Air-shower-triggered families detected by the hybrid experiments at high mountains

S.P.Besshapov*, K.V.Cherdintseva*, A.P.Chubenko*, N.M.Nesterova*, N.M.Nikolskaya*, V.P.Pavluchenko*, S.B.Shaulov*, R.A.Nam†, V.V.Piskal†, N.G.Vildanov†, L.I.Vildanova†, J.K.Janseitova‡, H.Aoki§, K.Honda¶, N.Inoue‖, N.Kawasumi, N.Martinic††, N.Ochi‡‡, N.Ohmori[x], A.Ohsawa[xi], M.Tamada[xii], R.Ticona††**

* *P.N.Lebedev Physical Institute, Leninsky prospect 53, 119991 Moscow, Russia*
† *Tien-Shan highmountain CR station, Mitina 3, 480021 Almaty, Republic Kazakhstan*
‡ *Jezkazgan University, Jezkazgan, Republic Kazakhstan*
§ *Faculty of Science, Soka University, Hachioji, Tokyo, 192-8577, Japan*
¶ *Faculty of Engineering, University of Yamanashi,Kofu, 400-8511, Japan*
‖ *Faculty of Science, Saitama University,Saitama, 388-8570, Japan*
** *Faculty of Education, University of Yamanashi,Kofu, 400-8510, Japan*
†† *Insitute de Investigaciones Fisicas, Universidad Mayor de San Andres, La Paz, Bolivia*
‡‡ *General Education, Yonago National College of Technology, Yonago, 683-8502, Japan*
[x] *Faculty of Science, Kochi University, Kochi, 780-8520, Japan*
[xi] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, 277-8582, Japan*
[xii] *School of Science and Engineering, Kinki University, Higashi-Osaka, 577-8502 Japan*

Abstract. **Characteristics of the air-shower-triggered atmospheric families detected in the hybrid experiment together with emulsion chamber and AS-array at Mt. Chacaltaya, Tibet and Tien-Shan are studied in detail by comparing with those of CORSIKA simulations using interaction models of QGSJET, SIBYLL and EPOS. In the Chacaltaya data, family-energy distribution in the events with air-shower size of $Ne \geq 10^7$ is favorable to heavy-dominant chemical composition of primary cosmic-rays but the lateral distribution is favorable to heavy-dominant composition. The Tien-Shan data, however, energy and lateral characteristics of the EAS-triggered families are not much different from those expected in simulations using QGSJET and EPOS models.**

***Keywords*: air-shower, emulsion chamber, mountain experiment**

I. Introduction

One of the main topics of cosmic-ray studies is to clarify the chemical composition of primary cosmic-rays around ”knee” region, $E_0 > 10^{15}$ eV, which gives important insight into physical origin of cosmic-rays. Direct observations of primary cosmic-rays in this energy range are still not possible and then various types of air-shower experiments at high mountains and also at ground level have been carried out[1], [2], [3], [4], [5], [6]. The experimental data in those indirect measurement are usually interpreted by comparing with Monte Carlo simulations assuming some models of cosmic-ray interactions. Many of experimental groups claim that the fraction of heavy primaries increases rapidly beyond the ”knee” region, e.g., the fraction of protons is estimated, by the Tibet AS-γ group shows[7], as small as ~ 10 % of all particles in $E_0 = 10^{15} - 10^{16}$ eV. The results, however, depends on their assumed interaction model. For example, the model EPOS recently proposed[8], [9] gives muon numbers much more than QGSJET model does. The events which can be interpreted due to heavy primary when we employ QGSJET model as nuclear interactions are interpreted due to proton primary when EPOS is used as an interaction model [10]. Thus the interpretations heavily rely on the Monte Carlo calculations. In fact, various experimental groups give various data on chemical composition and the results are still very confusing. We should examine whether the overall experimental data can be well interpreted by the assumed model before drawing a conclusion.

