Chapter-1

INTRODUCTION

The primary cosmic radiation (PCR) , coming from galactic and extra-galactic sources is the only stream of ultra high energy (UHE) cosmic particles available on the earth. The energy of the PCR ranges from ~10^9eV to ~10^{20}eV. The upper limit is far beyond the energy available in the accelerator laboratories on the earth and is not likely to be attained in the foreseeable future. The primary radiation appears to be composed of light and heavier nuclei. Some of the PCR sources may also be the sources of UHE gamma rays.

It has been possible to determine the energy distribution of the PCR nuclei in various experiments. The lower energy region (10^9 to 10^{11}eV) has been investigated in baloon flight measurements . Nuclear emulsion stacks sent to high altitudes by baloons and rockets have yielded data in the energy region 10^{11} to 10^{13}eV. For energies at and above 10^{14}eV, the estimates come from observations on extensive air shower(EAS).

Fig.1.1a shows the highest range of the PCR energy spectrum as measured by the AGASA array (Yoshida S. et al.[1]). An important feature of the spectrum is a bend known as "knee" at about 5X10^{15}eV. The break is conjectured to be the transition from galactic to extra-galactic particles. There is another apparent break known as the "ankle" , where the spectrum flattens . The "ankle" corresponds to an energy of about 10^{19}eV.

The PCR, mostly atomic nuclei, on entering the earth's atmosphere suffer different types of nuclear interactions with atomic nuclei in the atmosphere and produce different kinds of secondary nuclear particles . If the energy of the primary nucleus is greater than 10^{14}eV, the total number of secondaries in the atmospheric shower (EAS) is very large .

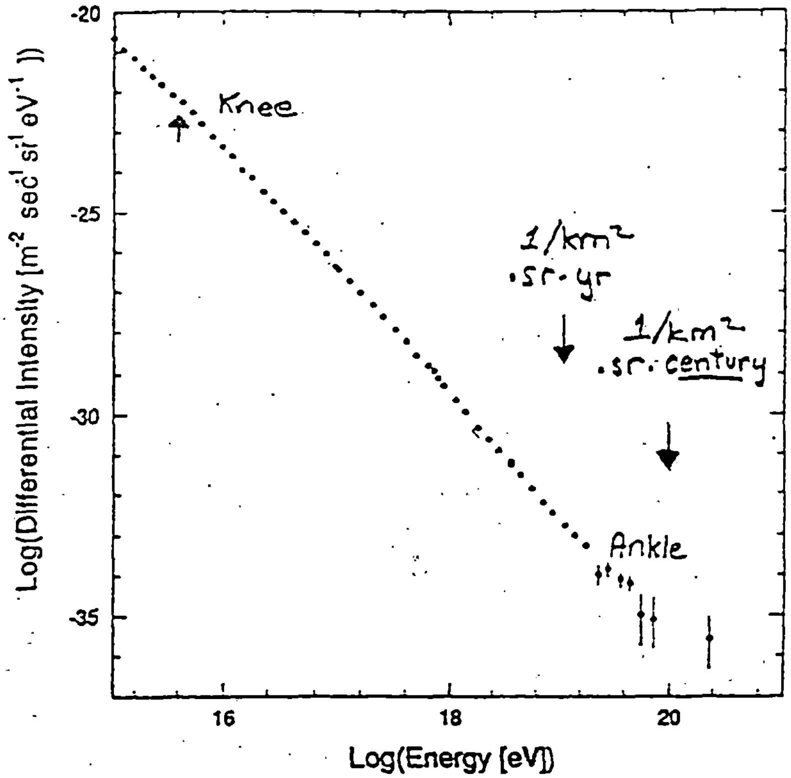

Fig. 1.1a.
The primary energy spectrum obtained at Akeno.

