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Study of nuclear interactions by observing family and air showers at Mt. Chacaltaya(*)

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Summary. — We operate an air shower array and an emulsion chamber simultaneously at Mt. Chacaltaya (5200 m, Bolivia), in order to study high energy nuclear interactions, induced by cosmic rays. We show that high energy electromagnetic component and hadronic component in the air shower are not described by the simulations, indicating that the energy spectrum of produced particles in multiple particle production is suppressed strongly in the forward region.

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1. – Introduction

Study of nuclear interactions by two-storey emulsion chambers, which consist of upper and lower emulsion chambers and a jet-producing layer in between, made clear characteristics of multiple particle production in the energy region of 10^{14} eV [1], most of which are confirmed by the experiments at CERN p̄p collider [2]. This owes to the excellent

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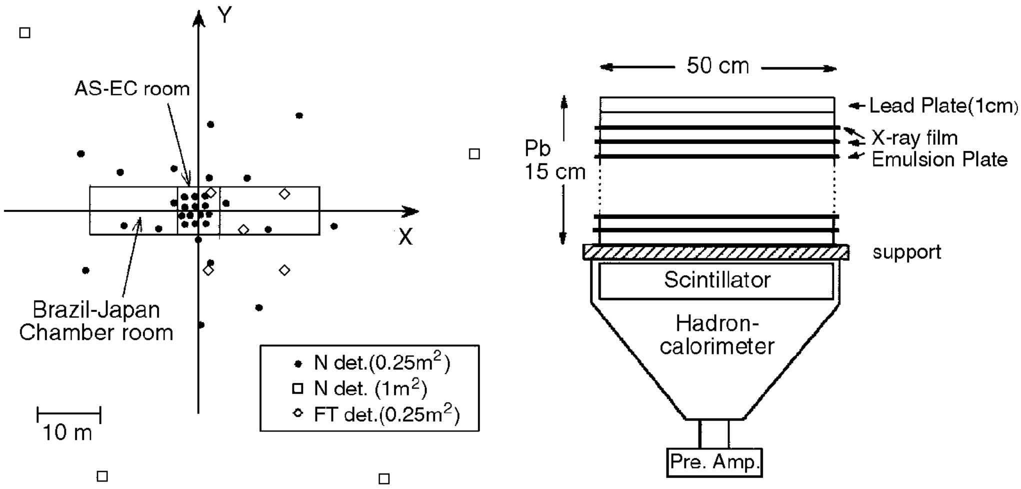

Fig. 1. – Air shower array (left) and a unit of emulsion chamber and hadron calorimeter (right). Emulsion chamber and hadron calorimeter, consisting of 32 units (50 cm × 50 cm each), are stored in AS-EC room at the center of the air shower array.

performance of emulsion chamber in energy and position determination. Next step of the study in 10^{15}–10^{17} eV is made by observing nuclear interactions in the atmosphere, called "families", by simple emulsion chambers of large area, because the intensity of high energy cosmic rays is very small.

The family data differ in several points from those of target interactions which are obtained by two-storey chambers: 1) unknown interaction height, 2) pollution of the event by overlapping of successive nuclear interactions and by secondary interactions of the produced particles, and 3) bias of the observed events due to high detection threshold energy of the emulsion chamber. Consequently the data of families are used only for the purpose to support the discoveries, made by two-storey chambers, in high energy region [1].

To overcome such shortcomings we started simultaneous observation of families and air showers which accompany the families [3, 4]. That is, we operate an emulsion chamber, a hadron calorimeter and an air shower array simultaneously. The importance of the experiment is to bridge the families and air showers, because both experiments have accumulated large amount of data independently. Therefore a large scale of the experiment is not needed.

2. – Experimental set-up

2˙1. *Detectors*. – The experiment is carried out at Mt. Chacaltaya (5200 m, Bolivia). The following is a brief description of the detectors and of their performance.

1) Air shower array

The air shower array consists of 35 plastic scintillators, which are distributed over an circular area of 50 m radius (fig. 1). The available data are of arriving time, direction, center position, size, etc. of air showers.

2) Emulsion chamber

TABLE I. – *Composition of the primary cosmic rays, assumed in the simulation.*

E_0 (eV)	H (%)	He (%)	CNO (%)	Heavy (%)	Fe (%)
10^{15}	42	17	14	14	13
10^{16}	42	13	14	15	16

The emulsion chamber, which is located in the center of the air shower array, consists of 32 units (50 cm × 50 cm each). Each unit is 30 cm Pb thick with 14 sensitive layers of X-ray films and/or nuclear emulsion plates (fig. 1).

