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ICRR-Report-352-96-3

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Submitted to Phys. Rev. D

(January, 1996)

SCAN-9603131

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SW96-12

**Simultaneous Observation of Families and Accompanied Air Showers
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Abstract

Simultaneous observations of families and accompanied air showers with emulsion chambers and the air shower array of electronic equipment at Mt. Chacaltaya (5,200 m, 540 g/cm²), reveal that families bear the data of nuclear interactions generated deep in the atmosphere. 47 outstanding families with $\Sigma E_\gamma \geq 10$ TeV are correlated with the accompanied air showers of the size $10^5 \sim 10^8$. Scatter plot of the average family energy *vs.* the size of the relative air shower requires further energy fractionizing process(es) in the propagation of high energy cosmic rays in the atmosphere, such as larger dissipative mechanism in nuclear interaction, heavier chemical composition of the primary cosmic rays, etc. We reach the conclusion that nuclear interaction changes its feature in the energy region $E_0 > 10^{16}$ eV, because the heavier composition, proposed so far, is not sufficient for the required dissipative process. Comparison with the data by HADRON experiment at similar altitude with similar technique shows that no larger deviations are present between both experiments.

PACS numbers : 13.85.-t, 13.85.Hd, 13.85.Tp

I. Introduction.

It is reported by several groups that the family intensity, measured by the emulsion chamber located at a high mountain, is several times as low as that expected from the intensity of the primary cosmic rays.¹⁾ This experimental result, in agreement among the experimental groups, leads to various speculations which cause further energy dissipation to the cosmic-ray propagation in the atmosphere, such as that the primary cosmic rays changes its composition, that the nuclear interaction changes its feature, etc. The final conclusion, however, has not been reached yet so far.

This is an important problem in views of both the high energy particle physics and astrophysics, because the energy region concerned is several times as high as the energies of the present high energy accelerators and coincides with the so-called "knee" region where the primary cosmic-ray spectrum has a bend.

Taking into account the fact that the primary cosmic-ray spectrum, employed in the above analysis, is obtained by air shower experiments, we can formulate the problem from another side. A primary cosmic-ray particle of mass number A and energy E_0 , incident upon the atmosphere, produces large nuclear and electromagnetic cascades (abbreviated as N&EM cascade) in the atmosphere.²⁾ An air shower experiment observes the whole of the particles, produced in the N&EM cascade, while an emulsion chamber experiment observes respective high energy particles ($>$ several TeV) among them. That is, the both experiments observe the same phenomenon (N&EM cascade) at different cut edge.

It is obvious that the conventional analysis, where both data by the air shower experiment and by the emulsion chamber experiment, carried out independently, are compared through a medium of a simulation, is far from complete. Combination of the both experiments enables us to observe the air showers and families without losing their correlations, i.e. what kinds of an air shower and a family are produced in a single N&EM cascade. It increases an amount of information considerably and reduces the possible ambiguities inherent to the indirect comparison.

The first experiment of this kind was carried out by Smorodin et al.³⁾ at an airplane altitude in the early 1960s in order to investigate the nucleon interactions at energies above 10^{13} eV. We started in 1968 the experiment of emulsion chambers associated with burst detectors, installed under the 20 m² spark chamber, in the central area of Tokyo air shower array in the Institute for Nuclear Study, University of Tokyo, in order to study high energy hadrons and large transverse momentum phenomena in air showers. Then the detectors were moved to Mt. Chacaltaya in 1977 for the present experiment (SYS).⁴⁾ Dake et al. started the experiment at Mt. Norikura in 1968 to study multi-core events of air showers and families (AS γ).⁵⁾ and the experiment HADRON of a large scale started at Tien Shan in 1985.⁶⁾ (See Table 1.) SYS experiment is a unique one of this sort under operation at present.

AS γ experiment at Mt. Norikura drew a conclusion that proton's fraction is poor, i.e. 20 % at $E_0 = 1.4 \times 10^{15}$ eV, among the primary cosmic-ray composition (Consequently the composition becomes heavier than that in low energy region, where proton fraction is 40 $\sim$ 50 %.), by comparing the frequency of families with $\Sigma E_{\gamma,H}$ (the total observed energy

in the family) in the experiment and in the simulation.^{5),7)} Recently they made re-analysis of their data to confirm the above-mentioned conclusion.¹⁰⁾ As it was shown in Table 2, however, the estimation of the primary cosmic-ray composition by the intensity argument depends on the assumed model of nuclear interaction. It was pointed out¹²⁾ that the energy spectrum of produced particles, assumed in their simulation code, shows weaker violation of the Feynman scaling law¹³⁾ than that observed by the accelerator experiments.[†] Therefore, if they assume the energy spectrum, consistent with the data by accelerator experiments, in their simulation code leaving other features of nuclear interactions untouched, they would reach a conclusion of less heavy-dominant composition. Some comments will be given in § IV to AS γ experiment.

HADRON experiment at Tien Shan, in their preliminary report, concludes that the primary cosmic-ray composition is a mixed one (a heavy composition in our vocabulary, defined in the remark in Table 2.) from the normalized integral size spectrum of air showers which are accompanied by families.⁶⁾ There is, however, a discrepancy of absolute value between the above-mentioned spectrum by the experiment and that by the simulation. Recent results of HADRON experiment¹⁵⁾ will be discussed in § III of the present paper in relation to the data of our experiment respectively, because their way of analysis is similar to ours.

The present paper consists of four sections. § II describes the experimental setup and the experimental procedure. § III presents the experimental results to show the origin of the families in relation to the air showers and to conclude that the change of the nuclear interaction is necessary for the required rapid energy dissipating process. § IV is devoted to summary and discussion on the content of the change of the nuclear interaction, on the assumptions in the simulation, and on the future prospect of the experiment.

[†]Some of the authors of AS γ experiment assert incorrectly that the x -distribution, assumed in their simulation code, is consistent with the data by the accelerator experiment.^{10),14)}

II. The SYS Experiment.

The experiment operating an emulsion chamber and an air shower array together at Mt. Chacaltaya was started in 1979 by SYS collaboration (Saitama University and Yamanashi University in Japan, and Universidad Mayor de San Andres in Bolivia).¹¹⁾ The geographic parameters of the Cosmic Ray Laboratory at Mt. Chacaltaya (Bolivia) are,

$$\begin{aligned}\text{Height} & \quad 5,200 \text{ m (540 g/cm}^2 \text{ of atmospheric depth)} \\ \text{Location} & \quad 16^\circ 21' \text{ S} \quad 68^\circ 08' \text{ W}\end{aligned}$$

Initial motivation for the experiment was to obtain the information on the primary particle interaction that produces the air shower, by observing the high energy hadrons and γ -rays in the air shower via the emulsion chamber. It depends on the consideration that most of the high energy particles, observed by the emulsion chamber, come directly from the same interaction that initiates the air shower. It will be shown in § III of this paper that this assumption is too simplified.

A. Experimental setup.

(i) Air Shower Array.

The configuration of detectors of the air shower array is shown in Fig. 1. The array covers an area of radius $R = 50 \text{ m}$ by 35 detectors of plastic scintillator — 31 detectors of 0.25 m^2 and 4 of 1 m^2 — to measure the lateral distribution of electron density of the air shower. And 5 plastic scintillators (0.25 m^2 each) with the fast-timing circuit, are located in pyramid shape in the center of the array to measure the arrival direction of the air shower.

