{1cm} (5.13) \]

For showers initiated by primary mass number \( A \), [77]

\[ \sigma_{X_m}^A = \sigma_{X_m}^P \left( 1 - 0.15 \ln A \right) \] \hspace{1cm} (5.14)
5.2.4. Estimation of Čerenkov pulse height:

Čerenkov light intensity depends on the distance from the shower core (Čerenkov LDF equation 2.12) and the track length integral. The lateral distribution power law index $\delta$ is related to the depth of shower maximum (Equation 2.13). Using simulated value of $X_m$ and $r$, $\delta$ is calculated for each event and Čerenkov intensity is calculated using equation (2.12).

Čerenkov intensity is also proportional to the track length integral $E_{em}$ of electrons, which is a function of primary energy, as given by Linsley [78].

$$E_{em} = E_p \left[1 - 2.8 E_p^{-0.17} (E_p \text{in GeV}) \right]$$ (5.15)

Now, under the assumption that Čerenkov pulse height $H$, recorded experimentally is proportional to Čerenkov intensity. We can write,

$$H \propto E_{em} \Phi(r)$$ (5.16)

The simulation procedure as described above is repeated 500 times for each model of primary mass composition, using high speed computer. This is equivalent to observing 500 air showers in real experiment. The pulse heights are first binned arbitrarily and then compared with the experimental data. The simulated pulse height range and class intervals are readjusted so as to best fit the experimental data.

The comparison with experimental data and analysis with discussion are reported in the next chapter.
CHAPTER VI

ANALYSIS OF EXPERIMENTAL DATA, RESULTS AND DISCUSSION

Experimental data are recorded by Digital Storage Oscilloscope as waveforms containing both optical Čerenkov and OR'ed particle pulse train, satisfying triggering criterion of minimum 100 ns time spread. These records are stored in computer as explained already for further analysis. For each event, the recorded number of particles, arrival time difference between the first and the last particles, called the thickness of the shower-front (\(\sigma\) in ns), the pulse height of optical pulse (in mV) are compiled manually in a data file. This file contains 303 numbers of selected events for analysis. This file is used as input to calculate particle density (\(\rho\)), core distance (\(r\)) and shower size (\(N\)), using Linsley's relations and CORSIKA reanalysis results, and these are recorded along with optical pulse height, in a output file using suitable FORTRAN program.

6.1: PULSE HEIGHT DISTRIBUTION:

From the recorded pulse height of the optical Čerenkov light, first the minimum and maximum heights are deduced using subroutine 'minmax'. These values are 50 mV and 940 mV respectively. The range of pulse height is therefore taken from 50mV to 950mV and divided into 18 number of class intervals each of size 50mV. The frequency of events in each bin is plotted against mean class intervals and compared with simulation results for four different mass composition models, viz., pure proton, pure iron, constant mixed and heavy to light, as already described in chapter V.

To analyse the difference between each model calculation and the experimental data, \(\chi^2\) value is calculated for each case, taking the sum of \({((Y_{\text{obs}} - Y_{\text{exp}})^2)/Y_{\text{exp}}}\), where, \(Y_{\text{obs}}\) is observed (measured) frequency and \(Y_{\text{exp}}\) is the expected frequency from simulation under different composition models. \(\chi^2\) per degree of freedom is the parameter, which has to be minimum for the best fit between calculated and measured data. The experimental pulse height distribution and \(\chi^2\) per degree of freedom are listed in table 6.1. Present analysis gives minimum value 16.25 for pure proton and a bit higher value, 19.92 for a composition changing from heavy to lighter.
Table 6.1: Distribution of Čerenkov Pulse height and photon density.