An electron or a photon of high energy, incident upon the chamber, produces a cascade shower in the chamber, and the electron component in the shower is detected by several successive sensitive layers. In this way the emulsion chamber is sensitive to electrons and photons, called "γ-rays" collectively, incident upon the chamber, and determines their positions and energies([1]). Emulsion chamber has high-detection threshold energy of $E_{\text{th}} = 1$–3 TeV.

A family, a nuclear collision in the atmosphere which is observed by emulsion chamber, is a bundle of showers with parallel direction of incidence. Available data are of direction, center position, total observed energy, etc. of the families, but not of the arriving time because the development of sensitive materials is made after $1 \sim 2$ years of exposure.

3) Hadron calorimeter

The hadron calorimeter of 32 plastic scintillators (50 cm × 50 cm each) is located beneath the emulsion chamber (fig. 1). Each unit of them detects charged particles under the emulsion chamber and hence 32 units of them supply us with a two-dimensional map of charged-particle density over the hadron calorimeter. These charged particles, mainly electrons and hadrons, are produced by hadrons, incident upon the emulsion chamber, through nuclear and electromagnetic cascade processes in lead of the emulsion chamber. It is worth noting that cascade showers which are produced by electrons and photons, incident upon the emulsion chamber, are absorbed completely before arriving at the bottom of the chamber. The available data are of center position, arriving time, size, etc. of the hadron component, estimated from the charged-particle density distribution, in the air shower.

2·2. *Corresponding air showers to families.* – Families, which have no data of arriving time, are correlated with the events of hadron calorimeter by the coincidence of the center of the event, and events of the hadron calorimeter are correlated with air showers by the coincidence of their arriving time.

3. – Analysis of experimental data

3·1. *Assumptions in the simulation.* – Analysis is made by comparing experimental data with those of simulated events, because nuclear interactions are not observed directly in most of the families. Simulation of air shower events is made on the following assumptions [3].

([1]) Emulsion chamber is sensitive to hadrons, incident upon the chamber, too, because a hadron produces a bundle of γ-rays in the chamber through the nuclear collision with Pb.

i) Primary cosmic rays

Energy and atomic number of primary cosmic rays are sampled from the energy distribution of

$$E^{-\gamma-1}\mathrm{d}E \qquad (\gamma = 1.7)$$

and from so-called normal composition of table I [5], respectively. The assumed composition is obtained by extrapolating the one in low energy region where direct measurement is possible.

ii) Hadron-air collisions

1) Collision mean free path of hadrons in the air

$$\lambda_{\mathrm{air}} = 760\sigma_{\mathrm{inel}}^{-0.63}\ (\mathrm{g/cm^2})\,,$$

$$\sigma_{\mathrm{inel}} = \sigma_0[1 + 0.0273\epsilon + 0.01\epsilon^2\theta(\epsilon)]\ (\mathrm{mb})\,,$$

where $\epsilon = \ln(E_0/200\ \mathrm{GeV})$ and $\theta(x)$ is a step function. The constant σ_0 is 32.2 (mb) and 20.3 (mb) for nucleon and pion collisions, respectively.

2) The collision of a hadron with an air nucleus follows the geometrical model.

3) Energy distribution of produced particles in inelastic collisions.

In each collision of a hadron with nucleons in an air nucleus, the multiple particle production is described by UA5 algorithm [6], which is a phenomenological simulation code to describe the UA5 Collaboration data by CERN $\bar{\mathrm{p}}\mathrm{p}$ collider [7]. It is worthy noting that the Feynman scaling law is violated both in the central and forward regions in the x-distribution of UA5 algorithm [4].

3˙2. *Total observed energy in the family.* – We obtain the total observed energy in the family by summing up the shower energies in the family, which is denoted by $\sum E_\gamma$. Figure 2 presents the average total observed energy in the family for several intervals of air shower size N_{e} [3]. The selected events are air showers which are accompanied by families with $n_\gamma \geq 5$ and $\sum E_\gamma \geq 10$ TeV ($E_{\mathrm{th}} \geq 2$ TeV). The air shower size is a good measure of the energy of the primary particle which initiates the air shower(2). That is, the relation $E_0/N_{\mathrm{e}} \simeq 2$ GeV is shown to be almost independent of the nuclear interactions and primary composition, assumed in the simulations, in the energy region of our concern at Mt. Chacaltaya.

The figure shows that the total observed energy in the family is lower than that by the simulation in large-size region of $N_{\mathrm{e}} \geq 5 \times 10^6$. A similar type of experiment at Tien Shan (3300 m, Kazakhstan) obtained the same results, which is presented in fig. 2 [8]. They indicate that the subdivision of energy in the atmosphere is stronger at high energies of $\sim 10^{16}$ eV than the one assumed in the simulation. That is, at least either of the assumptions in the simulation, the energy distribution of produced particles or the primary composition, should be modified into the one of stronger energy subdivision. Consequently the following hypotheses are possible.