The recording system of the air shower array is triggered when one of the burst detectors, described below, has the density $n_b > 10^3$.

(ii) Emulsion Chamber.

32 blocks (0.25 m^2 each) of emulsion chamber are installed in the center of the air shower array. (Fig. 1) The configuration of 32 blocks is shown in Fig. 2, and the structure of one unit in Fig. 3. The chamber generally consists of 30 sheets of lead plate (0.5 cm thick each), equivalent to 30 cascade unit (c.u.) or 0.81 inelastic collision mean free path (λ_{inel}) in total, and of 14 sensitive layers of X-ray films inserted under every 1 cm of lead plate. Some sensitive layers contain nuclear emulsion plates besides X-ray films for the calibration of energy. (See B (ii) in this section.) The emulsion chamber detects the electron showers produced by high energy particles incident upon the chamber, and measures their energies, positions and directions of incidence.

Table 3 shows the exposure list of emulsion chambers. In 1989 the detectors of the air shower array was increased so as to cover the emulsion chamber of Brazil-Japan collaboration,^{1),16)} too. Therefore the data of accompanied air showers is available for the high energy families observed by the emulsion chambers of Brazil-Japan collaboration. However, the present analysis concerns the data of SYS chambers from 1979 to 1986, which have a uniform quality.

(iii) Burst Detectors.

Burst detectors of plastic scintillator (0.25 m^2 each) are installed underneath the respective blocks of the emulsion chamber. (Fig. 3) A burst detector measures the number of

charged particles (called "burst density" n_b) which penetrate the emulsion chamber.

When the core of an air shower hits the burst detectors, many of them have signals of the burst density and the map of the burst densities determines the center of the burst.

B. Experimental procedure.

(i) Size of the air shower.

The lateral distribution of electron density, measured by the density detectors of the air shower array, is fitted to NKG function of Molière unit $r_0 = 155 \text{ m}$ ¹⁷⁾ to obtain the total electron number N_e , called "size", and the age parameter s of the air shower.

Fig. 4 shows the size spectrum of all the observed air showers in 1982. The spectrum is consistent with the one by BASJE, another air shower experiment at Mt. Chacaltaya,¹⁸⁾ in the size region of $5 \times 10^5 \sim 5 \times 10^6$.

(ii) Energy of γ -rays and hadrons.¹⁶⁾

A high energy particle of electromagnetic component (electrons and photons), incident upon the chamber, produces an electron shower in the chamber through the cascade process in lead plates. Hence the photo-sensitive layers, inserted at various depths in the chamber, observes the various stages of shower development. The electron shower is recorded as a small black spot, visible with the naked eye, on the X-ray film after photographic development. This performance of emulsion chamber shows that the incident electron and photon cannot be discriminated, and it is the reason why they are called " γ -rays" collectively by emulsion chamber experiment.

Routine in emulsion chamber experiment is to measure the darkness of the spots by the microphotometer with the slit of a certain size (usually the size of $200 \times 200 \mu\text{m}^2$) and to make a transition curve of darkness (the development of darkness along the depth of the chamber) for each shower. Comparison of the transition curve with those of various incident energies by the cascade theory,¹⁹⁾ determines the relative value of the energy and the starting depth Δt of the shower, because the darkness is related to the number of electrons in the shower. On the other hand, the electron number in the shower, obtained directly by the microscopic observation of the shower in the nuclear emulsion plates, determines the absolute value of the energy by comparing its transition curve with those of the cascade theory. An emulsion chamber detects the showers of the energy exceeding $\sim 1 \text{ TeV}$.

In the case of hadron incidence, the shower is originated by photons (mainly through the decays of π^0 's and η 's) which are produced by the nuclear interaction of the hadron with the lead plate. The visible energy of the shower is not the incident energy of the hadron E_h but a fraction of it $k_\gamma E_h$ where k_γ is the ratio of the total energy of γ -rays to the incident energy of the hadron. Accordingly the detection of hadrons depends on the collision probability in the chamber, the distribution of k_γ , and the detection threshold energy of the chamber.

The showers with the starting depth $\Delta t \geq 6 \text{ (c.u.)}$ are defined as hadron-induced ones, because the probability for γ -rays to have such a starting depth is $p < e^{-6} = 2.5 \times 10^{-3}$. Those showers will be called "hadrons" hereafter, and the visible energy of the hadron-induced shower is expressed by $E_h^{(\gamma)}$, i.e. $E_h^{(\gamma)} = k_\gamma E_h$.

(iii) ΣE_γ of the family.

Usually, when the emulsion chamber is hit by the core of an air shower, it detects a bundle of γ -rays and hadrons in the air shower, which is called "family". Identification of the showers composing the family is easy because they have the same zenith and azimuth angles on the map where trajectories of all the showers are projected on the horizontal plane.

Analyses made below are for the families which fulfill the following criteria;

- (1) Minimum energy of the shower $E_{min} = 2 \text{ TeV}$,
- (2) Number of γ -rays $N_\gamma \geq 5$,
- (3) Total energy of γ -rays $\Sigma E_\gamma \geq 10 \text{ TeV}$.

Fig. 5 shows ΣE_γ (the sum of γ -ray energies in the family) spectrum of the families. It agrees well with that by the Brazil-Japan collaboration with the pure emulsion chamber at Mt. Chacaltaya,^{1),16)} showing that energy determination of the showers is consistent in both experiments. It should be noted that the minimum energy is set 4 TeV in Fig. 5 in accordance with Brazil-Japan collaboration.

(iv) Coupling the family with the accompanied air shower.

Families have the data of (1) the arrival direction and of (2) the position, but not of (3) the arrival time, because the emulsion chamber is exposed to cosmic rays for 1 ~ 2 years continuously to accumulate cosmic-ray events. On the other hand, the air showers have three of them all. It is not easy to couple the air shower with the family directly by the data of their arrival directions and their positions, because it is common that there are several candidate air showers to one family within the allowance of the experimental errors. Hence the air shower is looked for through the mediation of the data of the burst in the following way.

- (1) List up the families in one block of the emulsion chamber.
- (2) List up the bursts which have their centers on the concerned block of the emulsion chamber.
- (3) Correspond the families to the bursts on the assumption that the order of magnitude of the family (ΣE_γ) is the same as that of the burst density at the center (n_b).
- (4) Examine the consistency of the arrival direction between the air shower and the family, and also of the position between the air shower core and the family center.

By this algorithm 47 among 67 observed families are coupled with air showers. Hence the coupling rate is 70 %, and it increases to 77 % taking the dead time of the air shower array into account. For the 47 coupled events the differences of the arrival directions between the family and the accompanied air shower are 5.4 ± 0.5 (deg) for zenith angle and 17.0 ± 1.8 (deg) for azimuth angle on the average. The difference of the positions between the family center and the air shower core is 0.49 ± 0.04 (m). The coupling rate increases to 88 % for the families with $\Sigma E_\gamma > 50 \text{ TeV}$.

The size spectrum of the accompanied air showers is shown in Fig. 4. One sees that all the air showers accompany families in the region $N_e > 10^7$, or that the primary cosmic rays

produce always the visible families in the region $E_0 > 2 \times 10^{16}$ eV.[†] The difference of both spectra in high size region, observed in Fig. 4, is due to the low statistics of the events. That is, that of all the air showers is based on the data in 1982, when the triggering of the recording system is made by the air shower, and the triggering is by the burst in the experiment of simultaneous observation, starting in 1979.