At Mt. Chacaltaya (5200m, Bolivia) and Tien-Shan (3340m, Kazakhstan) we have been carrying on a hybrid experiment operating simultaneously an air-shower array, a hadron calorimeter and an emulsion chamber for studying cosmic-ray nuclear interaction in the energy region around $10^{15} - 10^{17}$ eV[1], [3], [11]. The analysis of air-showers and associated families in the Chacaltaya hybrid experiment shows[1], [11], that the increase of heavier composition of primary cosmic rays alone can not explain the general characteristics of air-shower-triggered families, contrary to the results of Tibet group and others [4], [7], [12].

In order to check the argument based on the Chacaltaya data we compare experimental data so far obtained by three hybrid experiments at high mountains using EAS-array and emulsion chamber. It is not possible to compare directly the experimental data because the observation level and also details procedure of the analysis

TABLE I
HYBRID EXPERIMENTS AT HIGH MOUNTAINS

experimemt	atmospheric depth (g/cm^2)	thickness of the chamber (cmPb)	exposure $ST^\dagger$ (m^{2}y)	number of families with $N_e \geq 10^6$	number of families with $N_e \geq 10^7$
Chacaltaya hybrid	540	15	40	44	14
Tibet AS-γ	606	7.5	153.2	$\sim 110^\star$	$\sim 18^\star$
Tien-Shan "HADRON"	685	6 (G-block)	462.5	174	20

†) T: total live time of EAS-array, S: effective area of emulsion chamber
*) The figure is obtained by counting the data points in the diagram which can be seen in Ref.[13].

TABLE II
CHEMICAL COMPOSITION OF PRIMARY COSMIC-RAYS AND AIR-SHOWERS

	sampled primary particles									
	proton dominant					heavy dominant				
E_0 (eV)	protons	He	CNO	heavy	Fe	protons	He	CNO	heavy	Fe
$10^{15} - 10^{16}$	42 %	16 %	16 %	14 %	12 %	17 %	10 %	18 %	15 %	40 %
$10^{16} - 10^{17}$	42 %	12 %	13 %	15 %	18 %	14 %	8 %	17 %	14 %	47 %
	air-showers accompanied by families (CORSIKA/QGSJET)									
$10^6 < Ne < 10^7$										
	protons	He	CNO	heavy	Fe	protons	He	CNO	heavy	Fe
Chacaltaya	76 %	16 %	4 %	2 %	2 %	53 %	17 %	13 %	9 %	7 %
Tibet	77 %	17 %	6 %	1 %	0 %	63 %	19 %	10 %	4 %	4 %
Tien-Shan	80 %	12 %	4 %	3 %	1 %	62 %	20 %	10 %	5 %	4 %
$10^7 < Ne < 10^8$										
	protons	He	CNO	heavy	Fe	protons	He	CNO	heavy	Fe
Chcaltaya	55 %	13 %	11 %	11 %	10 %	21 %	10 %	19 %	14 %	36 %
Tibet	60 %	13 %	10 %	8 %	9 %	25 %	10 %	20 %	16 %	29 %
Tien-Shan	62 %	13 %	8 %	10 %	7 %	28 %	14 %	20 %	10 %	28 %

are different in the three experimental group, then we compare these experimental data through simulations.

II. HYBRID EXPERIMENT AT HIGH MOUNTAINS

We take into accounts the following three hybrid-experiments with EAS-array and emulsion chamber at high mountains.

• *Chacaltaya hybrid experiment*[1].

The air-shower array covers a circular area of about 50 m radius by 35 plastic scintillation detectors to measure the lateral distribution of electron density of the air-showers. 32 blocks of emulsion chambers (0.25 m^2 each) are installed in the center of the air-shower array. Each block of the emulsion chamber consists of 30 lead plates of 0.5 cm thick each and 14 sensitive layers of X-ray film which are inserted at every 1 cm lead. The total area of the emulsion chambers is 8 m^2. Burst detectors of plastic scintillator are installed underneath the respective blocks of the emulsion chamber.

