# COMPOSITION OF PRIMARY COSMIC RAYS NEAR THE KNEE

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## Abstract

The size dependence of high energy muons and the size spectrum obtained in the KGF air shower experiment suggest that the mean mass of cosmic rays remains nearly constant at $\sim$15 upto 5 x $10^6$ GeV and becomes one beyond. The composition model in which nuclei are removed at 7.5x$10^4$ GeV/nucleon due to photodisintegration and the proton spectrum steepens at 6.7x$10^6$ GeV due to leakage from the galaxy, which explains the KGF data, is shown to be consistent with data from other experiments also.

## Introduction

Data on various components on EAS from different experiments seem to suggest models of primary cosmic ray composition which are completely at variance with each other. The dependence of number of high energy muons on shower size together with the size spectrum from the KGF experiment[1] suggests that the mean mass number remains nearly constant upto about 4x$10^6$ GeV and becomes 1 beyond. The size dependence of 5 GeV muons and their fluctuations from the Tien Shan experiment[2] indicate that the composition remains unaltered over a wide range of primary energies which covers the knee in the primary spectrum. The elongation rate derived from early Cerenkov measurements [3,4] and observations on the fraction of delayed hadrons[5] have been interpreted in terms of an iron-rich composition near the knee, resulting from rigidity cut-off with a critical rigidity $\sim 10^5$ GV. Here we show that a composition model in which nuclei are removed due to photodisintegration near the source itself and the proton spectrum steepens due to leakage from the galaxy at a much higher energy, which explains the KGF data, can also account for most of the other data, if proper account is taken of the systematic effects in various experiments.

## Composition from the KGF data

The $N_\mu$-$N_e$ dependence of muons of energy $\geq$ 220 GeV and the size spectrum from the KGF experiment[1] are shown in Fig.1. Acharya et al[1] have shown that the muon data does not agree with the rigidity cut-off model[6] with a critical rigidity of $10^5$ GV and extragalactic protons becoming dominant at $10^9$ GeV, which predicts an increasing mean mass number with shower size in the size region $10^4$-4.$10^5$ and a high mean mass number at higher sizes. An important feature to be noted from Fig.1 is that the discontinuity in the $N_\mu$- $N_e$ dependence occurs at a size (4.$10^5$) which is a factor of 5 smaller than that at which the size spectrum steepens (2.$10^6$). In the lower size region, the mean mass number seems to be independent of size since the experimental slope of $N_\mu$-$N_e$ dependence agrees with the prediction for a constant composition. The data suggests a pure proton composition above a shower size of $10^6$.

These features can be understood in a model suggested by Chatterjee[7] in 1964, which is a modification of Peters' rigidity cut off model. In Chatterjee's model, the galactic component undergoes rigidity cut off at a critical rigidity of 3.$10^5$ GV and a pure proton extragalactic component becomes dominant at 2.$10^6$GeV, well before the cut off energy for iron nuclei.

An essential feature of the model is that the mean mass number is not allowed to increase with energy in the region where the composition is changing, by bringing in the extragalactic protons well below the iron cut-off energy . The difficulty with this model is that, apart from the need to exactly match the two proton components to yield a smooth spectrum, the energy dependence of the anisotropy[8] is difficult to understand. Also, the JACEE proton spectrum does not show any steepening upto $6.10^5$ GeV. The photo-disintegration model suggested by Hillas[9] in which nuclei are removed in the source itself at $\sim 10^5$ GeV/nucleon due to photodisintegration and protons suffer severe energy losses at a few times $10^6$ GeV due to photo pion production can also explain the data since protons continue almost upto the iron cut-off energy. Again the anisotropy is difficult to understand in this model, if the knee in the primary spectrum is due to energy losses in the photo pion production process.