C. Simulation.

The principle of our simulation is to use as simple assumptions as possible without losing the essential points, because most of them are not established yet in the concerned energy region, being the themes of investigation. What follows is a brief description on our simulation procedure.²⁰⁾

(i) Primary cosmic rays.

Energy spectrum of the primary cosmic rays is assumed to be,

$$E_0^{-\gamma}$$

in the integral form. The exponent γ is ~ 1.8 at $E_0 = 10^{15}$ eV and increases gradually to 2.0 with the energy. The energy region of the primary cosmic rays to be sampled is above 10^{15} eV.

The assumed chemical composition is so-called “normal” one which is estimated by Nikolsky by the analysis of the experimental data of air showers.²¹⁾ (See Table 4.) It is a light composition in our vocabulary. (See the remark in Table 2.)

(ii) Nuclear interactions.

Collision mean free path of hadrons in the air.

The collision mean free path of hadrons in the air is assumed to be

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

where the inelastic cross section of hadrons σ_{inel} is given by

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

with $\epsilon = \ln(E/200\text{GeV})$.²²⁾ The constant σ_0 has different values for nucleon-nucleon (N-N) and pion-nucleon (π -N) collisions ;

$$\sigma_0 = \begin{cases} 32.2 & (\text{mb}) & \text{N-N} \\ 20.3 & (\text{mb}) & \pi\text{-N} \end{cases}$$

The increasing cross section σ_{inel} reproduces the experimental data consistently in low energy region, giving a 10 % higher estimation than the experimental value at $\sqrt{s} = 1,800$ GeV.²³⁾

Hadron-air collisions.

We employ UA5 simulation algorithm²⁴⁾ for the model of multiple particle production of N-air collision. It is because we assume that N-N and N-air collisions have the same features

[†]We assume 2×10^9 (eV/electron) as the factor between the primary energy and the size of the air shower. See § II C (v).

of multiple particle production in the forward hemisphere of the collision, and because the propagation of cosmic rays in the atmosphere is governed mostly by the particles produced in the forward hemisphere. UA5 algorithm is the phenomenological simulation logic and reproduces the features of multiple particle production at $\sqrt{s} = 53, 200, 546$ and 900 (GeV) at CERN SPS $\bar{p}p$ collider. The energy spectrum of produced particles, predicted by the algorithm, shows a fair violation of Feynman scaling law both in the forward and central regions in terms of $dN/dx = (1/\sigma_{inel}) d\sigma/dx$ with $x = p_{\parallel}/E_0$, and the inelasticity distribution is approximately uniform between $0.1 \sim 0.9$ in the laboratory system, giving the average $\langle K \rangle = 0.40$. (See Appendix I.)

Further additional assumptions made in our simulation code are;

- (1) All the produced particles are pions.
- (2) π -air collisions follow the same algorithm as N-air collisions. Hence one should keep it in mind that the charge exchange process of the leading particle, $\pi^{\pm} \rightarrow \pi^0$, is not assumed.

Nucleus-air collisions.

The wounded-nucleon model is assumed for nucleus-air collisions.²⁵⁾ That is, the number of wounded nucleons which expresses the number of nuclear interactions in the air nucleus, is given by

$$N_w = A - A' - 4N_{\alpha} - N_{evap} \quad ,$$

where A is the mass number of the incident nucleus, A' that of the fragment nucleus after the collision, N_{α} the number of α particles, and N_{evap} the number of evaporated nucleons. These quantities, A' , N_{α} and N_{evap} , are sampled from the appropriate distributions.²⁰⁾

(iii) Electromagnetic interactions.

For the particles of electromagnetic component (electrons and photons) with the energy exceeding 1 TeV, the processes of pair creation and bremsstrahlung without Landau-Pomeranchuk-Migdal effect²⁶⁾ are taken into account.

(iv) Families.

Simulation for families is made in three dimensional way. That is, the coordinates and the energies are the available data for showers in the family. γ -rays and hadrons which have visible energy exceeding 2 TeV and location within the circles of 15 cm radius from the family center, are registered as family members. The interaction probability of hadrons in the chamber is assumed to be 0.7, and the visible energy of the hadron-induced shower is given by $k_{\gamma} E_h$ where k_{γ} is sampled from the Γ -distribution of $\langle k_{\gamma} \rangle = 0.15$.

(v) Air showers.

The simulation for the air showers is made in one dimensional way, and therefore only the size N_e is the directly available data.

Hadrons are traced down following the algorithm of nuclear interaction until their energies become 0.1 TeV or they arrive at the observation level of Mt. Chacaltaya. Those with the energy less than 0.1 TeV are assumed to have no further interaction, because the majority of them are pions that decay into muons.

Electrons with the energy less than 1 TeV are replaced by the analytic solution of electron number by the cascade theory under Approximation B¹⁹⁾ instead of being traced

down by the algorithm of electromagnetic interactions. However, photons are traced down until they convert to electron pairs, their energies become the critical energy in the air (80 MeV), or they arrive at the observation level.

The size of the air shower N_e is defined as the total number of charged particles which arrive at the observation level (Mt. Chacaltaya) among those produced by the above processes. The air shower size, thus defined, reproduces the well-known relation $E_0/N_e \simeq 2.0$ (GeV) on the average with a narrow dispersion of the distribution*.²⁰⁾

(vi) Statistics.

Table 5 shows the statistics of the simulated events.

*The distribution of E_0/N_e is not symmetric around the average value, having a long tail on the larger value side than the average on the log-scale as well as on the normal-scale, due to the large fluctuation of the starting points of air showers. Hence we will describe the distribution in terms of the average and the standard deviation, defined by $\sigma \equiv \sqrt{\langle x^2 \rangle - \langle x \rangle^2}$.

E_0	Primary Particle	Distribution of E_0/N_e		Remarks
		Average (GeV)	σ (GeV)	
$(1 \sim 1.5) \times 10^{15}$ eV	p	1.95	0.62 (32 %)	Events with $E_0/N_e > 5$ (GeV) are omitted.
"	Fe	2.08	0.09 (4.3 %)	

The sampled events are all the air showers, irrespective of the accompaniment of the families. The value is consistent with "31 % (standard deviation) at $N_e = 5 \times 10^5$ for the PD (proton-dominant) composition" in the simulation for Yangbajing (4,300 m) experiment.¹⁰⁾

III. Experimental Results.

(i) Energy spectrum of γ -rays in one family.

Energy spectra of γ -rays in one family, by the experiment and by the simulation, are shown in Fig. 6 for three different size regions of $N_e = 10^5 \sim 10^6$, $10^6 \sim 10^7$ and $10^7 \sim 10^8$. The experimental data show that the spectra of different N_e regions differ in the number of γ -rays in one family. Comparison of the spectra in the experiment and in the simulation shows that there is a discrepancy in the number of γ -rays, i.e. the experiment gives smaller number than the simulation, while the slopes of the spectra agree with each other. Meaning of the discrepancy will be discussed in (iii) of the present section.

The experiment HADRON at Tien Shan reported that the spectrum, expressed by the variable $x = E_\gamma/E_0$ where E_0 is estimated from N_e by assuming $E_0/N_e = 2.0$ GeV, becomes steeper suddenly in the size region exceeding 10^7 , compared with those in lower size region.¹⁵⁾ And they argue that nuclear interaction changes its feature at $\sim 2 \times 10^{16}$ eV. However such a change of the slope is not observed in Fig. 6 by our experiment.