• *Tibet AS-γ experiment* [1] [2], [7]

The air-shower array covers a area of 36,900m^2 by 221 scintillation counters each placed on a 15 m square grid. 400 blocks of emulsion chambers (0.20 m^2 each) are constructed near the center of the AS array. Burst detectors are placed just below the emulsion chambers. The total area of emulsion chamber is 80 m^2.

• *Tien-Shan "HADRON" experiment*[3]

Scintillator detectors covers a area mainly within radius ~70 m for the measurement of electron density of the air-showers. Two-storey emulsion chambers, which consists of Gamma-block of 6 cmPb, Hadron-block of 5cmPb and carbon layer of 60 cm thick between the two, together with four layers of ionization chambers, two are under G-block and the other two are above the H-block, are installed in the center of the EAS-array. The total area of the emulsion chamber is 162 m^2. In the present analysis we use air-shower triggered families detected in the Gamma-block.

Table 1 shows a brief summary of the above three hybrid experiments.

III. SIMULATIONS

For generating extensive air-showers and families we use CORSIKA simulation code(version 6.502 and 6.735) [14] employing QGSJET (QGSJET01c) model[15], SIBYLL (SIBYLL 2.1) model[16], [17]and also EPOS (EPOS 1.60) model[8], [9] for the cosmic-ray nuclear interaction. Primary particles of $E_0 \geq 10^{15}$ eV (sample A) and of $E_0 \geq 10^{16}$ eV (sample B) are sampled respectively from the energy spectrum of primary cosmic rays with proton dominant and heavy dominant chemical composition shown in Table 2. Shower size, N_e, at the observation point is calculated by using NKG option in the simulation. For high energy (e,γ)-particles and hadrons of $E \geq 1$ TeV, arriving upon the emulsion chamber, in the atmospheric families, we calculate further nuclear and electromagnetic cascade development inside the chamber taking into account exactly the structure of the emulsion chamber. We use QGSJET model for hadron-Pb interactions and a code

[1]There is no official publication on the details of air-shower triggered families. We can find scatter plot on $N_e - \sum E_\gamma$ and N_e-dependence of average $\sum E_\gamma$ in the web page of the talk by M.Shibata[13]. The Tibet data in the present analysis are obtained by reading the data points in the figures of his talk, then the results are preliminary.

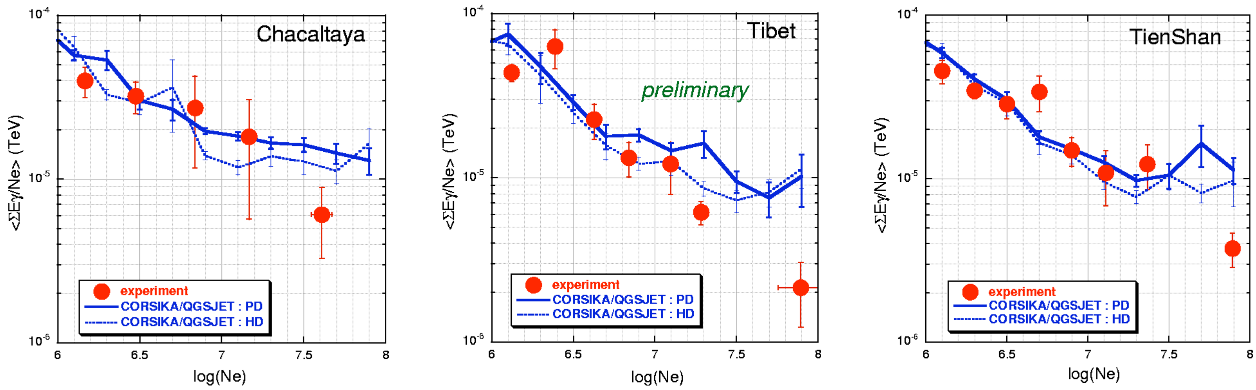

Fig. 1. Shower size dependence on family energy normalized by associate air-shower size. Circles are experimental data and lines are simulated data (CORSIKA/QGSJET) for proton dominant composition (solid) and heavy dominant composition (dotted).

