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Chacaltaya and Pamir Collaborations
Simultaneous Observation of Families and Accompanied Air Showers at Mt. Chacaltaya II

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1. Introduction.

An experiment which observes air showers by emulsion chamber and air shower array is under way at Mt. Chacaltaya.[1] The emulsion chamber makes detection and energy determination for high energy particles in the air shower core, while the air shower array determines the arrival time, arrival direction, the size, etc. of the air shower. One of the aims of the experiment is to study characteristics of high energy nuclear interaction which produces the air shower. (We call this interaction "the first interaction".)

A bundle of high energy particles, observed by the emulsion chamber, is called "a family", which bears information of the first interaction more directly than any other observables.

In Ref.[1] we reached a conclusion that some change is necessary in the characteristics of nuclear interactions in the energy region exceeding \(10^{16}\) eV. That is, the observed data cannot be explained by the extrapolation of the ordinary multiple particle production which are observed by the accelerator experiments. And, owing to the advantage of the simultaneous observation, the conclusion is free from the assumption of the primary cosmic-ray intensity which is obtained by assuming simple interaction models.

In the present paper we try to infer what kinds of change is necessary in the characteristics of the nuclear interactions. The data is the energy spectrum of electron-photon component (called "\(\gamma\)-rays") in one family in relation to the incident energy of the first interaction which is estimated from the air shower size \(N_e\) by the relation

\[ E_0 = \epsilon N_e \]  

with \(\epsilon = 2.0\) GeV.\(^*\)

2. Energy spectrum of \(\gamma\)-rays in one family.

Let us discuss how the characteristics of the first interaction is reflected to the energy spectrum of \(\gamma\)-rays in one family. (The spectrum will be abbreviated as ESG hereafter.) The discussion is made as simple as possible, because the present paper is the first trial toward this direction of analysis.

We assume that the primary particle which causes the first interaction is a proton with the energy \(E_0\). The first interaction has the following characteristics.

(1) The surviving particle after the collision has the energy spectrum,

\[ \delta(E - (1 - K)E_0)\,dE. \]  

(2) The produced charged pions have the energy spectrum,

\[ \phi(x)dx = A K'(1 - x)^{1/6}dx. \]  

\(^*\)It is examined by simulations that the relation holds well in the size region of \(10^9 \sim 10^1\), independently of the assumption of nuclear interactions.

-15-
with $A = 10/3$ and $x = E/E_0$.

(3) The produced $\pi^0$'s have the energy spectrum,

$$\int_0^1 \phi(x) dx.$$  \hspace{1cm} (4)

The inelasticity $\lambda$ has a uniform distribution between 0 and 1.

ESG is obtained by taking into account the nuclear and electromagnetic cascade processes in the atmosphere, which are initiated by the above particles produced by the first interaction.

Additional assumptions, which are necessary to consider the atmospheric diffusion of particles, are:

(4) Nuclear interactions in the atmosphere have the same characteristics as the first interaction, described above.

(5) Nuclear collision mean free paths of proton and pion are

$$\lambda_p = \text{const} \quad \text{and} \quad \lambda_\pi = 1.45 \lambda_p \hspace{1cm} (5)$$

Height of the first interaction above the chamber $t$ is measured in the unit of $\lambda_p$.

Analytic solution for ESG can be obtained easily because all the energy spectra of produced particles are of scaling-type.[2, 3]

3. Discussion.

Figures 1 ~ 4 show ESG's for the incident energies of $E_0 = 2 \times 10^{16}$, $2 \times 10^{15}$ and $2 \times 10^{14}$ eV (from the top), at various interaction height $t$ above the chamber.

(1) Fig. 1 presents the ESG at $t = 5\lambda_p$, showing how much the surviving particle and the produced pions of the first interaction contribute to ESG, separately. One can see that ESG consists mainly of the particles produced by the surviving particle. In other words, the family is governed mainly by the inelasticity of the first interaction.