In order to study the relation between the families and the accompanied air showers in more detail, we compare the energy spectra of γ -rays in one family, grouping the events both by ΣE_γ and N_e . That is, all the families with $\Sigma E_\gamma = 10 \sim 215$ (TeV) are classified into four groups of $\Sigma E_\gamma = 10 \sim 21.5$, $21.5 \sim 46.4$, $46.4 \sim 100$ and $100 \sim 215$ (TeV). Fig. 7 shows the energy spectrum of γ -rays in one family, for two groups of events with the same interval of $\Sigma E_\gamma = 46.4 \sim 100$ (TeV) but with different intervals of $N_e = 10^5 \sim 10^6$ and $10^6 \sim 10^7$, as an example. As can be seen in the figure, the energy spectra of the same interval of ΣE_γ agree well with each other in spite of the difference of size region. In other words, the energy spectrum of γ -rays in one family does depend on ΣE_γ of the family, but does not on N_e of the accompanied air shower. It is the case in the simulation, too.

It indicates that the family is produced deep in the atmosphere by a small number (one or two) of interactions of high energy hadrons in the air shower. Therefore there is no sharp correlation between the characteristics of the family and those of the accompanied air shower.

Fig. 8 presents the energy spectra of γ -rays in one family for four intervals of ΣE_γ without classifying the events by N_e to improve the statistics. On the whole the spectra in the experiment and in the simulation agree with each other with respect to both the slope and the number of γ -rays.

(ii) Energy spectrum of hadrons in one family.

The energy spectrum of hadrons in one family is shown in Fig. 7(b) for two groups of events with the same interval of $\Sigma E_\gamma = 46.4 \sim 100$ (TeV) but with the different intervals of $N_e = 10^5 \sim 10^6$ and $10^6 \sim 10^7$. Fig. 9 shows the energy spectrum of hadrons in one family for four intervals of ΣE_γ . These figures of hadrons confirm what are mentioned for the γ -rays in the family, i.e. the agreement of the energy spectra in one family for the families belonging to the same interval of ΣE_γ in spite of the different intervals of N_e , and the agreement of those by the experimental data and by the simulation for the families belonging to the same intervals of ΣE_γ .

Comparison of Figs. 9 (a) and (b) shows that only the spectrum of the highest ΣE_γ interval, i.e. $\Sigma E_\gamma = 100 \sim 215$ (TeV), deviates from that by the simulation, though the statistics is not sufficient yet. The observed increase of hadrons in the family may have some relation with the change of nuclear interaction in high energy region, which will be discussed elsewhere with better statistics of high energy events.

To conclude the present and previous subsections, our simulation code does simulate the features *inside* the family well, but does not the relation between the family and the air shower (or between the family and the primary energy of the event).

(iii) Correlation between $\langle \Sigma E_\gamma \rangle$ and N_e .

Fig. 10 shows the correlation between ΣE_γ and N_e . And Fig. 11 shows the dependence of the average value of ΣE_γ on N_e in the experiment and in the simulation. In the simulation the center of the family is distributed randomly over one block of the emulsion chamber in order to take into account missing showers which fall outside the emulsion chamber, though the effect is found small.

It is seen in Fig. 11(a) that $\langle \Sigma E_\gamma \rangle$ of the experiment has a smaller value than that of the simulation. Similar tendency is seen by the experiment HADRON at Tien Shan,¹⁵⁾ which is shown in Fig. 11(b). The discrepancy between the experiment and the simulation is found again in the relation between the family and the accompanied air shower.

The observed discrepancy, in Fig. 6 and in Fig. 11, indicates a more rapid energy dissipating process in the atmospheric propagation of cosmic rays at high energies. And the hypotheses for such a process under discussion are an increase of heavy components in the primary cosmic rays and the change of the nuclear interactions. The simulation shows, however, that the increase of iron component reduces the observed discrepancy only in part, because the simulated events of iron primaries have larger $\langle \Sigma E_\gamma \rangle$ than the value of the experiment, in high energy region $N_e > 10^7$.²⁰⁾ Hence the change of nuclear interaction is necessary for the required rapid energy dissipating process, whether one assumes the increase of heavy primaries or not.

It may be worthwhile to note the following points regarding the above analysis.

- (1) The analysis is free from the absolute intensity of the primary cosmic-ray spectrum.
- (2) It is not the reason for the ineffectiveness of the iron component to $\langle \Sigma E_\gamma \rangle$ that most of the families, produced by the iron component, disappear in the atmosphere before arriving at the chamber, because the primary cosmic rays produce always the visible families in the region $N_e > 10^7$, as was discussed in § II.
- (3) For the 47 families with accompanying air showers, the family centers always coincide with the core position of air showers within the experimental error. Hence there is no possibility that the families are produced locally at the periphery of the large air showers.

Figs. 11 (a) and (b) show that the experimental values of $\langle \Sigma E_\gamma \rangle$, at Mt. Chacaltaya and at Tien Shan, are similar in spite of the difference of altitudes, while the simulation shows that $\langle \Sigma E_\gamma \rangle$ at Mt. Chacaltaya is 2 ~ 3 times as large as that at Tien Shan. The reason for it may be attributed to the fact that the energies of γ -rays are over-estimated in HADRON experiment, because ΣE_γ spectrum at Tien Shan is not consistent with those at Mt. Chacaltaya and at Mt. Fuji.

(iv) It is important to see what kind of families are produced by the air showers of a fixed size, or, more specifically, the distribution of ΣE_γ at a fixed value of N_e ,

$$\varphi(x, N_e) dx \quad \text{with} \quad x = \Sigma E_\gamma \quad .$$

It can be observed in Fig. 10 directly along a fixed value of N_e , if the statistics of the events is large enough and if the most part of the distribution exists above the threshold of ΣE_γ . However unfortunately our experiment fulfills neither of the conditions. Hence, we will discuss it in another way.

The distribution can be expressed approximately by a single variable of $\Sigma E_\gamma / N_e^\delta$, because we have $\Sigma E_\gamma \propto E_0^\delta$ approximately. That is,

$$\varphi(x, N_e) dx = \phi\left(\frac{x}{N_e^\delta}\right) \frac{dx}{N_e^\delta} \quad .$$

The exponent δ assures the difference of the exponent between ΣE_γ spectrum and N_e spectrum. That is, the ΣE_γ spectrum is obtained in the following way.

$$\begin{aligned} & \int \phi\left(\frac{x}{N_e^\delta}\right) \frac{dx}{N_e^\delta} \gamma I_0 \left(\frac{N_e}{N_0}\right)^{-\gamma-1} \frac{dN_e}{N_0} \\ &= \beta I_0 x^{-\beta-1} dx \int y^\beta \phi(y) dy \quad \text{with} \quad \beta = \frac{\gamma}{\delta} \quad \text{and} \quad y = \frac{x}{N_e^\delta} \quad , \end{aligned}$$

where $\gamma I_0 (N_e/N_0)^{-\gamma-1} dN_e/N_0$ (with $\gamma = 1.8$) is N_e spectrum of the air showers. The integral spectrum of $x (= \Sigma E_\gamma)$ has the exponent β . We assume $\delta = 1.44$, because $\beta = 1.25$ by the experiment.

