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Primary Composition of Cosmic Rays around the Knee Energy Region from the measurement of Attenuation Length of EAS

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Abstract

The absorption and attenuation length of the electron-photon component in extensive air showers (EAS) of a given size has been determined over the size range 10^5 -10^6 particles using air shower data obtained with North Bengal University EAS array. The absorption length for proton flux in atmosphere has been calculated from theoretical model. The observed variation of the absorption length and attenuation length of EAS with shower size has been used to infer primary composition of cosmic rays in the knee region (E ~ 3 x 10^{15} eV) of the cosmic ray energy spectrum.

1 Introduction:

The steepening of the cosmic ray energy spectrum around 3 x 10^{15} eV (known as knee of the spectrum) is now well established (Erlykin & Wolfendale, 1997, Khristiansen & Kulokov, 1958) but the mechanism of producing the knee is still not understood. This important feature of the primary spectrum indicates a change in the source and/or in the acceleration mechanism and/or propagation characteristics of primary cosmic rays. It is expected that due to any such change the average mass composition of primary cosmic rays would be different before and after knee. So experimental study of mass composition of primary cosmic rays around the knee energy region is important in relation to its origin.

The frequency of cosmic ray extensive air showers (EAS) with a fixed shower size decreases exponentially as the thickness of the atmosphere increases depending on the attenuation length of the primary cosmic ray flux in the atmosphere. Attenuation length on the other hand depends on the inelastic cross section of the collisions between primary particle and air nuclei and thus sensitive to the mass of the primary particle. So if chemical composition of primary cosmic rays is different before and after the knee attenuation length of primary cosmic ray flux also should differ in the respective region accordingly. In the present work the attenuation length of air showers has been studied as a function of shower size (and hence as a function of primary energy) with a close-packed small air shower array covering the knee energy region and the results are used to infer the trend of average mass composition of primary cosmic rays around the knee energy region.

2 The Experiment:

The air shower experiment at North Bengal University campus (latitude 26°42' N, longitude 88°21' E, 150 m a.s.l.), INDIA, has been designed to detect air showers in the size range 10^5 -10^6 particles with a close-packed array (detector spacing ~ 8 m). With such a close-packed array, the determination of shower size and other parameters has been precise. Details of the experimental system, data acquisition and method of data analysis are described elsewhere (Bhadra et al, 1998, Basak et al, 1984).

3 Results:

The zenith angle distributions of the observed EAS for shower size greater than N_e in the shower size range 1 x 10^5 to 1 x 10^6 particles have been determined and are shown in figure 1. When the zenith angle is not too large the frequency of showers of size greater than N_e can be express as a function of zenith angle via the relation

$$F(z, > N_e, X_o) = F(0, > N_e, X_o) \exp[-X_o \{\sec(z) - 1\}/\Lambda] \quad .... (1)$$

Where $F(z, > N_e, X_o)$ is the frequency of showers at zenith angle z of shower size greater than N_e, $F(z, > N_e, X_o)$ is the same of $F(z, > N_e, X_o)$ but for zenith angle 0^0 , X_o is the atmospheric depth of observation point (1020 gcm-2 at NBU) and Λ is the absorption length (effective attenuation length) of the primary flux. Thus the slope of the logarithmic intensity distribution as a function of sec(z) gives absorption length Λ. Due to the presence of fluctuations in an EAS development the energy of the primary particle can not be determined precisely from the observed particle size but the mean primary energy range concerned in the present experiment is estimated comparing the observed shower size with the results of hybrid Monte Carlo simulation model (Trzupek & Poirier, 1993) for proton primary at sea level covering this primary energy range. The variation of estimated absorption length with energy is shown in figure 2. The result of Haverah Park observation (Ashton et al, 1975) in this energy region is also given in figure 2.

The absorption length is related with the attenuation length (λ) via the approximated relation $\lambda = \gamma\Lambda$, where γ is the power index of the integral shower size spectrum of primary cosmic rays. The value of γ has been determined from shower size spectrum of the observed showers. The knee position ($N_e = 5.5 \times 10^5$ particles) is determined by drawing straight lines on log(I) Vs log(N_e) plot below and after the sudden steepening of the spectrum. The variation of estimated attenuation length with shower size is shown in figure 3.