formulated by Okamoto and Shibata for electromagnetic cascade[18]. The energy of each shower is re-estimated by applying the procedure used in the experiments. Taking into accounts the effect of the existence of gap between two neighboring blocks of emulsion chambers, we pick up the events with shower-size $Ne \geq 10^6$ which accompany an atmospheric family with $\sum E_\gamma \geq 20$ TeV and $N_\gamma \geq 4$. Here $\sum E_\gamma$ and N_γ are energy sum and number of γ-rays with energy $E_\gamma \geq 4$ TeV. In Table 2 we show the fraction of protons, He, CNO, heavy and Fe components in the air-showers accompanied by families in case of QGSJET model. In the shower-size region of $10^6 \leq N_e < 10^7$, corresponding to $E_0 \approx 10^{15}–10^{16}$ eV, more than ~80 % of the air-showers which accompany families are due to proton- or He-primaries even when heavy dominant composition is assumed. In the larger shower-size region of $10^7 \leq N_e < 10^8$, corresponding to $E_0 \approx 10^{16} - 10^{17}$ eV, the chemical composition of primaries which produce air-showers accompanying families is similar to that of general air-showers because almost all air-showers in this size region accompany families.

IV. Longitudinal and lateral characteristics of the families

Fig.1 shows shower-size, N_e, dependence on the family energy normalized by the associate air-shower size N_e. The three experimental data, though the observation level is different, show the family energy accompanied by large air-showers is considerably smaller than those expected in simulations.

As is seen in Table 2, the chemical composition of the detected EAS-triggered families with shower size $N_e \geq 10^7$ reflects well those of primary cosmic-rays. So in the following, analyses are applied for those families with $Ne \geq 10^7$. Fig.2 shows depth dependence on the family-energy normalized by the size of the accompanied air-shower with $N_e \geq 10^7$. As is seen in the figure the Chacaltaya and Tibet data agree more or less to those expected in case of heavy-dominant primary composition and are clearly smaller than those

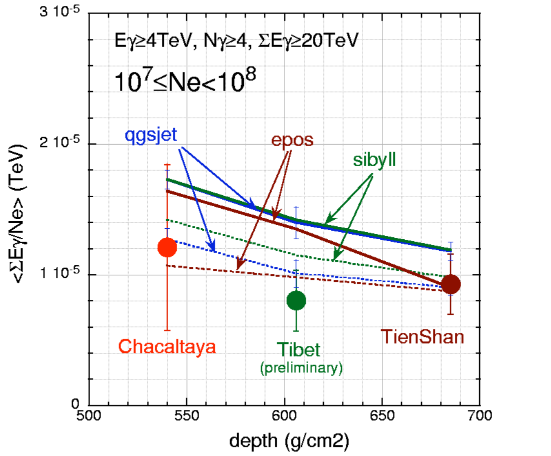

Fig. 2. Depth dependence on family energy normalized by air-shower size with $10^7 \leq N_e < 10^8$. Circles are experimental data and lines are simulated data (CORSIKA/QGSJET·SIBYLL·EPOS) for proton dominant composition (solid) and heavy dominant composition (dotted).

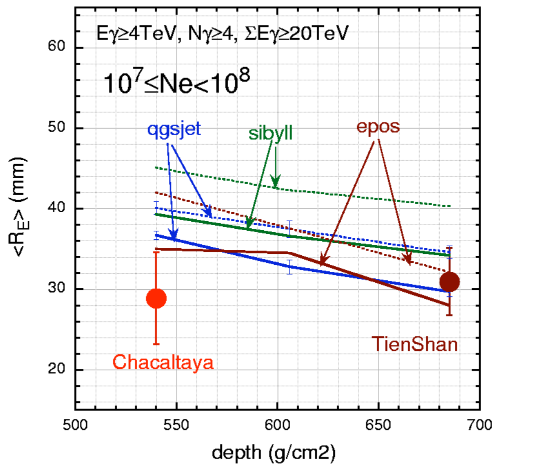

Fig. 3. Depth dependence on average lateral spread of the EAS-trggererd families with air-showers of $10^7 \leq N_e < 10^8$. Symbols are same to those in Fig.1.