We will discuss the distribution of $\Sigma E_\gamma / N_e^\delta$, which corresponds to,

$$\phi(y) dy \quad \text{with} \quad y = \frac{\Sigma E_\gamma}{N_e^\delta} \quad .$$

It means seeing the distribution of the events in Fig. 10 by rotating the y-axis from the vertical line to the slant line of $\Sigma E_\gamma \propto N_e^\delta$.

The y -distribution of the present experiment, shown in Fig. 12(b), have the maxima between $y = 10^{-8}$ and $y = 10^{-7}$. Naturally the value $\langle y \rangle = 1.0 \times 10^{-8}$ (TeV) reproduces the relation between both spectra of ΣE_γ and N_e , Fig. 4 and Fig. 5, consistently. The distributions of the experiment (Fig. 12(b)) are broad compared with those of the simulation (Fig. 12(c)) where the events of proton primaries are sampled. It shows that the families are produced not only by protons (with UA5 algorithm of nuclear interactions in the atmosphere) but also by other processes. For example, the families produced by iron primaries contribute to the left-hand side part of the distribution.

IV. Summary and Discussion.

(i) The observation of families and accompanied air showers is carried out at Mt. Chacaltaya (5,200 m) by operating the emulsion chamber and the air shower array simultaneously. It is the role of the present experiment to mediate the air shower experiment and the emulsion chamber experiment, both of which have accumulated a lot of data independently.

The analysis is made for 47 families of $\Sigma E_\gamma \geq 10$ TeV with accompaniment of air showers, which are the data during the first 7 years (1979 – 1986) of the experiment. Principal conclusions of the present experiment are,

(1) Energy spectra of γ -rays in one family are approximately the same, when the families are parameterized by ΣE_γ , irrespective of the size of the accompanied air shower. It is also the case for the hadrons in the family. It means that the family is produced deep in the atmosphere by a small number (one or two) of interactions of high energy hadrons in the air shower.

(2) The feature of the families is reproduced well by the present simulation code, when the families are parameterized by ΣE_γ .

(3) There is a discrepancy between the experimental data and the simulation of current assumptions, which is seen in Fig. 6 and Fig.11. For example, in the relation of $\langle \Sigma E_\gamma \rangle$ vs. N_e in Fig. 11, $\langle \Sigma E_\gamma \rangle$ of the experiment is smaller appreciably than that of the simulation in the region $N_e > 5 \times 10^6$. It indicates further energy dissipation in the atmospheric propagation of cosmic rays in high energy region $E_0 > 10^{16}$ eV, such as the heavy composition of the primary cosmic rays, the change of the nuclear interaction, etc. The simulation shows that the heavy composition reduces the observed discrepancy only in part. Therefore the change of nuclear interaction is necessary whether one assumes the increase of heavy primaries or not. This conclusion is free from the absolute intensity of the primary cosmic rays.

(ii) Taking into account the fact that the nuclear interaction model, assumed in the present simulation code, reproduces the violation of the Feynman scaling law consistently with the data by the accelerator experiments (at $\sim 10^{14}$ eV), it is not easy to assume much stronger violation of the law in the energy region $E_0 > 10^{16}$ eV. Hence it is more probable to assume that another channel, such as the production of Centauro species ²⁷⁾, opens in the nuclear interactions of high energies besides the channel of ordinary multiple particle production which is characterized by the pion dominance and small $\langle p_T \rangle$ value (~ 0.4 GeV/c) of produced particles.

(iii) If one applies Glauber theory ²⁸⁾ to hadron-air collisions in the simulation, one gets a larger value of the inelasticity ($\langle K \rangle = 0.62$) and a longer collision mean free path than those assumed in the present simulation. The former makes the energy dissipation larger, while the latter smaller. Hence the simulation code which takes the above alternative into account, gives similar values to the quantities discussed in the present paper. Details of the analysis by the code of the above alternative will be discussed elsewhere.

(iv) The relation between $\langle \Sigma E_\gamma \rangle$ and N_e is discussed by AS γ experiment in Ref. 29). It shows that $\langle \Sigma E_\gamma \rangle$ is almost constant and ~ 30 TeV over the size range of $N_e = 10^{4.5} \sim$

$10^{7.5}$, which is nothing but the threshold effect of ΣE_γ . The high energy region where air showers are accompanied by visible families without exception, has not been reached yet by AS γ experiment, due to the low altitude of the experimental site and/or the small area of the emulsion chamber. It is one of the reasons why the advantages of the simultaneous observation is taken little in their analysis, and why they had to devote much effort to couple families with air showers.^{5),7)}

(v) We will not propose at present any model of the primary cosmic-ray composition but assume that it does not change so drastically from that of the lower energy region. It is because the estimation depends critically on the model of nuclear interaction, the detail of which is not clear yet and is to be elucidated urgently.

(vi) It is one of the advantages of the simultaneous observation of families and the accompanied air showers that one can select the events of low production height. Those events are characterized by the small values of $N_e/\Sigma E_\gamma$ (i.e. the events in the left-upper region in Fig. 10) and of the age parameter s of the air shower. For these events we can assume that the incident particles are nucleons which penetrate deep in the atmosphere, and that the families and the accompanied air showers are initiated by the same interactions. On such assumptions ΣE_γ of the family and N_e of the accompanied air shower enables us to estimate the production height and the primary energy of the event consistently.

Secondly, taking into account the fact that the family is produced mainly by one or two interactions of high energy hadrons in the air shower, which is one of the conclusions of the present paper, the distribution of ΣE_γ 's along the fixed value of N_e in Fig. 10 reflects the energy spectrum of hadrons produced in the nuclear interaction to initiate the air shower. It enables us to study nuclear interactions at the fixed energy in the energy region $E_0 > 10^{16}$ eV.

These items will be reported elsewhere with a better statistics of the events.

Acknowledgment

The authors wish to express their gratitude to the financial support by the Japan Society for the Promotion of Science, which made it possible to realize this international collaboration. This experiment is also supported partly by International Scientific Research Program and the Scientific Research Funds of the Ministry of Education, Science and Culture in Japan, by the Institute for Cosmic Ray Research, University of Tokyo, and by the Nissan Science Foundation.

The authors are indebted to the Bolivian staff of Cosmic Ray Laboratory at Mt. Chacaltaya, in particular, R. Anda, O. Villegas, A. Velarde who were/is the director of Instituto de Investigaciones Físicas, Universidad Mayor de San Andrés, to which the Laboratory belongs. They are also grateful to Prof. S. Okamoto, the former President of Saitama University, Prof. T. Okumura of Saitama University, Prof. Masaharu Machida, the former

President of Yamanashi University, and Prof. S. Miyake, the former director of Institute for Cosmic Ray Research, for their continuous encouragement. They thank Prof. Masaru Machida for his contribution at the early stage of this experiment.

The data processing was made by FACOM M780 at the Computer Room, Institute for Nuclear Study, University of Tokyo, by ACOS-6 at the Information Processing Center of Yamanashi University, and by HITAC at the Information Processing Center of Saitama University. The X-ray films and nuclear emulsions were developed at facilities of Institute for Cosmic Ray Research, University of Tokyo.

Appendix I. UA5 Simulation Algorithm.

UA5 algorithm is the simulation logic, developed by UA5 collaboration,²⁴⁾ to reproduce the data of multiple particle production, which are observed by their detectors of streamer chamber at CERN SPS $\bar{p}p$ collider at $\sqrt{s} = 53, 200, 546$ and 900 GeV. It consists of the codes of GENCLE and DIFF. The former is for non-single-diffractive process, and assumes basically the production and subsequent isotropic decay of small hadron clusters. The latter is for single-diffractive process, the cross section of which is assumed to be 19 % of the total inelastic cross section.