4. Absorption length for proton flux in air:

In the case of evolution of proton component of cosmic rays in the atmosphere the interaction mean free path ($\lambda_{in}^{\ p\text{-}air}$) is inversely proportional to the inclusive proton-air collisions cross section ($\sigma_{in}^{p\text{-}air}$)

$$\lambda_{in}^{\ p\text{-}air} = 2.41 \times 104 / \sigma_{in}^{p\text{-}air}\,(\text{mb}) \quad \text{gm cm}^{-2} \quad ....(2)$$

Since no data on hadron-nucleus collisions are available at PeV energies from collider experiments, $\sigma_{in}^{p\text{-}air}$ only can be estimate from proton-proton total cross sections ($\sigma_t^{p\text{-}p}$) using theoretical model. Following Glauber model (1970), one can write

$$\sigma_{in}^{p\text{-}air} = \int d^2b \, \{ 1 - [1-(1/2A)\, \sigma_t^{p\text{-}p} \int \rho(b,z)dz]^{2A}\}$$
$$\approx \int d^2b \, \{ 1 - \exp[-\sigma_t^{p\text{-}p} \int \rho(b,z)dz]\} \quad ....(3)$$

Where b is the impact parameter, A is the atomic weight of the nucleus and $\rho(r)$ is the nuclear density which is normalized in such a way that

$$\int \rho(r) d^3r = A$$

In the present work nuclear density $\rho(r)$ has been calculated using Durand-Pi (1988) parameterization $\sigma_{in}^{p\text{-}air}$ has been calculated from eqn. 2 using Donnachie & Landshoff parametrization (1992) of Regge theory for $\sigma_t^{p\text{-}p}$. Subsequently $\lambda_{in}^{\ p\text{-}air}$ has been determined .The relation between interaction mean free path and absorption length for a nucleonic flux having power law primary energy spectrum of power index γ may be expressed by the Bellandi et al equation (1992) as

$$\Lambda(E) = \lambda_{in} /(1-x\gamma)$$

Where x is the elasticity of nucleon -air interactions. Using the energy dependence of inelasticity (k = 1-x) as $k = .176\, s^{.095}$ as obtained from cosmic ray data in this energy region (Bhadra , this proceeding) Λ has been calculated for proton primary and the variation of Λ with energy is shown in figure 2 (solid line). The value of γ is taken as 1.8 for the whole energy range as reported by JACEE collab. (Ashikimori et al, 1997). By taking traditional value of k i.e. k = 0.5 the energy dependence of absorption length is also estimated and is presented in figure 2 (dash line). The observed values of Λ for proton primary as measured by Akeno (Hara et al, 1983) and EAS-TOP group (Aglietta et al, 1997) in this energy range are also shown in fig.2.

5 Conclusion:

Absorption and attenuation length of air showers has been estimated experimentally using angular method i.e. from the zenith angle distribution of EAS for different shower size thresholds around the knee energy region of the primary cosmic ray spectrum. The variation of attenuation length and absorption length with shower size has been studied. It has been observed that the mean value of attenuation length is initially slowly decreasing with energy before the knee but around the knee it suddenly increases and remains almost constant thereafter. This result primarily indicates a change in the mass composition from heavier to lighter primaries around the knee because for heavier primaries more attenuation is expected. In Tien Shan experiment (Danilova et al, 1995) also similar trend of variation of attenuation length with shower size was observed. However when energy dependence of absorption length is studied and compared with the theoretical results for proton primary and also with the observed absorption length of proton component of primary cosmic rays in air by Akeno (Hara et al, 1983) and EAS-TOP (Aglietta et al 1997) groups the present result favors the dominant proton composition of primary cosmic rays, both before and after the knee and no significant change in the mass composition has been seen around the knee of the spectrum. Due to the presence of fluctuations in an EAS development the relation between absorption length and attenuation length is not a simple proportioality and this might be the reason for appearance of different composition picture from the study of variation of attenuation length with energy.