1.1 The Extensive Air Shower (EAS) :

A schematic diagram of the development of EAS in the atmosphere is shown in fig.1.1b. When a high energy PCR nucleus is incident on top of the atmosphere, it loses its energy in successive nuclear interactions as it propagates down. As a result, different kinds of secondary particles are produced. The created particles are hadrons, such as pions, kaons, nucleons, hyperons and their anti particles. The secondary hadrons, practically continue in the direction of the primary and undergo further nuclear interactions and as a result a hadronic cascade is developed. Many of the pions undergo decay with a mean life $2.6X10^{-8}$ sec. and produce muons and neutrinos. The muons produced in the decay of charged pions, come down to sea level because of their relatively longer life time (mean life $2.2X10^{-6}$s.), constitute the penetrating or hard component of the EAS. The neutral pions (Π^{o}) decay almost immediately to produce two gamma ray photons (γ), which initiate electromagnetic cascade. In the electromagnetic cascade, at each stage each gamma ray photon produces a pair of electrons ($e^{\pm}$). The energy of the photon is equally distributed between the two particles. Each electron, when accelerated or decelerated by nuclear coulomb field during their motion, it lose a fraction of their energy by bremstrrahlung. The photons, thus created are also of high energy and hence they create electron pairs. The process goes on until the energy of the individual electron drops to the point that it is unable to create any further photon. Thus at the detector level, millions of electrons, positrons and photons are present. These constitute the electron-photon component of the EAS.

Since most electrons are ultra-relativistic all through and their velocities are higher than the velocity of light in the atmosphere, they give rise to a considerable amount of Cerenkov radiation. The electrons in the shower front also give rise to coherent emission of radio waves in the frequency range of 1MHz to several hundred MHz .

Again if the PCR is an UHE gamma ray, two types of interactions take place between the UHE gamma ray and the atmospheric air nuclei- photonuclear interaction and electromagnetic interaction process of e^+e^- pair and $\mu^+\mu^-$ pair production. In the photonuclear interaction, muons are generated through production and subsequent decay of pions $[\Pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\tilde{\nu}_{\mu})]$. The cross section for photonuclear interaction is given (Bezrukov L.B. et al[2]) as

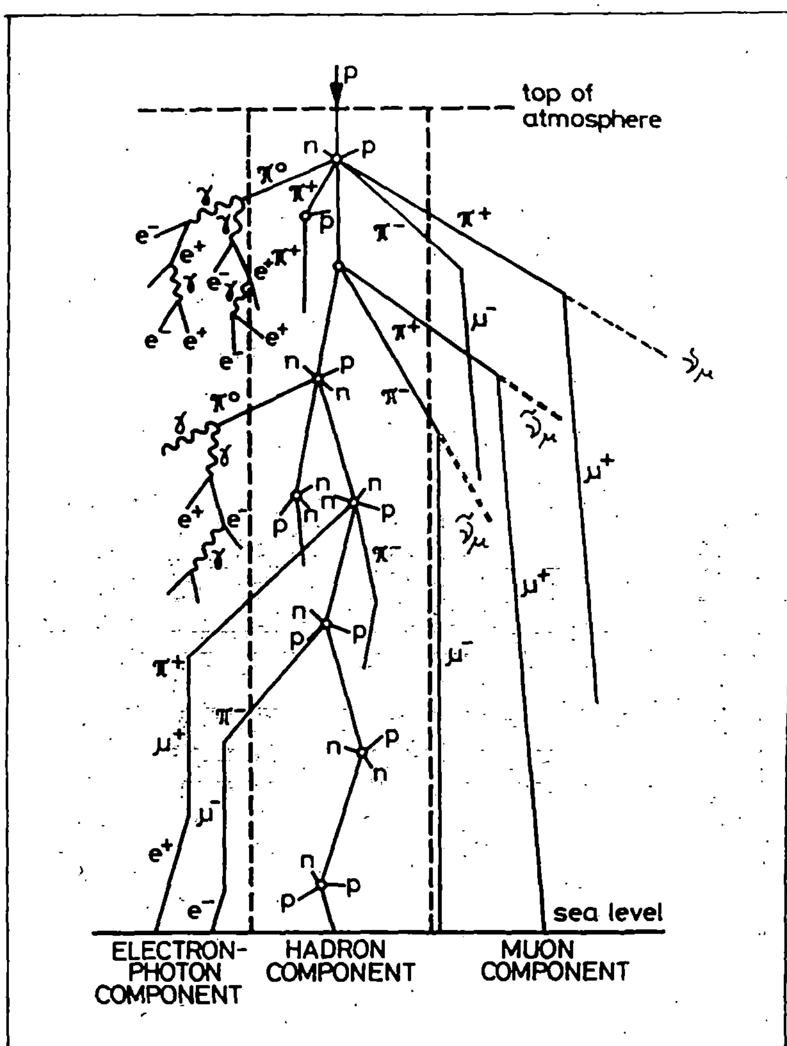

Fig. 1.1b.
A schematic diagram of EAS development in the atmosphere (neutrinos are not shown in all the muon and pion decay).