We will give below some comments on the characteristics of UA5 algorithm, relevant to cosmic-ray experiments.

(1) Inelasticity.

In UA5 algorithm the inelasticity is not the input but the output of the algorithm. The inelasticity distribution in the laboratory system is approximately uniform between 0.1 and 0.9, because the x -distribution of the leading particle in the center-of mass system is approximately uniform between 0.1 and 0.9. One should keep it in mind that the UA5 algorithm predicts the inelasticity of $\langle K \rangle = 0.4$ in the laboratory system at $E_0 = 1.5 \times 10^{14}$ eV (or $\sqrt{s} = 546$ GeV), indicating a decreasing inelasticity with the incident energy.

(2) Violation of the Feynman scaling law in the forward region.

Our discussion is made in terms of the rapidity distribution $dN/dy \equiv (1/\sigma_{inel})d\sigma/dy$, because it is equivalent to the discussion in terms of x -distribution owing to the relation $dN/dy = x dN/dx$. Fig. A1 shows the rapidity distributions of produced particles in the forward region at different energies, predicted by UA5 algorithm. The distributions show clearly the violation of the Feynman scaling law in the forward region, and are consistent with the data of UA7 collaboration.³⁰⁾ To convert the rapidity distribution of π^0 's, observed by UA7 collaboration, into that of the charged particles, $n_{charged}/n_{\pi^0} = 2.0$ and $\sigma_{inel} = 49.0$ (mb) are assumed.

One should notice that the statement that a certain interaction model reproduces the data by UA5 collaboration, does not mean *a priori* that it reproduces the experimental data in the forward region, for example those by UA7 collaboration, because UA5 data concern only the central region.

Table 1. Experiments operating with the emulsion chamber and the air shower array at high mountains.

Experiment	Start	Mountain (Height, Depth)	Emulsion Chamber (1) Area (2) Thickness	Air Shower Array (1) Density detectors (Area) (2) Core detector (3) Burst detector	Statistics of the events (Definition of the family)
AS γ ^{5),7)}	1968	Mt. Norikura (2,700 m, 738 g/cm ²)	(1) 20 m ² (2) 14 c.u. Fe	(1) 32 Scintillators (R= 40 m) (2) Spark chamber (54 m ²) (3) Scintillator (18 m ²)	99 events ($\Sigma E_{\gamma,H} \geq 10$ TeV, $n_{\gamma,H} \geq 2$, $E_{\gamma,H} \geq 2$ TeV)
SYS ⁴⁾	1979	Mt. Chacaltaya (5,200 m, 540 g/cm ²)	(1) 8 m ² (2) 30 c.u. Pb	(1) 44 Scintillators (R = 50 m) (2) — (3) Scintillator (8 m ²)	47 events ($\Sigma E_{\gamma} \geq 10$ TeV, $n_{\gamma} \geq 5$, $E_{\gamma} \geq 2$ TeV)
HADRON ⁶⁾	1985	Tien Shan (3,300 m, 700 g/cm ²)	(1) 162 m ² (2) 12 c.u. Pb + 70 g/cm ² C + 10 c.u. Pb	(1) 28 Scintillators (R = 70 m) (2) — (3) ionization chambers (162 m ²)	1531 events ($\Sigma E_{\gamma} \geq 10$ TeV, $n_{\gamma} \geq 2$, $E_{\gamma,H} \geq 2$ TeV)

Table 2. Conjectures on the chemical composition of the primary cosmic rays and the assumed extent of the violation of Feynman scaling law.

Author(s)	Conclusion on the composition of the primary cosmic rays [†]	Violation of Feynman scaling law in the assumed nuclear interaction model	Experimental Data
M. Shibata ⁸⁾	light	strong	Fuji
	heavy	weak	
J.R. Ren et al. ⁹⁾	heavy	weak*	Fuji/Kanbala
M. Shima et al. ^{5),7)}	heavy	weak*	Norikura
To. Saito et al. ¹⁰⁾	heavy	weak*	Norikura
Kempa et al. ¹¹⁾	light	strong	Fuji

[†] The composition, consistent with that in low energy region ($< 10^{13}$ eV) which has the proton fraction $40 \sim 50$ %, is called "light" composition.

* The simulation code is the same.

Table 3. Exposure list of the emulsion chambers and the electronic detectors of the air shower array in SYS experiment.

Series	Emulsion Chamber		Air Shower Array Detectors
	Construction - Disassembly	Area (Thickness, Sensitive layers, Burst det./Target)	
I-79	79/05/29 - 79/11/26	8 m ² (15 cm Pb, 14 layers, burst det.)	78/04/10 Density 31 (0.25 m ²) 4 (1 m ²) FT 5 (0.25 m ²)
II-0A	80/05/25 - 80/09/26	"	
III-0B	80/10/23 - 81/03/20	"	
IV-82	82/09/16 - 83/08/11	"	
V-83	83/10/07 - 84/08/23	"	
VI-84	84/09/17 - 85/09/19	"	
VII-85	85/11/29 - 86/11/25	"	
VIII-88	88/01/12 - 89/10/06	"	87/09/30 Density 31 (0.25 m ²) 4 (1 m ²) FT 8 (0.25 m ²)
IX-89-C23	89/11/11 - 91/03/11	8 m ² (15 cm Pb, 14 layers*, burst det.) 46 m ² (14 cm Pb, 5 layers*) 38 m ² (11 cm Pb, 4 layers*, 60 cm C)	89/11/24 Density 36 (0.25 m ²) 4 (1 m ²) FT 8 (0.25 m ²)
X-91-C24	91/03/16 - 92/10/12	8 m ² (15 cm Pb, 14 layers, burst det.) 42 m ² (13 cm Pb, 12 layers, 30 cm CH ₂ CH ₂) 38 m ² (11 cm Pb, 5 layers*, 60 cm C)	91/10/25 Density 36 (0.25 m ²) 4 (1 m ²) FT 8 (0.25 m ²)
XI-93-C25	93/11/10 -	8 m ² (9 cm Pb, 8 layers, burst det.) 41 m ² (9 cm Pb, 8 layers)	5 (1 m ²)

* Japanese and Russian X-ray films.

Table 4. Chemical composition of the primary cosmic rays, assumed in the simulation.

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

Table 5. Statistics of the simulated events.

No. of simulated primaries ($E_0 > 10^{15}$ eV)	23,452
No. of families by the simulation	13,274
No. of families by the criteria	8157

Reference.

