Abstract: Characteristics of air-showers and accompanied high energy atmospheric families detected in the hybrid experiment at Mt. Chacaltaya are studied in detail and compared with those of simulations taking into accounts the specific detection bias of the experiment. It is shown that the observed characteristics of the atmospheric families accompanied by large air showers, $N_e > 10^7$, and also those of air-showers accompanying families cannot be explained simply by increase of heavy nucleus in primary cosmic-rays. Discussions are also given on the comparison with the results of the other hybrid experiments on high mountains.

Introduction

For many years the chemical composition of primary cosmic-rays around the "knee" region, $E_0 > 10^{15}$ eV, has been widely studied. The arguments are mainly based on the EAS experimental data. The data are usually interpreted by comparing with detailed Monte Carlo simulations, so the conclusions fully depend on the assumed interaction model. The results so far published are confused\[1\], though many groups argue that the chemical composition develops a tendency to increase heavier element above the "knee".

At Mt. Chacaltaya (5200m, Bolivia) we carry 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\[2\]. The main idea is to detect high energy particles which provide more direct information on the nuclear interaction of the primary cosmic rays together with air-showers. Emulsion chambers detect high energy particles of $E \geq \sim 1$ TeV of both the electromagnetic and hadronic components. The combination of both air-shower data and emulsion chamber data enable us to observe both the air-showers and families without losing their correlation.

Hybrid experiments of similar type are also carried out in Tibet AS$\gamma$ experiment\[3\] and in HADRON experiment at Tien-Shan \[4\]. The Tibetan group recently published their results\[5\] on proton and alpha spectra above the knee, $E_0 \geq 10^{15}$ eV, by applying neural net analysis to the air-showers accompanied by $\gamma$-families under the assumption that the model of high energy cosmic ray nuclear interaction which they use holds good in this energy region. The fraction of protons is estimated, in their analysis, as small as $\sim 10$ % of all particles in $E_0 = 10^{15} - 10^{16}$ eV. The analysis, however,
depends on the assumed model of cosmic ray nuclear interactions in their Monte Carlo simulations. The validity of the assumed models has never been checked experimentally, specially in the most forward region of the interaction which is most effective for the cosmic-ray study.

We have shown[2], based on the analysis of air-showers and associated families in the hybrid experiment, 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.

In the present analysis, the Chacaltaya hybrid experimental data are compared with those of simulations which are now widely used in cosmic-ray studies. The results again shows the models can not fully describe general characteristics of air-showers accompanied by families.

**Chacaltaya hybrid experiment**

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. Five fast-timing plastic scintillation detectors are located in the center of the array to measure the arrival direction of 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 (0.5 cm thick each) and 14 sensitive layers of X-ray film which are inserted at every 1 cm lead. There exists a gap between the two neighboring blocks. The gap size is from $\sim 10$ cm to $\sim 30$ cm. Some details of the setup are given in Ref.[2]. A bundle of $(e, \gamma)$ particles and hadrons with same zenith and azimuthal angles, called "atmospheric family", is detected by the emulsion chamber. Burst detectors of plastic scintillator are installed underneath the respective blocks of the emulsion chamber. We pick up the air-showers accompanied with families in which the number of $(e, \gamma)$-particles of $E_\gamma \geq 2$ TeV is larger than 5. In the analyzed area of series exposure of the emulsion chambers, $\sim 44$ m$^2$·y, we observe 72 air-showers of size $N_e \geq 10^6$ which accompany the families. Among them, 20 air-showers has size $N_e \geq 10^7$.