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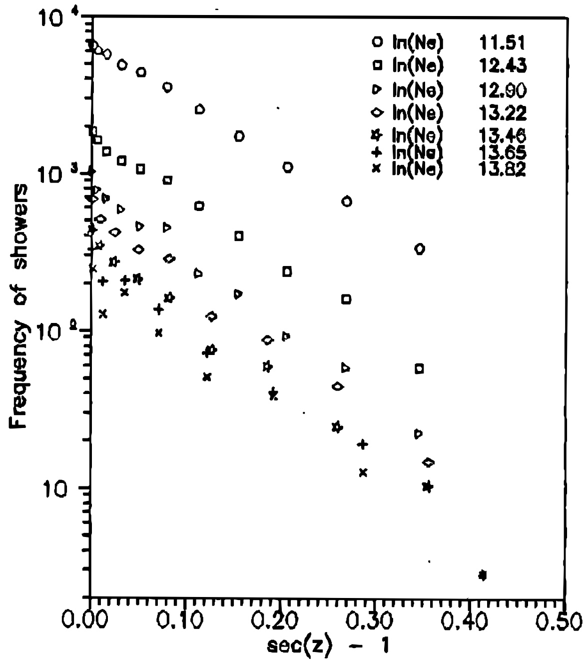

Fig. 1 Zenith angle distribution of observed showers for different threshold of shower size.

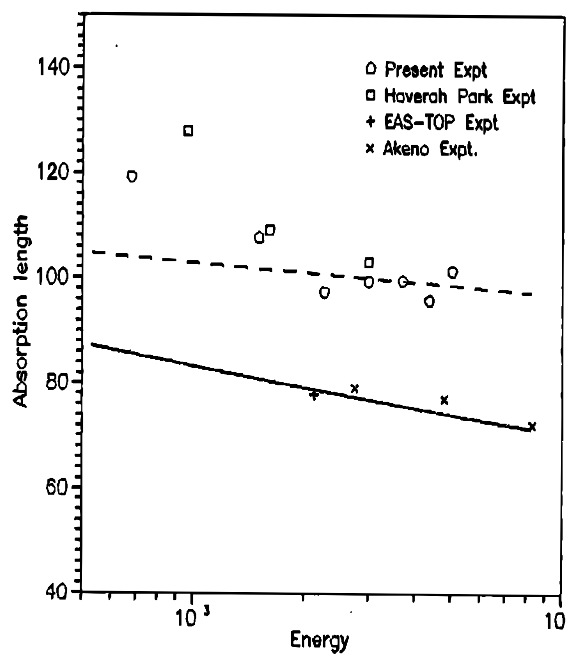

Fig. 2 Absorption length as a function of energy. Solid and dash lines are considering k is energy dependent and k is equal to 0.5 respectively.

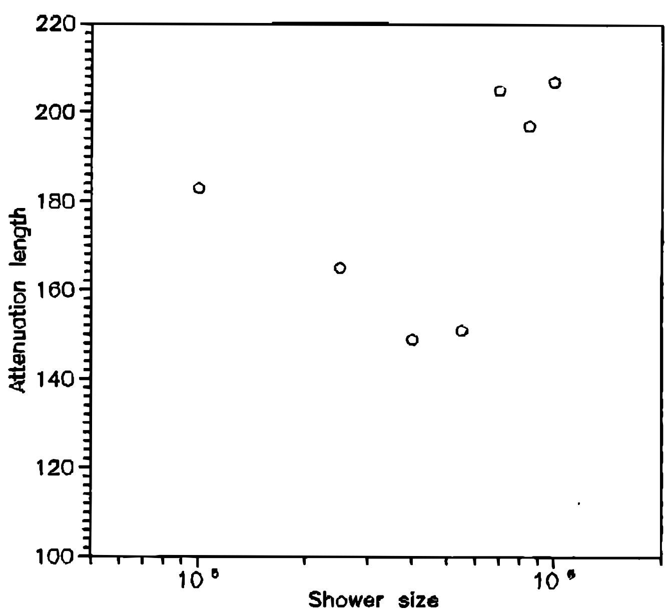

Fig. 3 Attenuation length as a function of shower size .