- 1) S.G. Bayburina et al. (Pamir Collaboration, Mt. Fuji Collaboration and Chacaltaya Collaboration, Nucl. Phys. **B191** (1981) 1.
L.T. Baradzei et al. (Chacaltaya and Pamir Collaboration), Nucl. Phys. **B370** (1992) 365.
- 2) K. Greisen, Ann. Rev. of Nucl. Sci. Vol.10 (1960) 63.
- 3) Yu.A. Smorodin, M.V. Solov'yev, R.A. Antonov, L.T. Baradzei, V.V. Rykov, E.A. Kanevskaya, A.V. Apanasenko, S.I. Tulinova and O.W. Sorokin, Proc. 9th Int. Conf. on Cosmic Rays (London), Vol.2 (1965) 827.
- 4) T. Matano, M. Machida and K. Ohta, Acta Phys. Hung. **29**, Suppl.3 (1970) 451.
T. Matano, M. Machida, K. Ohta, I. Imai, M. Nagayasu, I. Tsushima, N. Kawasumi, K. Honda, K. Hashimoto, C. Aguirre, R. Anda, R. Debbe and C. Navia, Proc. 17th Int. Conf. on Cosmic Rays (Paris), Vol.11 (1981) 314 and 318.
T. Matano, M. Machida, I. Imai, M. Nagayasu, K. Nagasaki, I. Tsushima, N. Kawasumi, K. Honda, K. Hashimoto, N. Martinic, R. Anda, R. Debbe, J. Zapata, L. Siles, P. Miranda and C. Aguirre, Proc. 18th Int. Cosmic Ray Conf. (Bangalore), Vol.11 (1983) 338.
T. Matano, M. Machida, I. Tsushima, N. Kawasumi, K. Honda, K. Hashimoto, C. Navia, N. Martinic and C. Aguirre, Proc. 19th Int. Cosmic Ray Conf. (La Jolla), Vol.6 (1985) 296.
T. Matano, T. Kobata, K. Mori, N. Inoue, I. Tsushima, N. Kawasumi, K. Honda, K. Hashimoto, N. Martinic, A. Reguerin, R. Ticona and C. Aguirre, Proc. 21st Int. Cosmic Ray Conf. (Adelaide), Vol.8 (1990) 174.
N. Kawasumi, K. Honda, I. Tsushima, K. Hashimoto, K. Mori, N. Inoue, R. Ticona, T. Matano, N. Martinic, Z. Aliaga, A. Reguerin and C. Aguirre, Proc. 22nd Int. Cosmic Ray Conf. (Dublin), Vol.4 (1991) 253.
N. Kawasumi, I. Tsushima, K. Honda, K. Hashimoto, T. Matano, K. Mori, N. Inoue, R. Ticona, N. Martinic, Z. Aliaga, A. Reguerin and C. Aguirre, Proc. Int. Workshop on Super High Energy hadron Interactions (Tokyo, 1991), ed. by Y. Fujimoto, S. Hasegawa and A. Ohsawa (1991) 306.
N. Kawasumi, I. Tsushima, K. Honda, K. Hashimoto, T. Matano, K. Mori, N. Inoue, R. Ticona, A. Ohsawa, M. Tamada, N. Martinic, Z. Aliaga, A. Reguerin and C. Aguirre, AIP Conf. Proc. No.276 (1992) 88.
N. Kawasumi, I. Tsushima, K. Honda, K. Hashimoto, T. Matano, K. Mori, N. Inoue, R. Ticona, A. Ohsawa, M. Tamada, N. Ohmori, N. Martinic, N. Gironda, F. Osco and C. Aguirre, Proc. 23rd Int. Cosmic Ray Conf. (Calgary), Vol.4 (1993) 104.
N. Kawasumi, I. Tsushima, K. Honda, K. Hashimoto, T. Matano, K. Mori, N. Inoue, A. Ohsawa, M. Tamada, N. Ohmori, N. Martinic, R. Ticona, N. Gironda, F. Osco and C. Aguirre, Proc. VIII Int. Symp. on Very High Energy Cosmic Ray Interactions (Tokyo, 1994), ed. by Y. Fujimoto et al. (1994) 283.

- 5) S. Dake, Y. Hatano, M. Hazama, K. Jitsuno, K. Nishikawa, M. Sakata and Y. Yamamoto, *Acta Phys. Hung.* **29**, Suppl.3 (1970) 671.
S. Dake, M. Hazama, K. Jitsuno, K. Nishikawa, M. Sakata, Y. Yamamoto and Y. Hatano, *Nuovo Cim.* **B41** (1977) 55.
M.Sakata, Y.Yamamoto and S.Dake, *Nuovo Cim.* **70A** (1982) 297.
Y. Fukushima, C. Hamayasu, T. Mitsumune, To. Saito, M. Sakata, M. Shima, Y. Yamamoto, S. Dake, M. Kawamoto, M. Kusunose, N. Ohmori, K. Kasahara, T. Shirai, S. Torii and N. Hotta, *Phys. Rev.* **D39** (1989) 1267.
- 6) D.S. Adamov, V.V. Arabkin, K.V. Barkalov, N.G. Vildanov, A.G. Duvoby, A.D. Erlykin, B.B. Kadirsisov, S.K. Machavariani, A.A. Nam, N.M. Nesterova, S.I. Nikolsky, V.P. Pavljuchemko, P.V. Stavrev, K.V. Cherdyntseva, A.P. Chubenko and S.B. Shaulov, *Proc. 20th Int. Conf. on Cosmic Rays (Moscow)*, Vol.6 (1987) 144.
- 7) M. Shima, To. Saito, M. Sakata, Y. Yamamoto, K. Kasahara, T. Yuda, S. Torii and N. Hotta, *Phys. Rev.* **D39** (1989) 1275.
- 8) M. Shibata, *Phys. Rev.* **D24** (1981) 1847.
- 9) J.R. Ren et al., *Phys. Rev.* **D38** (1988) 1404.
- 10) To. Saito, T. Yuda, K. Kasahara, S. Torii, N. Hotta, M. Sakata and Y. Yamamoto, *Astr. Part. Phys.* **1** (1993) 257.
- 11) J. Kempa and J. Wdowczyk, *J. Phys* **G9** (1983) 1271; *Proc. VIII Int. Symp. on Very High Energy Cosmic Ray Interactions (Tokyo, 1994)*, ed. by Y. Fujimoto et al. (1994) 603.
- 12) Report of the Meeting "Hadron Interactions in $10^{15} - 10^{17}$ eV" (Tokyo, 1993) (in Japanese), ed. by S. Hasegawa, A. Ohsawa and T. Shibata. (1993) 31 and 61.
- 13) R. Feynman, *Phys. Rev. Lett.* **23** (1969) 1415.
- 14) T. Yuda, *Proc. 22nd Int. Cosmic Ray Conf. (Dublin)*, Vol.5 (1991) 313.
- 15) V.V. Arabkin, S.I. Nikolsky, K.V. Cherdyntseva and S.B. Shaulov, *FIAN Preprint No.140* (1991) (Lebedev Phys. Institute)(in Russian); *Proc. 22nd Int. Cosmic Ray Conf. (Dublin)* Vol.4 (1991) 269 and 273.
S.B. Shaulov, *Proc. Int. Workshop on Super High Energy hadron Interactions (Tokyo, 1991)*, ed. by Y. Fujimoto, S. Hasegawa and A. Ohsawa (1991) 228; *AIP Conf. Proc. No.276* (1992) 94.
- 16) C.M.G. Lattes et al. and M. Akashi et al. (Brazil-Japan emulsion chamber collaboration), *Prog. Theor. Phys. Suppl.* No.47 (1971) 1.
- 17) K. Greisen, *Progress in Cosmic Ray Physics (North Holland, Amsterdam)*, Vol.3 (1958) 3.
K. Kamata and J. Nishimura, *Prog. Theor. Phys. Suppl.* No.6 (1958) 93.
- 18) F. Kakimoto, T. Kaneko, Y. Mizumoto, K. Suga, N. Inoue, K. Nishi, Y. Yamada, N. Tajima, E. Gotoh, H. Nakatani, H. Yoshii, R. Anda, C. Aguirre, P.K. MacKeown, K. Murakami, T. Hara, Y. Toyoda and T. Maeda, *J. Phys.* **G9** (1983) 339.
- 19) J. Nishimura, *Handbuch der Physik (Springer)* Vol.46/2 (1967) 1.
- 20) M. Tamada, *J. Phys.* **G20** (1994) 487; *Proc. Int. Workshop on Super-High Energy*