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(2) Air shower size is defined as the number of charged particles in the air shower. It consists of hadron, electron (e^+ and e^-) and muon components, among which the electron component is dominant.

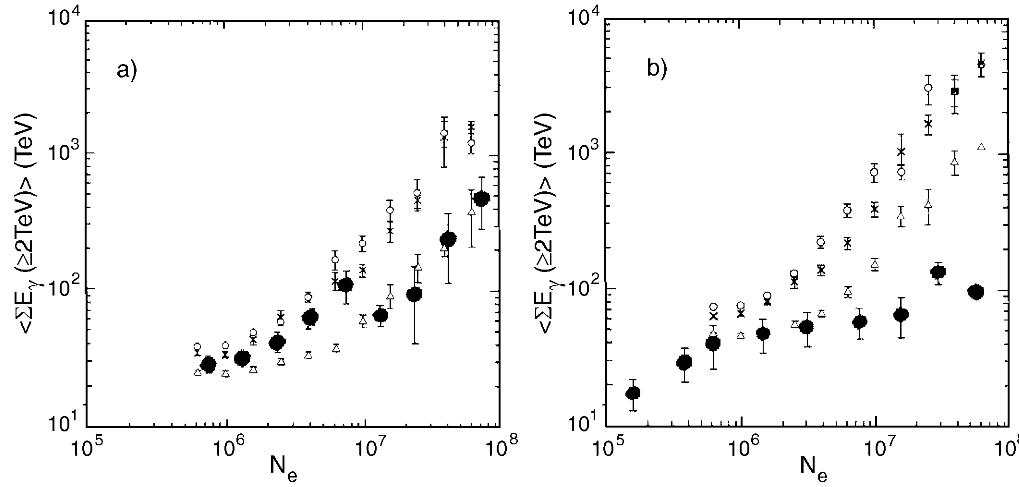

Fig. 2. – Correlation between the total observed energy in the family and air shower size, obtained by the experiments at Tien Shan (a) and at Mt. Chacaltaya (b). Model-A stands for UA5 algorithm.

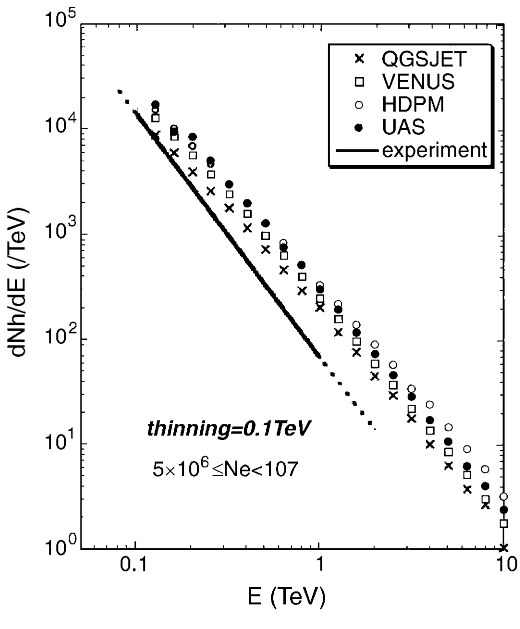

Fig. 3. – Differential energy spectrum of hadrons in the air showers of the size region $N_e = 5\times10^6$–10^7. The solid line part corresponds to the experimental data, because the observed lateral distribution of charged-particle density is limited in the region of $r = 0 \sim$ several meters. Plots are those by simulation codes which are employed presently to follow atmospheric diffusion of cosmic rays.

1) The Feynman scaling law is violated in the forward region more strongly than assumed in UA5 algorithm.

2) The composition of the primary cosmic rays becomes heavier or the fraction of irons becomes larger than the one in low energy region.

Figure 2 shows also that a proposed heavy composition of the primary cosmic rays [9] reduces but does not describe fully the observed discrepancy. Therefore we reach a conclusion that the proposal (1) is valid at high energies.

3·3. *Hadron component in the air shower*. – We can estimate the energy-lateral distribution of hadrons, incident upon the emulsion chamber, from the charged-particle density map which is obtained by the hadron calorimeter, by taking into account the nuclear and electromagnetic cascade processes in lead of the chamber [4].

Figure 3 presents the expected differential energy spectrum of hadrons in the air shower. The energy spectrum is expressed in the differential form, because the observed lateral distribution of charged-particle density is limited in the region of $r = 0 \sim$ several meters. The figure shows that the number of hadrons is smaller than that by the simulation, indication of which is consistent with the one in fig. 2. It is important that both components, the high-energy γ-rays of ≥ 2 TeV and the hadrons of $0.1 \sim 1$ TeV, in the air shower show the same tendency.

KASCADE experiment (at sea level, Germany) obtained the same conclusion from the study of hadronic cores of extensive air showers by the large hadron calorimeter [10].

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