<table>
<thead>
<tr>
<th>Pulse height (mV)</th>
<th>Class mark (mV)</th>
<th>Čerenkov flux density (photons/m²) (×10^4)</th>
<th>Frequency</th>
<th>Errors</th>
<th>$\chi^2$/d f (model) Proton / Iron / CM / H to L</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 - 100</td>
<td>75</td>
<td>0.77</td>
<td>3</td>
<td>1.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 - 150</td>
<td>125</td>
<td>1.27</td>
<td>10</td>
<td>3.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 - 200</td>
<td>175</td>
<td>1.79</td>
<td>90</td>
<td>9.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 - 250</td>
<td>225</td>
<td>2.3</td>
<td>83</td>
<td>9.11</td>
<td>16.25/ 47.58/ 36.83/ 19.92</td>
<td>Proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 - 300</td>
<td>275</td>
<td>2.81</td>
<td>41</td>
<td>6.4</td>
<td></td>
<td>Composition</td>
</tr>
<tr>
<td>300 - 350</td>
<td>325</td>
<td>3.32</td>
<td>31</td>
<td>5.57</td>
<td></td>
<td>Favoured</td>
</tr>
<tr>
<td>350 - 400</td>
<td>375</td>
<td>3.38</td>
<td>12</td>
<td>3.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 - 450</td>
<td>425</td>
<td>4.44</td>
<td>17</td>
<td>4.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450 - 500</td>
<td>475</td>
<td>4.86</td>
<td>7</td>
<td>2.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 - 550</td>
<td>525</td>
<td>5.54</td>
<td>2</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 - 600</td>
<td>575</td>
<td>5.88</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 - 650</td>
<td>625</td>
<td>6.57</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>650 - 700</td>
<td>675</td>
<td>6.90</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 - 750</td>
<td>725</td>
<td>7.41</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750 - 800</td>
<td>775</td>
<td>7.92</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800 - 850</td>
<td>825</td>
<td>8.61</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850 - 900</td>
<td>875</td>
<td>8.94</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>900 - 950</td>
<td>925</td>
<td>9.45</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6.1: Čerenkov pulse height spectrum for pure proton composition model.

Fig. 6.2: Čerenkov pulse height spectrum for pure iron composition model.
Fig. 6.3: Čerenkov pulse height spectrum for constant-mixed composition model.

Fig. 6.4: Čerenkov pulse height spectrum for heavy to light composition model.
Comparison with simulation for four composition models are shown in fig. 6.1 to 6.4. Thus, based on pulse height distribution measurement, the inferred mass composition is predominantly protons, with a tendency of mass composition becoming lighter at the highest energies.

**6.2 : ČERENKOV LATERAL DISTRIBUTION :**

It is well known that, Čerenkov lateral distribution reflects the longitudinal development of EAS, and in particular, slope of the Lateral Distribution Function ‘$\delta$’ is linearly related with the depth of shower maximum [93]. Again depth of maximum development of a shower depends on primary mass composition. It is found that the rate of change of depth of shower maximum ($X_m$) with log of primary energy, called elongation rate is constant. Modified elongation rate theorem of Linsley gives two parallel lines as plots of $X_m$ versus log($E_p$) for mass composition $A=1$ (proton) and $A=56$ (iron) [ equation 2.16 a & b]

Now, as we have only one Čerenkov detector, it is not possible to derive lateral distribution for each individual events. Therefore, data are grouped into narrow shower-size bins, so that within one group, all the events on the average have the same shower size, hence, approximately the same average primary energy.

Using a FORTRAN program, maximum and minimum values of recorded $N$ are deduced as $1.57 \times 10^7$ and $1.98 \times 10^9$ respectively. Next step is to divide the range (7.109 to 9.295 in the log scale) from lower limit 7.1 to upper limit 9.3, with class interval 0.2, and group the records in output files for each bin separately. For each shower size bin, average $\langle \log(N_p) \rangle$ is used to deduce the average primary energy using the relation [CORSIKA reanalysis, equation 2.19]

$$\langle \log(E_p) \rangle = 11.3458 + 0.798 \langle \log(N_p) \rangle$$

Logarithm of Čerenkov flux density is plotted as function of logarithm of core distance for each bin and shown in fig.6.5 to 6.11, along with the expected LDF. For a power law LDF, this is a straight line with slope as the power index $\delta$. The value of ‘$\delta$’ and its error are estimated by least square method using the software, 'gnuplot' and these are used to deduce the mean depth of maximum (with error), using the relation, ( equation 2.13)

$$\delta = 0.001 \langle X_m \rangle + 1.6$$
Mean $<X_m>$ with the measured error are plotted as function of $<\log(E_p)>$ and compared with lines given by modified ER theorem in fig.6.11.