- Hadron Interactions (Tokyo, 1991), ed. by Y. Fujimoto, S. Hasegawa and A. Ohsawa (1991) 263; AIP Conf. Proc. No.276 (1992) 126.
- 21) S.I. Nikolsky, Proc. 3rd Symp. on Cosmic Rays and Particle Physics (Tokyo, 1984) (Inst. for Cosmic Ray Research, Univ. of Tokyo) (1984) 507.
 - 22) A.H. Hillas, Proc. 16th Int. Cosmic Ray Conf. (Kyoto, 1979), Vol.6 (1979) 13.
 - 23) N.N. Amos (E710 collaboration), Phys. Lett. **243B** (1990) 158.
 - 24) G.L. Alner et al. (UA5 collaboration), Nucl. Phys. **B291** (1987) 445.
 - 25) Y. Niihori, T. Shibata, I.M. Martin, E.H. Shibuya and A. Turtelli Jr., Phys. Rev. **D36** (1987) 783.
 - 26) L.D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk U.S.S.R. **92** (1953) 535 and 735.
A.B. Migdal, Phys. Rev. **103** (1956) 1811.
 - 27) C.M.G. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep. **65** (1980) 151.
S. Hasegawa, AIP Conf. Proc. No.85 (1981) 500; ICRR-Report 151-87-5 (Inst. Cosmic Ray Research, Univ. of Tokyo) (1987).
 - 28) R.J. Glauber, Nucl. Phys. **B21** (1970) 135.
 - 29) To. Saito, T. Yuda, K. Kasahara, S. Tori, N. Hotta, M. Sakata, Y. Yamamoto, Proc. 22nd Int. Cosmic Ray Conf. (Dublin), Vol.4 (1991) 82.
 - 30) E. Pare, T. Doke, M. Haguenaue, V. Innocente, K. Kasahara, T. Kashiwagi, J. Kikuchi, S. Lanzano, K. Masuda, H. Murakami, Y. Muraki, T. Nakada, A. Nakamoto, and T. Yuda, Phys. Lett. **B242** (1990) 531.

Figure captions.

- Fig. 1 Complete schema of the air shower array. 35 density detectors of plastic scintillator cover the area of the radius $R = 50$ (m). The emulsion chamber is located in the room (2).
- Fig. 2 Configuration of the blocks of the emulsion chamber in the room (2).
- Fig. 3 Structure of the emulsion chamber and the burst detector. Each block of the emulsion chamber is 50×50 (cm²) of area and 15 cm Pb thick with 14 sensitive layers of X-ray films, inserted at each 1 cm of lead plate. The burst detector of plastic scintillator is located underneath the emulsion chamber.
- Fig. 4 Size spectrum of the air showers. Open circles are for all the observed air showers and the full circles for those which accompany the families. The solid line is the spectrum of all the air showers by BASJE, another air shower experiment at Mt. Chacaltaya.
- Fig. 5 ΣE_γ spectrum of the families. The solid line is the spectrum by Brazil-Japan collaboration, another emulsion chamber experiment at Mt. Chacaltaya. The minimum energy E_{min} is set 4 TeV in the definition of the family for this figure, in accordance with Brazil-Japan collaboration.
- Fig. 6 Energy spectrum of γ -rays in the family for three regions of the size of the accompanying air showers ; $N_e = 10^5 \sim 10^6$ ($\square$), $N_e = 10^6 \sim 10^7$ ($\triangle$), and $N_e = 10^7 \sim 10^8$ ($\circ$). (a) experimental data and (b) simulation.
- Fig. 7 Energy spectrum of γ -rays (a) and hadrons (b) in the family for two groups of families. $E_h^{(\gamma)}$ in Fig.(b) is the visible energy of the hadron-induced shower.
 $\square$: Families with $\Sigma E_\gamma = 46.4 \sim 100$ (TeV) and $N_e = 10^5 \sim 10^6$,
 $\triangle$: families with $\Sigma E_\gamma = 46.4 \sim 100$ (TeV) and $N_e = 10^6 \sim 10^7$.
- Fig. 8 Energy spectrum of γ -rays in the family for four regions of ΣE_γ , without classifying the data by N_e of the accompanying air shower. Figures (a) and (b) are by the experimental data and by the simulation.
 $\diamond$: $10 \leq \Sigma E_\gamma$ (TeV) < 21.5,
 $\square$: $21.5 \leq \Sigma E_\gamma$ (TeV) < 46.4,
 $\triangle$: $46.4 \leq \Sigma E_\gamma$ (TeV) < 100,
 $\circ$: $100 \leq \Sigma E_\gamma$ (TeV) < 215.
- Fig. 9 Energy spectrum of hadrons in the family for four regions of ΣE_γ . The energy in the figure $E_h^{(\gamma)}$ is the visible energy of the hadron-induced shower. Figures (a) and (b) are by the experimental data and by the simulation.
 $\diamond$: $10 \leq \Sigma E_\gamma$ (TeV) < 21.5,
 $\square$: $21.5 \leq \Sigma E_\gamma$ (TeV) < 46.4,
 $\triangle$: $46.4 \leq \Sigma E_\gamma$ (TeV) < 100,
 $\circ$: $100 \leq \Sigma E_\gamma$ (TeV) < 215.

- Fig. 10 Diagram between ΣE_γ (the total observed energy in the family) and N_e (the size of the air shower).
- Fig. 11 Correlation between $\langle \Sigma E_\gamma \rangle$ (the average value of ΣE_γ) and N_e . Figures (a) and (b) are by the present experiment and by HADRON experiment. The full circles are by the experiment and the open circles by the simulation.
- Fig. 12 The distribution of $y = \Sigma E_\gamma / N_e^\delta$.
 (a) Scatter plot of ΣE_γ of the families and $y = \Sigma E_\gamma / N_e^\delta$ where N_e is the size of the air shower. ΣE_γ is proportional to N_e^δ approximately. (See the text in § IV.)
 (b) Histograms of $y = \Sigma E_\gamma / N_e^\delta$ for the events with a certain values of ΣE_γ , by the experiment.
 solid line : $10 \leq \Sigma E_\gamma \text{ (TeV)} < 31.6$
 dashed line : $31.6 \leq \Sigma E_\gamma \text{ (TeV)} < 100$
 dotted line : $100 \leq \Sigma E_\gamma \text{ (TeV)}$
 (c) The same as (b) by the simulation of proton primaries. The total area under the histograms is normalized to the histogram in (b).
- Fig. A1 Rapidity density of charged particles in the forward region. The dotted line is the scaling distribution, and the full lines, (a) and (b), are the prediction by UA5 simulation algorithm at $\sqrt{s} = 200$ GeV and 900 GeV, respectively. The open circles are the data by UA7 collaboration (at $\sqrt{s} = 630$ GeV), where $\sigma_{inel} = 49.0$ (mb) and $n_{charged}/n_{\pi^0} = 2.0$ are assumed.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. A1