(2) Fig. 2 shows ESG at various interaction heights of $t = 3\lambda_p$, $5\lambda_p$, and $8\lambda_p$, above the chamber. The slopes of ESG are almost the same irrespective of the production heights and the primary energies. Furthermore ESG at a certain depth $t$ (in the unit of $\lambda_p$) is almost identical for the different value of $\lambda_p$, because ESG is governed mainly by the nuclear cascade (but not by the electromagnetic cascade).

(3) Fig. 3 shows ESG at $t = 5\lambda_p$ by the primary particle of a proton and an iron with the same primary energy. Iron is assumed to be a bundle of $A(=56)$ protons with the energy of $E_0/A$, i.e. the superposition model.

ESG of iron primary has much steeper slope than that of proton primary. The experimental data in Fig. 4 shows that the slope is similar to that of proton primary for all the incident energies, which probably indicates that the strong attenuation of ESG is not due to the increase of the heavy nuclei component.

(4) Fig. 4 shows that ESG of the experiment for $N\pi = 10^6 \sim 10^8$, $10^8 \sim 10^9$ and $> 10^7$ (from the bottom), which correspond to the average energies of $E_0 = 2 \times 10^{14}$, $2 \times 10^{15}$ and $2 \times 10^{16}$ eV, respectively. ESG for $N\pi = 10^8 \sim 10^9$ is biased to a larger number of $\gamma$-rays, because the families with a smaller number of $\gamma$-rays are not observed by emulsion chamber.

HADRON, the same type of experiment at Tien Shan, discuss the possible chance of the features of nuclear interaction, based on their experimental data that ESG changes at $N\pi \sim 10^7$.[4] Such a change of the spectrum is not found by our experiment, though the statistics of the events is not high. And it should be pointed out that the change of the nuclear interaction, if exists, would appear less directly and less clearly in ESG than they reported.

Above statement does not mean that there is no change of nuclear interaction. The curves in Fig. 4 are ESG at $t = 8\lambda_p$. We find a good agreement between the experimental data and the calculation for $E_0 = 2 \times 10^{14}$ eV, but it is not the case for $2 \times 10^{15}$ eV. Because the discrepancy cannot be explained by the increasing cross section, it is to be attributed to the change of nuclear interaction in the energy region $\sim 10^{16}$ eV.

References.

Study of primary cosmic ray composition from gamma ray families in air shower cores


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We have observed high energy gamma families and associated air showers simultaneously at Mt. Chacaltaya. Monte Carlo simulations were calculated for the present experimental setup. From comparisons with both results, mechanism of gamma family production, change of interaction model, study of the chemical composition are discussed.

1. Introduction

Bundles of high energy ($E_r > 1$ TeV) $\gamma$ rays, electrons and hadronic $\gamma$ rays have been observed with emulsion chambers at mountain altitude. The characteristics of nuclear interactions and the chemical composition of primary cosmic rays have been discussed.

In the present experiments, we observed $\gamma$ families by emulsion chambers installed in the center of SYS (Saitama, Yamanashi and San Andres University) air shower array and also air showers simultaneously[1]. In large air shower size region $\gamma$ families are observed always in air shower cores. Such accompanied air showers provide important informations on behavior of $\gamma$ families.

Since the air shower size is converted to energy of primary cosmic ray of air shower with the simple relation, we can study the relation of $\gamma$ families and the primary energy of associated air showers. It is impossible in emulsion chamber experiments without air shower informations to know the primary energy dependence of the number of $\gamma$ family and also the energy spectra of $\gamma$ rays in the $\gamma$ families.

In order to understand experimental results in detail, the Monte Carlo simulation is important. So we calculated simulation for the present experimental setup.

In this paper, we shall discussed the production of $\gamma$ family, its dependence on the chemical component of primary cosmic ray.

2. Experiments and Simulation

We have observed air showers and $\gamma$ families with the SYS air shower array and emulsion chambers at Mt. Chacaltaya in collaboration with Japan and Bolivia. Gamma families are linked with particular air showers.