\[
\langle X_m \rangle^p = 76.5 \log E_p - 577 \text{ (for Proton)}
\]

\[
\langle X_m \rangle^{fe} = 76.5 \log E_p - 712 \text{ (for Iron)}
\]

where $X_m$ is in gm/cm$^2$ and $E_p$ is in eV, deduced as a.

Following table shows the result of analysis of each group of data using least square method (gnuplot)

Table : 6.2 : Cerenkov lateral distribution parameter from binned data.

<table>
<thead>
<tr>
<th>bin no.</th>
<th>no. of events</th>
<th>$&lt;\log(Np)&gt;$</th>
<th>$&lt;\log(Ep)&gt;$</th>
<th>best fitted slope</th>
<th>error on slope</th>
<th>Measured depth of maximum($X_m$)+/- error (gm/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>14</td>
<td>7.3</td>
<td>17.17</td>
<td>-1.9 +/- 25.9%</td>
<td></td>
<td>299 +/- 77.15</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>7.9</td>
<td>17.65</td>
<td>-1.82 +/- 17.1%</td>
<td></td>
<td>221 +/- 37.62</td>
</tr>
<tr>
<td>6</td>
<td>42</td>
<td>8.1</td>
<td>17.81</td>
<td>-2.29 +/- 28.4%</td>
<td></td>
<td>692 +/- 196.24</td>
</tr>
<tr>
<td>7</td>
<td>93</td>
<td>8.3</td>
<td>17.97</td>
<td>-2.37 +/- 24.5%</td>
<td></td>
<td>766 +/- 187.78</td>
</tr>
<tr>
<td>8</td>
<td>47</td>
<td>8.5</td>
<td>18.13</td>
<td>-2.35 +/- 15.4%</td>
<td></td>
<td>749 +/- 114.79</td>
</tr>
<tr>
<td>9</td>
<td>26</td>
<td>8.7</td>
<td>18.29</td>
<td>-2.03 +/- 15.0%</td>
<td></td>
<td>430 +/- 64.5</td>
</tr>
</tbody>
</table>

Total number of 303 events are binned in 12 size groups, out of which bin numbers 1,3,4,10,11 and 12 containing 28,4,10,23,5 and 2 data points respectively are not considered due to insufficient statistics or inconsistency.
Fig. 6.5: Experimental Čerenkov lateral distribution with fitted curve for energy bin $\langle \log(E_p) \rangle = 17.17$

Fig. 6.6: Experimental Čerenkov lateral distribution with fitted curve for energy bin $\langle \log(E_p) \rangle = 17.65$
Fig. 6.7: Experimental Čerenkov lateral distribution with fitted curve for energy bin $\langle \log(E_p) \rangle = 17.81$

Fig. 6.8: Experimental Čerenkov lateral distribution with fitted curve for energy bin $\langle \log(E_p) \rangle = 17.97$
Fig. 6.9: Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 18.13 \)

Fig. 6.10: Experimental Čerenkov lateral distribution with fitted curve for energy bin \( \langle \log(E_p) \rangle = 18.29 \)
6.3 : DISCUSSION :

Figures 6.5 to 6.10 show the experimental lateral distribution of Čerenkov flux density along with best fitted lines. Based on these measurements of the slope of Čerenkov LDF in the log scale, 'δ' is estimated with respective errors. These values are used to deduce the average depth of shower maximum, $\langle X_m \rangle$ with error for each bin. Under the assumption that the grouped data have the same primary energy corresponding to mean shower size of each bin (deduced from miniarray reanalysis result), $\langle X_m \rangle$ is plotted against average log of primary energy, $\langle \log(E_p) \rangle$ [fig.6.11]. When compared with modified elongation rate theorem of Linsley, we see that, errors on data are such that there is no sensitivity to change of mass composition.