$$\sigma_{\gamma\text{-}p}(E) = 114.3 + 1.647 \ln^2 (0.0213E) \ [\mu b]$$

where E is the energy of the primary gamma ray in GeV.
This cross section is small compared to the electromagnetic interaction cross section for e^+e^- and $\mu^+\mu^-$ pair production. The production of $\mu^+\mu^-$ pair by photons is analogous to the creation of e^+e^- pair in nuclear coulomb field and in the asymptotic case of full screening of the nuclear field by the atomic electrons.

$$\sigma_{\mu+\mu-}/\sigma_{e+e-} = (m_e/m_\mu)^2$$

which is very small. As a result, gamma ray initiated showers should be muon poor. Wdowezyk (Wdowezyk J.[3]) first made detailed theoretical calculation and concluded that muon content in gamma ray initiated showers should be lower than that of normal showers.
The secondary particles thus created because of the incidence of a high energy PCR nucleus or UHE gamma ray, are strongly beamed in the forward direction, and on the average retain the directionality of the PCR. At each interaction level, the particles spread out laterally because of multiple coulomb scattering with the air nuclei. The total number of particles i,e, shower size of the EAS at first increases with increasing atmospheric thickness, attains a maximum and then begins to decrease due to the absorption through energy loss processes of the electrons and photons in the atmosphere.
Most of the secondary particles near the maximum of shower development are electron-photon component or soft component and muon component or hard component. Some strongly interacting particles (hadrons ,~1%), Cerenkov radiation and radio-waves are also present at the detector level. Considering the scope of the present experiment, electron-photon component and muon component of EAS are discussed briefly.

1.2. **The electron-photon component:**

The electron-photon component is the most abundant component in EAS and constitute almost 90% of the shower particles. Considering the scope of the present experiment, properties of EAS are described briefly in the following sections .

1.2.1. Lateral distribution of electrons:

The lateral spread of electrons in the electromagnetic cascade is due to several causes, the angles of emission of π^o mesons in hadron-hadron collision, the angle between the γ-rays in the π^o decay, the angle between the electron pair in pair production process of γ-ray, the angle of scattering of electrons off air nuclei. Several workers show that the actual distribution of the number of particles per unit area (i,e, density) is a function of distance from the axis of the shower.The density of the shower particles is maximum at the core of the shower and it falls off rapidly with distance from the core. From their calculation it appears that the shape of the distribution does not change with the number of particles at the maximum development.

The density of electrons at some distance r from the shower core, $\Delta(r)$ is given by

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

where N_e is the total number of electrons in EAS i,e, shower size, r_o is the Moliere unit of length, $f(r/r_o,s)$ is the lateral distribution function (ldf) or structure function and s is a parameter, termed as shower age , which is linked to the longitudinal development of the shower.

Different authors proposed different functional form of the 'ldf.' The most extensively used 'ldf' is given by Nishimura and Kamata (Nishimura J. et al [4]) in the Greisen (Greisen K.[5]) approximation and is known as NKG function. The form of the function is given by

$$f(r/r_o,s) = C(s).(r/r_o)^{s-2}.(1+r/r_o)^{s-4.5} \quad \text{........................(1.2)}$$

Where C(s) is the normalisation constant, r_o =79m at sea level and s is the age parameter which describes the stage of development of the shower. According to the cascade theory, longitudinal age is given by

$$s = 3t/(t+2\ln(E_o/\varepsilon_o)) \quad \text{...(1.3)}$$

where t is the thickness of the atmosphere, E_0 is the primary energy and ε_0 is the critical energy for electrons in air and is equal to 84MeV.