Incroporating the good features of the two models, we propose the following model. Nuclei are removed due to photodisintegration at an energy/nucleon of $7.5\times10^4$ GeV, as in Hillas' model. Upto this energy, the spectra of various components are, as given by JACEE measurements[10], expressed as $K\,E^{-2.68}\,dE$, with K = 1.29, 0.76, 0.90, 0.35 and 0.57 for mass numbers 1, 4, 14, 26 and 56. The iron spectrum is taken as the difference between the all particle flux from the Tien Shan experiment[11] (which agrees with the Grigorov all particle spectrum) and the sum of all components from JACEE. The spectral index of protons increases by 0.5 at $6.7\times10^6$ GeV due to leakage from the galaxy. The values of the critical energies are estimated by identifying the discontinuity of $N_\mu$-$N_e$ dependence at $4\times10^5$ as due to removal of iron nuclei and the steepening of the size spectrum at $2.10^6$ as due to leakage of protons and using the scaling model with rising cross sections[12]. Cosmic rays upto $\sim 10^{10}$ GeV are of galactic origin. The anisotropy can be understood as due to leakage of protons. There is no need for a second component. The spectra of various components and the all particle spectrum according to this model are shown in Fig.2. The Tien-Shan spectrum is higher than the model since they use the same composition to derive the primary energy spectrum over the energy region where it is continuously changing according to this model. The mean mass number and percentage of iron as a function of primary energy (a) and size at 920 g/cm$^2$ (b) in this model are shown in Fig.3. It can be seen that the mean mass remains nearly constant even though the composition is continuously changing upto $4\times10^6$GeV ($N_e = 5\times10^5$) and becomes 1 beyond. The percentage of iron reaches a maximum of 32% at $4\times10^6$ GeV and then falls off to zero. The proton fraction also increases with energy. Obviously, this model explains the $N_\mu$- $N_e$ dependence. The size spectrum at 920 g/cm$^2$ expected from this model is compared with the KGF data in Fig.4 (Curve b). The first three experimental points are corrected for detection efficiency of flat showers and shown as filled circle. The agreement is obvious. Curve (a) is for the same model, but the spectral index for all the components is 2.72 with intensities normalised at 100GeV/nucleon. Thus, the present model, with the spectra mentioned earlier, explains the KGF data.

## Comparison with other experimental data

Estimates of the position of shower maximum, $t_m$, from measurements of pulse profile[3] and lateral structure of Cerenkov photons[4] in small showers have indicated iron-rich composition in the energy region $10^6$-$10^7$GeV. The measurements of pulse profiles have been shown to be subject to the systematic errors[13,14] and thus may not be reliable. The values of $t_m$ obtained from lateral structure are systematically smaller than those from pulse profile measurements suggesting that they also may be subject to systematics. Recent measurements[15,16] using large areas of photomultipliers and triggering with Cerenkov light itself, thus being relatively bias-free, are shown in Fig.5 along with earlier measurements at higher primary energies, which do not seem to have such systematic effects. It can be seen that these new measurements do not show the abnormal elongation rate and do not require an iron-rich composition. In order to see the change of composition in this model, accurate measurements over a wide energy range from a single experiment are required.

The composition derived from delayed hadrons[5] relies heavily on Monte Carlo simulations. Even though the authors paid careful attention to the details of the simulation, some of the factors, such as the neglect of nuclear target effects, a cut off energy of 3 GeV for hadrons in the simulations together with the finding of Mincer et al[17] that low energy hadrons do produce large signals at a surprisingly large rate, would result in a larger fraction of delayed hadrons in both proton and nucleus initiated showers, thus reducing the requirement of iron from 40% at $10^6$GeV. Thus the present model, which predicts the iron abundance to increase with energy, with a value of 25% at $10^6$GeV, would be in agreement with their data. The Tien Shan data on low energy muons[11], which requires unchanging composition, is however difficult to understand in this model.

## Conclusions

The composition model in which nuclei are removed at $7.5\times10^4$GeV/nucleon in the source and proton spectrum steepens at $6.7\times10^6$GeV due to leakage from the galaxy explains most of the EAS data. Study of anisotropy of suitably selected mu-rich showers can distinguish between the photo disintegration and rigidity cut off models, since the former does not predict any anisotropy for nuclei near the cut off energies.

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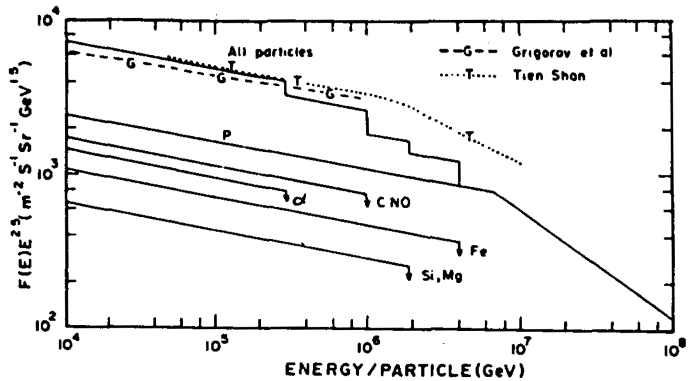