![Fig.6.11: Plot of $\langle X_m \rangle$ vs average $\langle \log(E_p) \rangle$ for each bin compared with modified ER Theorem of Linsley.](image)

Conclusion and remarks of our theoretical as well as the experimental investigations are reported in the next Chapter VII.
CHAPTER VII

CONCLUSION

7.1. CONCLUDING REMARKS:

Cosmic Ray Physics has made enormous progress in recent years and importance is shifted to UHE region due to diverse experimental findings with low statistics, specially around the so called GZK cutoff. We still do not have definitive models for the origin, acceleration and propagation of cosmic rays. The energy region from the first knee to the second knee (1–100 PeV) needs better and more definitive experiments to measure the mass composition of galactic Cosmic Rays [51]. Different experiments do not agree as to the location of the rigidity cutoff and search for local sources remains puzzling. Questions still remain, are the highest energy galactic Cosmic Rays heavy nuclei?; are there Cosmic Rays beyond GZK cutoff, if so what are they?

Gauhati University miniarray is the smallest EAS array detecting UHE giant air showers operating in a hybrid mode, simultaneously measuring optical pulse from the centre of the miniarray. However, the data are subjected to large fluctuation both in particle detection and optical photon detection. Primary energy is estimated through the parameter shower size which is also indirectly measured from a small sample of shower front using miniarray. Mass composition estimated indirectly relies on simulation model. Further, the Lateral Distribution Function parameter ‘$\delta$’ is deduced from data grouped in narrow shower size or energy bins, where individual optical pulse heights are found to scatter around a power low LDF. Estimates of slope of LDF in the Log scale for selected shown size bins are used to derive depth of shower maximum as a function of primary energy.

Contribution of GU Miniarray detector to UHECR world data cannot be discarded as the structure function exponent of energy spectrum measured by mini array in the energy range $10^{17}$-$10^{18}$ eV, is comparable to result of other groups. It has mainly two important advantages of low cost and small size requiring less labour and time. However, the systematic errors of present measurements are such that it is difficult to have good sensitivity to make precise measurement from one miniarray and one Čerenkov detector only. These drawbacks may be overcome by
increasing the size of the miniarray and using more than one mini arrays so that more particles can be detected per event and unwanted events may be distinguished easily.

It is indeed very difficult to draw conclusion about primary mass composition with so many restrictions on primary and secondary parameters. More number of Čerenkov detectors with reflecting mirrors would definitely improve our results. The other constrains in doing the optical measurements are requirement of cloudless, moonless, dry weather conditions, rarely found in this part of our country.

In future, along with the proposed extended miniarray detector (with RPC), combination of more numbers of miniarrays and an array of Čerenkov counters may be setup, so as to collect more optical data for each shower event. This will help to deduce the LDF parameter more accurately. Further, detailed pulse profile measurement will help to draw reliable conclusion regarding primary mass composition.
APENDIX I

A program to copy BMP files from DSO to hard disk
DSO is set in SINGLE ACQUISITION MODE

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <conio.h>
#include <windows.h>
#include "c:\borland\bce55\bin\decl-32.h"
#include <malloc.h>
#include <stdlib.h>

#define ARRAYSIZE 1024
#define BDINDEX 0 // Board Index
#define PRIMARY_ADDR_OF_SCOPE 1 // Primary address of device
#define NO_SECONDARY_ADDR 0 // Secondary address of device
#define TIMEOUT T30s // Timeout value = 10 seconds
#define EOTMODE 1 // Enable the END message
#define EOSMODE 0 // Disable the EOS mode