of simulations in case of proton dominant chemical composition in primary particles. For the Tien-Shan data, the difference between proton-dominant and heavy dominant composition is not clear, specially in the case of EPOS model. Fig.3 shows depth dependence on the average lateral spread of the families defined by $R_E = \Sigma ER/\Sigma E$. [2] As is seen in the figure the heavy dominant composition gives systematically larger lateral spread of the families, because heavy primaries produce atmospheric families with large lateral spread. SIBYLL model gives systematically larger lateral spread than QGSJET and EPOS models do and the lateral spread in case of proton-dominant composition with SIBYLL model is nearly same to that in case of heavy-dominant composition with QGSJET and EPOS models. Thus the lateral spread of the families depends on the assumed interaction model. The Chacaltaya data shown in Fig.3 are close to (or even smaller than) those expected in case of proton-dominant composition, though the Tien-Shan data are just between the two different chemical composition in case of QGSJET and EPOS models.

Fig.4 show a correlation diagram on energy and lateral spread of the families. We can see a general tendency that increase of heavy component in primary cosmic-rays results in decrease of family energy and increase of lateral spread. The Chacaltaya data, however, shows the family energy is nearly same to that expected in heavy dominant case but lateral spread is smaller than proton-dominant case. The Tien-Shan data are more less close to those expected in QGSJET and EPOS models with two different chemical compositions.

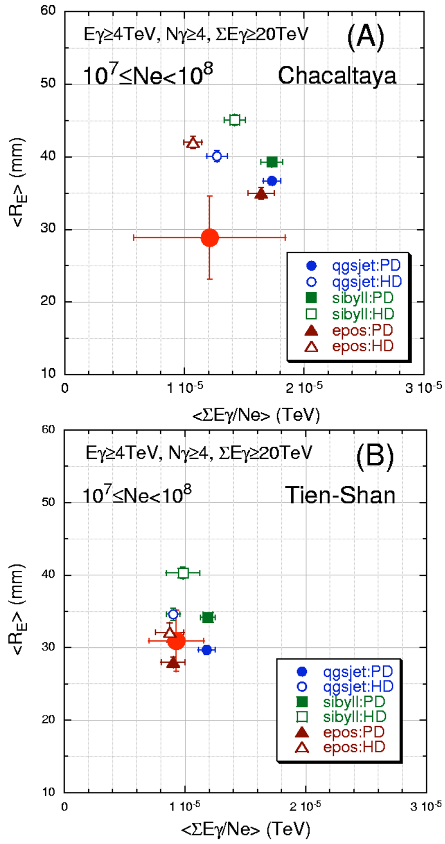

Fig. 4. Correlation diagram on family energy normalized by shower size and average lateral spread of the EAS-trggererd families with air-showers of $10^7 \leq N_e < 10^8$ for Chacaltaya (A) and for Tien-Shan experiment (B).

V. Discussions

The energies of EAS-triggered families accompanied by the air-showers of $Ne \geq 10^7$ detected by Chacaltaya and Tibet hybrid experiments is favorable to heavy-dominant primary composition. The lateral spread of those families are favorable to proton-dominant composition in Chacaltaya data. Thus the Chacaltaya data can not be explained simply by adjusting the chemical composition of primary cosmic-rays. The Tien-Shan data, however, show that the longitudinal and lateral structure of those EAS-triggered families are not much different from those expected in simulations using QGSJET and EPOS models. The method combining air-showers detected by air-shower array and high energy atmospheric families detected by emulsion chambers are different in Chacaltaya and Tien-Shan experiment. We need to consider how these methodological difference affects the experimental data.

The observed number of events of air-showers accompanied by an atmospheric family is still small and we need much more events to draw the firm conclusion.

[2]We do not find any data on lateral spread of the EAS-triggered families in Tibet experiment.

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