Fig. 2

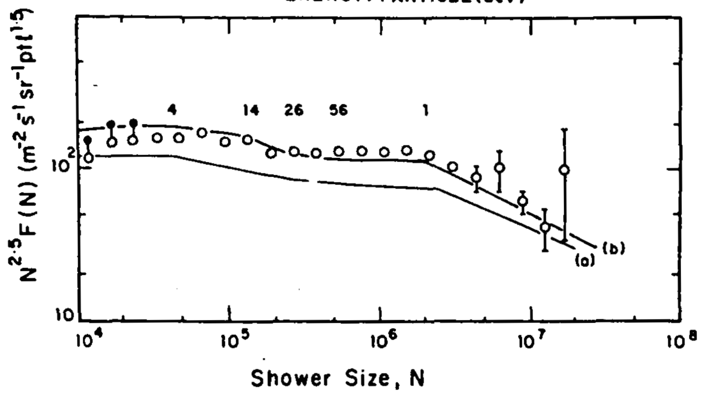


Fig. 4

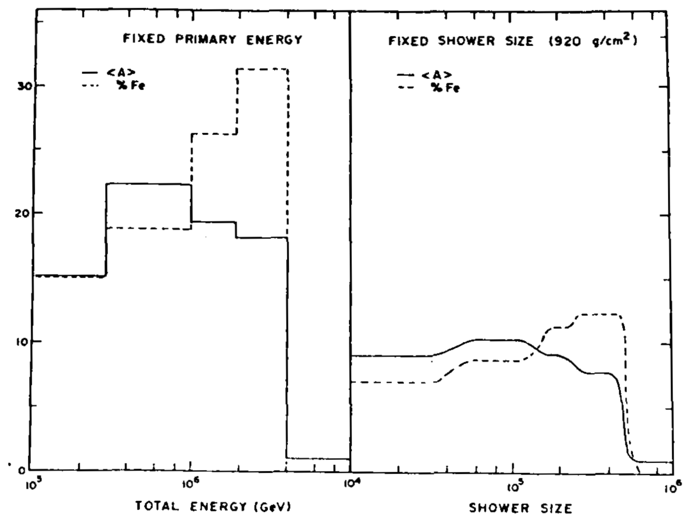


Fig.3

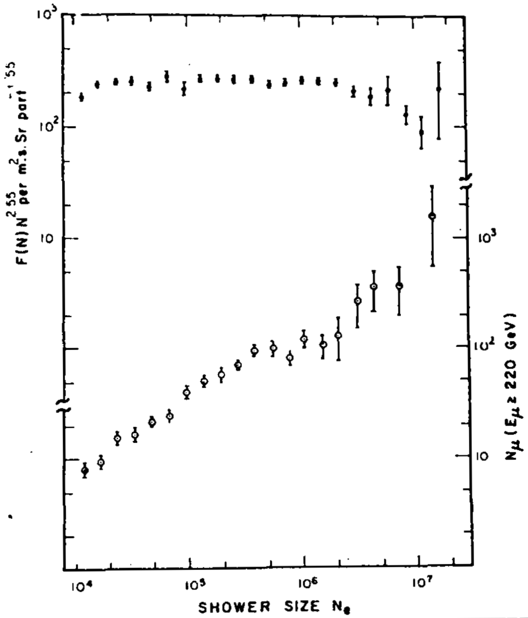


Fig.1

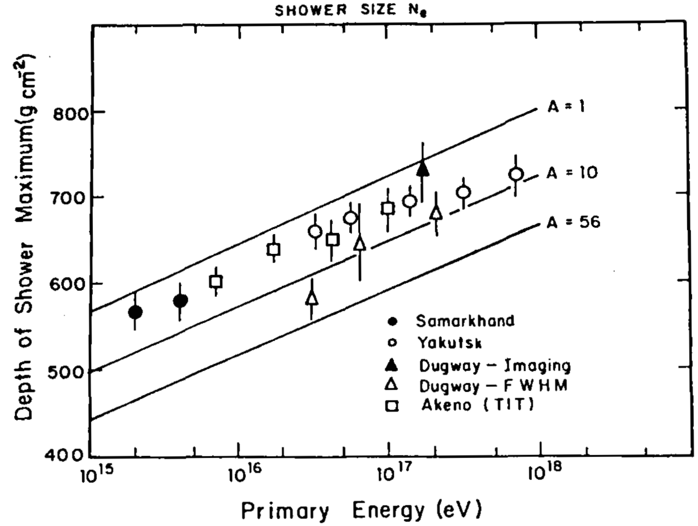


Fig.5