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Names of the output BMP files

char output[100][7]=
{"bmp1","bmp2","bmp3","bmp4","bmp5","bmp6","bmp7","bmp8","bmp9","bmp10",
"bmp11","bmp12","bmp13","bmp14","bmp15","bmp16","bmp17","bmp18","bmp19",
"bmp20","bmp21","bmp22","bmp23","bmp24","bmp25","bmp26","bmp27","bmp28",
"bmp29","bmp30","bmp31","bmp32","bmp33","bmp34","bmp35","bmp36","bmp37",
"bmp38","bmp39","bmp40","bmp41","bmp42","bmp43","bmp44","bmp45","bmp46",
"bmp47","bmp48","bmp49","bmp50","bmp51","bmp52","bmp53","bmp54","bmp55",
"bmp56","bmp57","bmp58","bmp59","bmp60","bmp61","bmp62","bmp63","bmp64",
"bmp65","bmp66","bmp67","bmp68","bmp69","bmp70","bmp71","bmp72","bmp73",
"bmp74","bmp75","bmp76","bmp77","bmp78","bmp79","bmp80","bmp81","bmp82",
"bmp83","bmp84","bmp85","bmp86","bmp87","bmp88","bmp89","bmp90","bmp91",
"bmp92","bmp93","bmp94","bmp95","bmp96","bmp97","bmp98","bmp99","bmp100";
main()
{
    int Dev;
    int i;
    int n;

    char ValueStr[ARRAYSIZE+1];
    /**********************************************************************************/
    /* The following contains string to set the DSO parameters */
    /**********************************************************************************/

    char sa[]="ACQUIRE:STATE RUN";
    char sb[]="HARDCOPY:FORMAT BMP";
    char sd[]="HARDCOPY:PORT GPIB";
    char sc[]="HARDC STAR";
    char sf[]="ACQUIRE:STATE?";

    /*************************INITIALIZATION SECTION**************************/
    /*
    /***************************************************************************/

    /**********************************************************************************
    /* The application brings the oscilloscope online using ibdev. A */
    /* device handle, Dev, is returned and is used in all subsequent */
    /***************************************************************************/
/* calls to the device. */

Dev=ibdev(BDINDEX, PRIMARY_ADDR_OF_SCOPE, NO_SECONDARY_ADDR,
           TIMEOUT, EOTMODE, EOSMODE);
if (ibsta & ERR)
{
    printf("Unable to open device\nibsta = 0x%x iberr = %d\n",
           ibsta, iberr);
    return 1;
}

/* Clear the internal or device functions of the device. If the error bit ERR is set in ibstra, print the error message. */

ibclr (Dev);
if (ibsta & ERR)
{
    printf("Unable to clear device\nibsta = 0x%x iberr = %d\n",
           ibsta, iberr);
    return 1;
}

/* MAIN BODY SECTION */

/* Set the DSO to RUN MODE */

ibwrt(Dev, sa,strlen(sa));
if(ibsta & ERR)
{
    printf("Unable to set the DSO to run mode\nibsta = 0x%x iberr = %d\n",
           ibsta, iberr);
    return 1;
}

/* Set output format to BMP */

ibwrt(Dev, sb,strlen(sb));
if (ibsta & ERR)
{
    printf("Unable to set output to bmp format\nibsta = 0x%x iberr = %d\n",
           ibsta, iberr);
return 1;
}

ibwrt(Dev, sd, strlen(sd));
if (ibsta & ERR)
{
    printf("Unable to set output port to GPIB\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
    return 1;
}

ibwrt(Dev, "HEADER OFF", 10L);
if (ibsta & ERR)
{
    printf("Unable to header off\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
    return 1;
}

for(i=0;i<=100;i++)
{

do
    ibwrt(Dev, sf, strlen(sf));
    if (ibsta & ERR)
    {
        printf("Unable to get status of acquire\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
        return 1;
    }

/* Read the status of ACQUIRE.Continue reading the status if the status is */
/* '1' i.e The DSO is in run mode. If The DSO is in Status '0' i.e it has */
/* acquired data then come out of The Loop and Copy The BMP file to hard */
/* disk */
/* Make the LOOP 101 times to copy the BMP file 100 times */