<table>
<thead>
<tr>
<th>$E_0$ (eV)</th>
<th>protons</th>
<th>He</th>
<th>CNO</th>
<th>heavy</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{15}$ – $10^{16}$</td>
<td>42 %</td>
<td>16 %</td>
<td>16 %</td>
<td>14 %</td>
<td>12 %</td>
</tr>
<tr>
<td>$10^{16}$ – $10^{17}$</td>
<td>42 %</td>
<td>12 %</td>
<td>13 %</td>
<td>15 %</td>
<td>18 %</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of the events

**Simulations**

For generating extensive air-showers and families we use CORSIKA simulation code(version 6.502) [6] employing QGSJET (QGSJET01c) model[7] and also SIBYLL (SIBYLL 2.1) model[8] for nuclear interaction. 20,000 primaries of $E_0 \geq 10^{15}$ eV (sample A) and 6,000 primaries of $E_0 \geq 10^{16}$ eV (sample B) respectively are sampled from the energy spectrum of primary cosmic rays with proton dominant chemical composition shown in Table 1. Shower size, $N_e$, at the observation point is calculated by using NKG option in the simulation. For high energy $(e, \gamma)$-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 formulated by Okamoto and Shibata for electromagnetic cascade[9]. We also take into accounts effects of the existence of gap between two neighboring blocks of emulsion chambers. That is, the emulsion chambers can detect $(e, \gamma)$ particles and hadrons in the peripheral part of the high energy families even when the event center enters the gap between the emulsion chambers, because atmospheric families have some lateral spread. In those events, we can detect only a part of the event as a family event. This effect works the family energy smaller$^1$. Around 30% of the observed families have their center just in the gap between the

$^1$ In Ref.[2], the effect of the gap is not taken into accounts in the simulation and then the average energy of families accompanying EAS is a little larger than the present results.
blocks and periphery of those events are detected as families which satisfy the selection criteria.

**Comparison with simulations**

**Energy of EAS-triggered families**

In the simulated events we pick up the air-showers accompanied with families applying the selection criteria same to the experiment. In Table 1 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. 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 almost same to that of general air-showers because almost all air-showers in this size region accompany families.

Fig.1 shows a diagram on air-shower size, $N_e$, and average energy sum, $< \log \sum E_\gamma >$, of accompanied families.

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**Lateral spread of EAS-triggered families**

Fig.3 shows a distribution of average lateral spread, defined by $< r \equiv \sum E_\gamma R_\gamma / \sum E_\gamma >$, of fami-
Figure 3: Distribution of average lateral spread $<\gamma R>$ of $\gamma$-rays in the families associated with air-showers of $10^7 \leq N_e < 10^8$. Circles are experimental data and lines are simulated data for proton primaries (dash-dotted), iron-primaries (shaded) and all particles with spectrum.

lies associated with air-showers of the size $10^7 \leq N_e < 10^8$. Here we use families of energy $10 \leq \sum E_\gamma < 1,000$ TeV. Lateral spread of the families is a little larger in SIBYLL model than in QGSJET model. It is seen that the lateral spread of the events induced by protons is smaller than that by heavy primaries. The experimental distribution agrees more or less with simulations assuming proton dominant primary composition shown in Table I, that is, around one half of the detected events are proton-induced ones in this size region. The result contradicts to the argument on the $f$-distribution given in the previous section in which almost all of the events are possibly due to heavy primaries.

Summary and discussions

We have studied in detail the characteristics of the family associated with air-showers of size $N_e \geq 10^7$. The average family energy associated in large air-showers of $N_e \geq 10^7$ is clearly smaller than those of simulations which are widely used in high energy cosmic ray studies. It indicates as if almost all those events are due to heavy primaries. The lateral spread of the families in those events, on the contrary, shows that almost all the events are due to proton or light nuclei. In fig.4 we show a correlation diagram on average family energy normalized by shower-size and average lateral spread, for the events with $10^7 \leq N_e < 10^8$.

As is clearly seen in the figure, no models explain the experimental data, though the number of experimental data is small. It is not possible to explain the experimental data simply by adjusting the chemical composition of primary cosmic-rays, though there are many arguments about increase of heavy nuclei in primary cosmic rays in energy larger than $10^{15}$ eV. The present detailed analysis of air-showers and associated families shows a necessity of the change of the nature of nuclear interaction in those high energy region of $E_0 \geq 10^{16}$ eV.

References