However, for several years, a number of authors has pointed out that the NKG function does not give a good description of the electron lateral distribution of air shower.

The electron 'ldf' given by Hillas and Lapikens (Hillas A.M. et al [6]) is of the form

$$f(r/r_0,s) = C(s).(r/r_0)^{a1+a2(s-1)}.(1+r/r_0)^{b1+b2(s-1)} \quad ....(1.4)$$

where the parameters chosen for the best fit of the present experimental results (chapter-3) are

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

Linsley proposed a double parameter function, characterised by α and η (Linsley J. [7]), to replace the NKG function and is given by

$$f(r/r_0) = C(\alpha,\eta).(r/r_0)^{-\alpha}.(1+r/r_0)^{-(\eta-\alpha)} \quad ....(1.5)$$

When r approaches zero, the distribution is determined by α and when r approaches infinity, the distribution is determined by η.

Capdevielle (Capdevielle J. N. et al [8]) assumed that the shower age parameter in the 'ldf' should be the local age for radial development of shower and defined as

$$s(r) = \alpha \log \beta(r/r_0) + s_t,\ \text{for } r < 150m \quad ....(1.6)$$

where s_t is the longitudinal age parameter at the level of observation and α,β are constants. With this modification, 'ldf'of electrons by Capdevielle et al is given by

$$f(r/r_0,s) = C(s).(r/r_0)^{s(r)-2}.(1+r/r_0)^{s(r)-4.5} \quad ....(1.7)$$

By fitting any one of the above functions to the observed density of shower particles, shower parameters viz. shower size (N_e), shower age (s) and shower core location (X_0,Y_0) are determined.

1.2.2. **The local age parameter in EAS :**

The formula of Nishimura, Kamata and Greisen (NKG) has been much used both in the simulation of EAS also in the description of experimental results. However it doesn't correspond exactly to the observed shape of the lateral distribution of electrons, because of the use of unique value of age parameter over the whole radial distance from the core. At the level of observation of showers, the electron density distribution showing a fit to an effective age parameter (s) results from the superposition of a number of local young and old electron-photon cascades having individual local age parameter. Capdevielle proposed (Capdevielle J.N.et al. [9]) that the age parameter depending on distance from the core, known as local age parameter and for a given structure function, the local age parameter is as follows -

$$s(r) = [1/(2X + 1)] .[(X+1).(\delta \ln f/\delta \ln X)+ (2+\beta_0)X +2]$$

Here $\beta_0 = 4.5$, f is NKG function, $X = r/r_0$ and r_0 = Moliere unit of length.
The relation between the longitudinal age (s_t) and local age [s(r)] is

$$s(r) = \alpha \log\beta \, (r/r_0) + s_t \quad \text{for } r < 150\text{m}.$$

where α and β are constants.

1.2.3. **Shower size spectrum:**

By the term shower size spectrum, it means that the number of showers, F(N)dN, containing total number of particles between N and N+dN, whose axes are incident upon unit area in unit time at the shower size N. If all showers have the same structure, then the relation between density spectrum $\nu(\Delta)d\Delta$ (no. of showers between the densities in the range Δ & $\Delta+d\Delta$ particles per sq.m. observed per unit time per unit area) and the size spectrum at a given point (Galbraith W.[10]) is

$$\nu(\Delta)d\Delta = 2\pi \int_0^\infty r.F(N)dN.dr \quad \text{...(1.8)}$$

Assuming that all showers have the same structure, the density at a distance r from the axis is given by

$$\Delta(r) = f(r).N \quad \text{...(1.9)}$$

Substituting the values of N from above equation to equation (1.8) we get,

$$\nu(\Delta)d\Delta = \int_0^\infty 2\pi r.F[\Delta(r)/f(r)].d[\Delta(r)/f(r)].dr \quad \text{.......................(1.10)}$$

Now, if we represent size spectrum as

$$F(N)dN = K.N^{-\gamma'-1}.dN \quad \text{...(1.11)}$$

where γ' is the spectrum index
we have,

$$\nu(\Delta)d\Delta = 2\pi.K'.\Delta^{-\gamma'-1}.d\Delta.\int_0^\infty r.f(r)^{\gamma'}.dr \quad \text{................................(1.12)}$$