/* Set output port to GPIB */
ibrd(Dev, ValueStr, ARRAYSIZE);
if (ibsta & ERR) {
    printf("Unable to read state\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
    return 1;
}

ValueStr[ibcntl-1]="0';
 sscanf(ValueStr, "%d", &n);

while(n==1);

ibwrt(Dev, sc, strlen(sc));
if (ibsta & ERR) {
    printf("Unable to hardcopy start\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
    return 1;
}

ibrdf(Dev, &output[i][0]);
if (ibsta & ERR) {
    printf("Unable to set the output file\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
}
return 1;
}

/**************************************************************************
/*  Set the Command to again Run the DSO for next acquisition            */
/**************************************************************************/

ibwrt(Dev, sa,strlen(sa));

if (ibsta & ERR)
{
    printf("Unable to run\nibsta = 0x%x iberr = %d\n", ibsta, iberr);
    return 1;
}

printf("file no is %d\n",i);

return 1;
APENDIX II

FORTRAN Program to Calibrate Čerenkov Counter

Input parameters:
- radius of PMT = r0 = 6.4 cm
- radius of water tank = r1 = 20 cm, height of water tank = z1 = 22 cm
- Čerenkov angle = 41 degrees; tan(θc) = tn
- effective path length for Čerenkov photon emission = z
- area over which Čerenkov photons are distributed = ar
- area of overlap = ar0

Number of Čerenkov photons falling on PMT = qp

```fortran
real r, rr, r0, r1, z1, tn, z, ar, ar0, arx, qp, ph, big, sml, rang
integer ci, ix, nc, lx, ux, ibin, ic, jfr
dimension ph(1000), jfr(100)
parameter(pi = 3.141592654, r0 = 6.4, r1 = 20., z1 = 22., tn = 0.8692867)
open(8, file='cercl1', status='new', access='sequential', form='formatted')
open(9, file='cercl2', status='new', access='sequential', form='formatted')
write(*, *) 'random number seed ?'
read(*, *) ix
do 20 i = 1, 20
   rr = rn(ix)
   r = rr * 20.
   if(r.lt.r0) then
      z = (r + r0)/tn
      ar = pi * (r + r0)**2
      ar0 = pi * r0 * r0
   else if(r.lt.(r1 - 2*r0)) then
      z = 2*r0/tn
      ar = 4*pi*r*r0
      ar0 = pi*r0*r0
   else
      z = (r1 - r)/tn
      ar = pi*r0*(2*r - r0)
      rx = r1 - r - r0
      arx = abs(rx)
      if(arx.lt.3.2) then
         ar0 = pi*r0*r0/2 + 2*r0*rx
      else if(rx.lt.0.) then
         ar0 = r0*(r0 + rx)
      else
         ar0 = pi*r0**2 - r0*(r0-rx)
      endif
   endif
   qp = 200*z*ar0/ar
   continue
20 continue
```

103
ph(i)=qp
write(8,25) i, ph(i)
20 continue
25 format(5x,I5,5x,F10.2)
nc=i
big=ph(1)
sml=ph(1)
do 30 i=1,nc
   if(ph(i).gt.big) then
      big=ph(i)
   endif
   if(ph(i).lt.sml) then
      sml=ph(i)
   endif
30 continue
rang=big-sml
ci=10
lx=int(sml/10)*10
ux=int(1+big/10)*10
ibin=(ux-lx)/10
c Cerenkov pulse height (=photon number) in the ith observation = ph(i)
c rang = range ; lx= lower limit; ux= upper limit;
c ci= class interval;  ibin= total number of bins.
c jfr(i)= frequency in the ith bin.
   write(*,*) 'big=', big, 'small=', sml, 'range=', rang
   write(*,*) 'lower=', lx, 'upper=', ux, 'total bins=', ibin
   do 40 i=1,ibin
      jfr(i)=0
40 continue
do 50 i=1,nc
   ic=int((ph(i)-lx)/10)+1
   jfr(ic)=jfr(ic)+1
50 continue
do 60 i=1,ibin
   write(9,65) i, jfr(i)
60 continue
65 format (2(5x,I5))
   close(8,status='keep')
   close(9,status='keep')
stop
endc*******************************************************************
c FUNCTION
FUNCTION
   Random Number Generator
   Random Number Generator
   ...........................................................
   function rn(iseed)
   function rn(iseed)
      parameter(m=714025,ia=1366,ic=150889)
iseed = mod(iseed*ia+ic,m)
iseed = abs(iseed)
rn = float(iseed)/float(m)
end
APENDIX III

