Composition of Primary Cosmic Rays at Energies $10^{15}\sim10^{16}$ eV Inferred from Mt.Fuji Emulsion Chamber Experiment

Mt.Fuji Emulsion Chamber Collaboration:

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The $\Sigma E\gamma$ spectrum in $10^2\sim 5\times10^3$ TeV observed at Mt.Fuji ($\sim$3725 m a.s.l.) strongly suggests that the flux of primary protons in $10^{15}\sim10^{16}$ eV is lower by a factor of $2\sim3$ than a simple extrapolation from lower energies; the integral proton spectrum tends to be steeper than $E^{-1.7}$ around 10^{14} eV and the spectral index becomes ~2.0 around 10^{15} eV. If the total flux of primary particles has no steepening up to $\sim10^{15}$ eV, then the fraction of primary protons to the total flux should be $\sim$ 20 % in contrast to $\sim$45% at lower energies.

1. Introduction. As well known, the integral energy spectrum of all primary particles steepens to $E^{-2.0}$ over $\sim5\times10^{15}$ eV in contrast to $E^{-1.6}$ at lower energies. This "knee" of the spectrum may come from 1) a change of the acceleration mechanism resulting in a steeper source spectrum and/or 2) a breakdown of magnetic trapping in the galaxy. Study on the composition around the "knee" is an important key to resolving the problems of the origin and propagation of cosmic rays. However, the definite result has not yet been obtained because of the too low primary flux for the direct observation and too poor response of the air shower observation to the primary mass.

The emulsion chambers (EC) at Mt.Fuji have been extended to the scale of 1000 $m^2\times$ year, and a few hundred events produced by primaries with energy $10^{15}\sim10^{16}$ eV have been accumulated[1)]. Meanwhile, accelerators has clarified the feature of nuclear interactions up to 150 TeV (in lab. energy). These circumstances enable us to investigate the primary composition around the "knee" by analysing the EC events through simulations based on a reliable model of nuclear interactions.

2. γ-ray Family. A group of high energy particles (mostly γ-rays with energy > a few TeV) produced by successive collisions of a primary particle with air nuclei is called a family. Particles which penetrate deep in the atmosphere can produce families effectively, otherwise produced particles are usually absorbed in the atmosphere. Therefore protons are most efficient in producing families; the average energy of protons responsible for γ-ray families with $\Sigma E\gamma$>100 TeV is $\sim 2\times 10^{15}$ eV while that of irons is almost one order of magnitude higher.

It has been found that the fraction of proton-induced families in all families in ΣE_{γ}>100 TeV is $\sim$ 70% even if protons constitute only $\sim$ 10% of all particles around 10^{15} eV. Therefore, if we convert the family intensity into the primary flux assuming that all families are produced by protons, we obtain an upper bound of the proton flux within an accuracy of 30%.

<u>3. Monte-Carlo Simulation.</u> The Monte-Carlo method has been used to simulate the family phenomena and to deduce the primary intensity by comparing the obtained family flux with the experimental one. Important factors in the simulation are the cross-section of nuclear interactions, the leading particle spectrum and the secondary particles spectrum (especially, the degree of scale breaking in the fragmentation region). These are summarized in the following.

<u>*Cross Section*</u> Using the data of $\bar{p}p$ and pp interactions up to 150 TeV, the mean free path of the N-Air collision is expressed as $\lambda=\lambda_0\times E^{-\delta}$, where E is in TeV, δ is 0.04 $\sim$ 0.06 and λ_0=82 g/cm^2.

<u>*Elasticity*</u> Two cases of the elasticity distribution are assumed as shown in Fig.1. Case *A* disregards the difference between protons and neutrons and gives the average elasticity of 0.44. In case *B* is considered the absence of the diffraction peak in charge exchange processes, for which we refer to p-C and p-Be data[3] at 100 - 400 GeV. The average elasticity in a non-charge exchange process like p+Air→p+X is 0.45 while that of p+Air→*n*+X is 0.28. With a charge exchange probability of 28 %, the average elasticity in case *B* becomes 0.40.

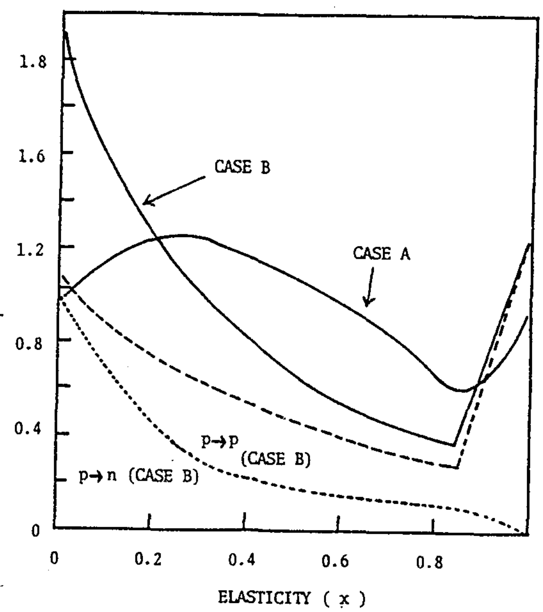

Fig.1 Elasticity distribution.

<u>*Energy distribution of secondary particles*</u> The QCD-jet[2] automatically introduces a mild scale braking in the fragmentation as shown in Fig.2a. The rapidity distribution shown in Fig.2b is compatible with the CERN-SPS data. To see the effect of a strong violation of scaling in the fragmentation region we employed a fireball model of which the multiplicity grows as $E^{1/4}$.