The integral is independent of Δ, and thus the experimental density spectrum [$\nu(\Delta)d\Delta = K.\Delta^{-\gamma-1}.d\Delta$] may be compared with the equation (1.12).
clearly , $\gamma' = \gamma$
Thus the differential size spectrum can be written as

$$F(N)dN = A.N^{-\gamma-1}.dN$$

and for integral size spectrum

$$I(>N) = C.N^{-\gamma}$$

where A and C are constants.
Thus, we see that the size spectrum can be represented by a power law with exponent γ and the exponent in the size spectrum is the same as density spectrum.
The observed shower size spectrum in the present work shows a "knee" in the shower size region (5-7) X10^5 particles.
The shower size is a measure of the total energy of the primary particle. The relation between the shower size (N_e) and primary energy (E_o) can be expressed as

$$E_0 \sim N_e^{\beta}$$

The value of β is 0.87 (Trzupek et al.[11]).
Thus, shower size spectrum represents the primary energy spectrum.

1.2.4. Zenith angle distribution:

If $R(>N)_\theta$ be the rate of showers at a zenith angle θ and $R(>N)_o$ be the rate of vertical showers at a vertical depth t, then zenith angle distribution can be written in the form of cosine power as

$$R(>N)_\theta = R(>N)_o . \cos^n\theta.$$

The value of the index 'n' decreases with increase of altitude. Using this power index, barometric coefficient i.e., the variation of rate of showers of a given size with change of barometric pressure can be calculated (section-4.1.3, chapter-4).

1.3. The muon component:

Muons, having no strong interaction with matter, reach the observation level, losing its energy only by ionisation, from the point of their production. The ionisation loss in the atmosphere is comparatively small and the mean life of muons is comparatively long. The number of muons after reaching a maximum in the atmosphere decreases slowly with increasing atmospheric depth. As a consequence, muons become the dominant component of the cosmic radiation near the sea level. Muons constitute about 6-9% (Yash Pal [12]) of the total number of particles in EAS and spread out to much wider area than the electromagnetic component.

The muons of different energies in EAS have been studied using magnetic spectrographs associated with the air shower array. The lateral distribution of low and high energy muons can be represented by the equation of the form-

$$\rho_\mu (\geq E_\mu, r, N_e) \sim r^{-\alpha(\geq E\mu)} \quad \text{................(1.13)}$$

where α is a fitting parameter. The values of α obtained from the present experiment ("Part-B" of the thesis, Chapter-5) for muon threshold energy ($>E_{\mu}$) 2.5GeV lies between 0.553 to 0.662 for shower size $5.97X10^4$ to $1.79X10^6$ particles.

1.4. Current status of the data acquisition system for the observation of EAS:

Data acquisition system is an important part for the observation of EAS. The main aim of any data acquisition system is to collect large amount of air shower data within few μs. In a number of observations it has been found that occassionally EAS are coming within short time interval (few ms) (Klebsadel R.W. et al [13],Smith G.R. et al.[14], Hillas A.M. et al.[15]) having similarity with low energy gamma ray bursts. Again, for the search of discrete point sources of ultra-high energy cosmic gamma rays, which demands a large air shower statistics, small dead time data acquisition system is necessary.

Considering these aspects, a new data acquisition system (Chakrabarti C. et al.[16]) has been developed in the course of the present work. The new data acquisition system has a provision to extend the array by adding any number of detectors to collect air shower data. In the present system, parallel processing technique is used instead of serial multiplexing technique so that the required time of data acquisition is less. Here analog pulse heights are digitised simultaneously for all the channels and these particle density data and particle arrival time data are automatically recorded in a 32 kbyte - 8 bit RAM and subsequently stored in the Computer hard disk. Nearly 200μs is needed for the collection of air shower data in an individual EAS. The system does not require a dedicated computer for the collection of air shower data. Only at the time of data transfer from external memory to the hard disk, the computer is connected to the data acquisition system through a standard parallel port.

In the year 1979. Akeno group (Hara T. et al.[17]) reported a automatic data registration system for the Akeno EAS array. The data registration and monitoring detectors at Akeno EAS array are performrd with a central computer system, with which all the air shower data of more than 3000 channels for an individual event are automatically recorded. Total time required for registration of signals from all the detectors is about a few seconds.