START

DEV ← BRING THE DEVICE ONLINE

IS ERR. BIT SET?

YES → PRINT = "UNABLE TO OPEN DEVICE ", ERR

NO → DEV ← CLEAR THE DEVICE

IS ERR. BIT SET?

YES → PRINT = "UNABLE TO CLEAR DEVICE ", ERR

NO → DEV ← SET THE DSO TO RUN MODE

IS ERR. BIT SET?

YES → PRINT = "UNABLE TO SET THE DSO TO RUN MODE ", ERR

NO → DEV ← SET OUTPUT FORMAT TO BMP

IS ERR. BIT SET?

YES → PRINT = "UNABLE TO SET OUTPUT TO BMP FORMAT ", ERR

NO → STOP

1

STOP
1. DEV ← SET THE OUTPUT PORT TO GDB
   
   IS ERR BIT SET ?
   
   YES
   PRINT = "UNABLE TO SET THE OUTPUT PORT TO GDB. ERR.
   STOP
   
   NO
   DEV ← HEADER OFF
   
   IS ERR BIT SET ?
   
   YES
   PRINT = "UNABLE TO HEADER OFF. ERR.
   STOP
   
   NO
   FOR I = 0 TO 100
   
   2
   
   3
   
   5
   
   DEV ← GET THE STATUS OF ACQUIRE
   
   IS ERR BIT SET ?
   
   YES
   PRINT = "UNABLE TO GET THE STATUS OF ACQUIRE. ERR.
   STOP
   
   NO
   READ VALUE STR
   
   2
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2. Calibration of Particle Detectors with Digital Storage Oscilloscope.

3. Cosmic Ray mass composition above $10^{17}$ eV.
   Proc. 2nd Regional Conference on Physics Research in North East, vol-1,

4. Resistive Plate Counters as Particle Detectors for Cosmic Ray Experiment.
   Proc. 2nd Regional Conference on Physics Research in North East, vol-1,

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6. Development of Resistive Plate Counter for the Extended Mini-Array Experiment
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8. Optical Pulses Associated with UHE Cosmic Rays.

   Proc. 29th ICRC, Pune, India, Vol. 8, p. 81-84.

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INTERNATIONAL / NATIONAL CONFERENCE SEMINER / SCHOOL / WORKSHOP / SYMPOSIA ATTENDED.

(i) Joined in the Winter School on Gamma Ray Astronomy organized by Tata Institute of Fundamental Research, Mumbai & Inter University Centre for Astronomy and Astrophysics, Pune, at the High Energy Gamma Ray Observatory Centre, Panchmarhi, during Oct.26 to Nov.5, 1998.

(ii) Participated First National Conference on Thermo physical Properties (Solid & Fluid), Department of Physics, Gauhati University, Guwahati, during March 11th to 13th, 1999.


(v) Joined in the Advanced Lecture Series of Ph.D. Teaching Programme on Data Acquisition System and Heavy Ion Reaction at Nuclear Science Centre, New Delhi during 28th April to 22nd May, 2000.


(vii) Participated Spring School on Soft Computing Data Mining and Image Processing organized by Indian Statistical Institute, Calcutta and Gauhati University, Guwahati, during 12-16 March, 2001 at Gauhati University.


(ix) Participated International conference on Solid and Fluid held at Gauhati University, Guwahati, during Oct. 8-11, 2001.

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