In Table 1, the models are characterized by the parameters discussed above. The calculated flux of γ-ray families at $\Sigma E\gamma$=100 TeV for each model is listed by normalizing the flux to model QA6.

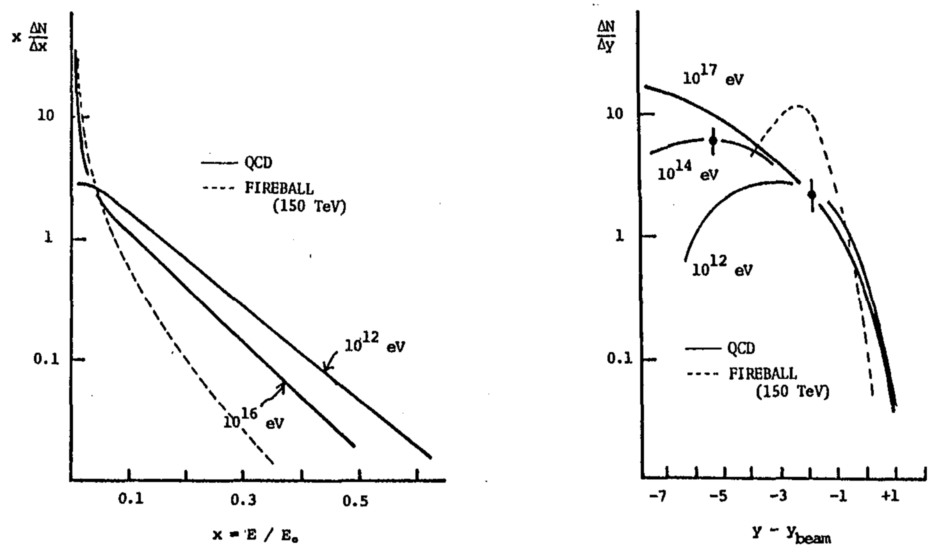

Fig.2a x-distribution of secondary pions in p-Air collisions at 10^{12} eV and 10^{16} eV. A mild-violation of scaling is seen in the model with QCD jet.

Fig.2b y-distribution corresponding to Fig.1. Black dots show data by the CERN-SPS. Correction due to Air-target effect is included.

Table 1. Interaction model and the relative flux of γ- ray family.

model	x distribution	elasticity	m.f.p.(δ)	flux ratio
QA4	QCD	case A	0.04	1.32
QA6	QCD	case A	0.06	1
QB6	QCD	case B	0.06	0.72
FA4	Fireball	case A	0.04	0.41

4. Proton Spectrum in $10^{15}\sim10^{16}$ eV. Under the assumption that all γ-ray families are produced by protons, an expected spectrum of protons is deduced as shown in Fig.3. The upper bound is given by model QB6 and the lower one by model QA4. As mentioned already, a maximum of 30 % decrease might take place in the expected flux (due to the heavy primary contribution). Even if we take the experimental errors (both statistical and systematic) into account, we are forced to conclude that the proton spectrum should steepen around 10^{14} eV, and the ratio of protons to all particles in $10^{15}\sim10^{16}$ eV should be lower by a factor of $2\sim3$ than that at lower energies.

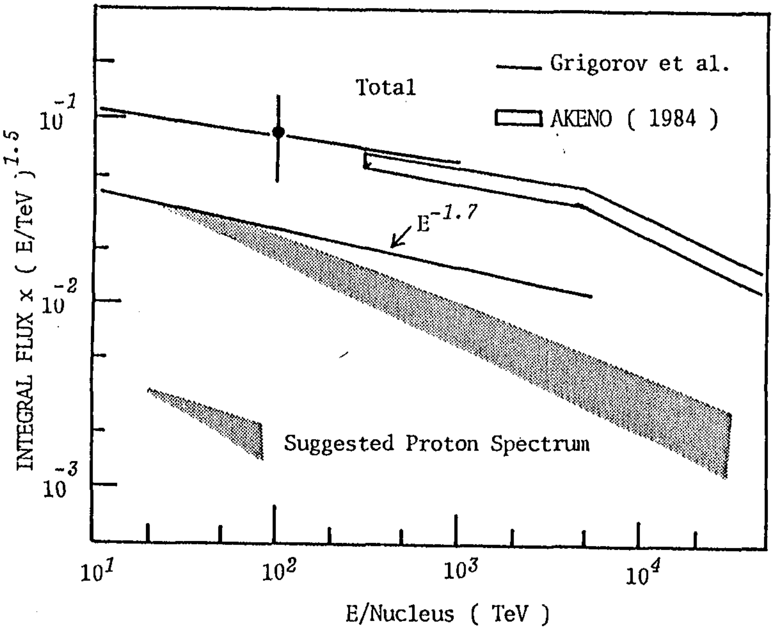

Fig.3 Expected primary proton spectrum.

5. Discussion. By an analysis of air shower data, some authors reported a proton-dominant composition[4]. In their estimation, a scaling violation in the central region are included to be consistent with the CERN-SPS data while the x-distribution in the fragmentation region is not properly considered, which is most effective to the cosmic-ray propagation in the atmosphere. Even if we assume a strong scaling violation (FA4) which is unrealistic already at the accelerator energies as shown in Fig.2b, the expected proton flux never exceeds the simple extrapolation from low energies.

The general (i.e., all observed particles independent of family correlation) hadron and γ spectra observed at Mt.Fuji also supports the present picture[5]. In Ref.6, we estimated the composition around the "knee" by the use of the "rigidity cut-off model". The proton spectrum there is consistent with the present estimation.

Acknowledgement.

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