In the 1981 Paris Conference, Bruce (Bruce A. et al [18]) reported that they used a micro-computer controlled multistation air shower detection system for use in the study of medium energy air shower. The micro-computer controls acquisition and conversion of the analog scintillation detector outputs and provides classifications, formatting and storage of necessary data from each event. Use of the micro-computer offers advantages in data handling as well as provides overall system simplicity and flexibility. Co-ordination of the analog multiplexer and analog-to-digital converter by the computer allows for rapid data acquisition and therefore reduce system dead time.

Astley (Astley S.M. et al [19]) reported in the 1981 Paris Conference, that they made a microprocessor controlled system for the collection of air shower data for Haverah Park array. In the array, shower particles are detected by deep water Cerenkov detectors and plastic scintillator detectors. They used a microprocessor with each detector for the advantage that a comparatively slow Computer can be used to record data from a large number of detectors. The data handling system has a advantage that the electronic hardware may be made completely interchangeable, for easy servicing and the detector identification being read from switches by the microprocessor.

In the La-jolla Conference (1985) , Ng L.K. (Ng L.K. et al. [20]) reported, a micro-computer controlled data acquisition system for their medium size shower array in the University of Hong Kong. In the data handling system, analog pulses are digitised by a slow but high precision ADC (MC14514) and the relative time delays are digitised by a time-to-amplitude converter (TAC). Different parts of the data acquisition system are connected to the central processing station through transceiver buses and controlled by the master pulse, which produced by a four-fold coincidence. Time resolution of the TAC is better than 1ns.

Bhat P.N. et al (Bhat P.N.et al [21]) described a real time data acquisition system for very high energy gamma ray astronomy. The extensive air shower produced by TeV gamma rays are detected by an array of parabolic mirrors (or a group of mirrors called a bank) for the collection of Cerenkov light produced by the secondary (e^+, e^-) with a fast photomultiplier at the foci. The system records the time of occurrance of the event correct to a micro-second, the scalars, which record various counting rates, the latch information signifying which mirrors or banks have triggered during the event, the pulse height in each photomultiplier to be read from a CAMAC-ADC module and the relative time delays between various banks from a CAMAC-TDC module. This is accomplished by an indegenously designed hardware system built around a Q-bus based PDP 11/23 processor through a general purpose 16 bit parallel I/O interface viz DRV 1-11.The event rate is in the 2-20 Hz.

Lu Y. reported (Lu Y. et al.[22]) in the 22nd ICRC, a multiprocessor controlled data acquisition system (DAS) for the collection of air shower data for their GRAND project. The DAS hardware and software have been designed to handle large amount of data in a short time in an individual air shower event. They used three computers with a 32bit address bus, a 32bit data bus , a 68020 microprocessor, a 2 megabyte dynamic memory(DRAM) and a 2.0 Gbyte 8mm magnetic tape drive. Air shower data from PWC's temporarily stores serially into a random access memory (SRAM). The data are then transfered from SRAM to DRAM under Computer control. The DAS allows the system to handle a maximum data burst rate of 96 megabytes/sec. The DAS can record a data rate of 400 events per second, of 7,000 bits per event. The system is fast and reliable.

Allen G.E. et al reported (Allen G.E et al.[23]) in the Rome Conference about a data acquisition (DAQ) system for high data transfer rate for the Milagro air shower array. Here first water Cerenkov detector was specifically designed to study EAS. Expected event rate for Milagro air shower is of the order of 1 to 2 kHz, which corresponds to a data rate of more than 1 megabyte/sec. They used MC68340 processor with direct memory access (DMA), which controls the data flow through bus into two dual port memory (DPM). An on-line Computer is used to read the data from memory with a data rate of 40MB/sec.

Ammev S.S. reported about (Ammev S.S. et al [24]) the data acquisition system of the EAS-100 array. The expected EAS rate in the array is 400 events/hour. Synchronisation and data acquisition in the array is done in two level system- every 16 detector units are served with one intermediate registration unit (IRU), 25 IRU are served with one central registration unit (CRU). IRU receives data from detector unit, stores it in IRU buffer and transmit data to CRU . CRU receives data from IRU and stores the received infromation in buffers and transmits then to the Computer.

The summary given above is may not be complete without a reference to Pierre-Auger Observatory (Mantasch P.M.[25], Hovjat C. [26,27]).
A new giant air shower project proposed is the Pierre Auger Observatory. It is an international collaborative effort for observation of cosmic rays at the highest energies (10^{19}eV). Two air shower detector arrays each with an aperture of 600 km.^{2} steradian, one in the northern hemisphere and other in the southern hemisphere are proposed to be installed by the year 2001. The objective of the project is to measure the high energy end of the primary cosmic ray spectrum as well as to study directional distribution and nuclear charge composition of the primary radiation at the highest energies.

1.5. Results on shower size spectrum of previous experiments:

The study of electron shower size spectrum is one of the subjects of interest for the researchers of EAS because of its dependence on the energy spectrum of primary cosmic radiation. The electron size spectra of EAS reported by many authors have considerable difference from one another about the size where the 'knee' occurs, the sharpness of the kink and dependence of the 'knee' on the observation level.

In the München Conference, 1975, Catz reported (Catz Ph. et. al.[28]) that the integral size spectrum shows a 'knee' at log Ne ~ 6.0 and the value of the spectrum index changes from (1.59 ± 0.002) to (2.19 ± 0.02) with showers of zenith angle < 33^o. From the measurement of integral shower size spectrum by Samarkand EAS array (Aliev M. et al.[29]) with showers of zenith angle $\leq 30^o$ in the size range 2.5×10^5-3.2×10^6, they found a spectrum 'knee' in the size region $(6\text{-}9) \times 10^5$ and the value of the spectral index changes from (1.47±0.05) to (2.10±0.09) before and after the 'knee'. In the Moscow Conference, 1987, Adamov (Adamov D.S. et al.[30]) reported that the integral size spectrum obtained in the size range 2×10^5-2×10^7 with zenith angle $\leq 30^o$ has a bend at $N_e \sim 10^6$ and the spectral index before and after the bend is (1.55±0.02) and (1.86±0.025).

Aglietta presented in the Calgary Conference, 1993(Aglietta M. et al [31]), the size spectrum of primary cosmic rays in the energy region 10^{14}-10^{16} eV by EAS-TOP array(800gm/cm^2) with a 'knee' at $\log(N_e) = 6.05$ and the change in exponent of power law size spectrum from 1.67 to 2.04. He concluded that the measured size spectrum is comparable with the expectation from the extrapolation of direct primary spectra measured at lower energies within the experimental uncertainties. In the same Conference, Dedenko (Dedenko L.G. et al [32]) showed by the Tien-Shan data that, in the size spectrum, there is a 'bend' at $N_e \sim 10^6$ and it does not depend on zenith angle.

In the year 1995, Danilova reported that (Danilova E.V. et al [33]) there is no dependence between the position of shower size spectrum 'knee' and depth of observation level. It is not easy to explain this fact without drastic change of nuclear interaction in frame of usual models of generation and propagation in the interstellar space of cosmic particles. A group (Antonian S.V.Ter et al.[34]), working by MAKET-ANI array (3200 m.a.s.l.) reported that in the shower size spectrum, 'knee' depends on age parameter of EAS and changes its position from 5.1×10^5 with $s<0.8$ to 5.6×10^6 with $s>1.2$ and the value of the size spectrum exponent changes from $[(0.15\pm0.03).\ln(s)+1.5]$ to (2.15 ± 0.1) before and after the 'knee'.

Again in the work of Asakimori (Asakimori K. et. al.[35]), they have not found any 'knee' in the size spectrum.This result is different from others and they consider this as "due to difference in estimation of the selection bias, the lateral distribution function used for the size determination, the arrangement of detectors , and the method of analysis etc". In the 1985 Lajolla Conference, Chan S.K. et al. also reported (Chan S.K. et. al.[36]) integral shower size spectrum which can be expressed by a single power law with a slope 1.83 ± 0.01, indicating that there is no 'knee' in the size spectrum.