Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 23–26

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Air showers accompanied by high energy atmospheric families observed by Chacaltaya hybrid experiment

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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, $Ne > 10^7$, and also those of air-showers accompanying families can not 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 ususally 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 dedvelops 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, 3]. 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 ASγ experiment[4] and in HADRON experiment at Tien-Shan [5]. The Tibet group recently published their results[6] 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 γ-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 ~ 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, γ) 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, γ)-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 $Ne \geq 10^6$ which accompany the families. Among them, 20 air-showers has size $Ne \geq 10^7$.

Table 1: Chemical composition of the events

sampled primary particles					
E_0 (eV)	protons	He	CNO	heavy	Fe
$10^{15}-10^{16}$	42 %	16 %	16 %	14 %	12 %
$10^{16}-10^{17}$	42 %	12 %	13 %	15 %	18 %
air-showers accompanied by families (CORSIKA/QGSJET)					
size Ne	protons	He	CNO	heavy	Fe
$10^{6}-10^{7}$	70 %	15 %	6.6 %	5.6 %	2.8 %
$10^{7}-10^{8}$	48 %	13 %	12 %	13 %	14 %

Simulations

For generating extensive air-showers and families we use CORSIKA simulation code(version 6.502) [7] employing QGSJET (QGSJET01c) model[8] and also SIBYLL (SIBYLL 2.1) model[9, 10] 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,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 formulated by Okamoto and Shibata for electromagnetic cascade[11]. 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, γ) 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 blocks and periphery of those events are detected as families which satisfy the selection criteria.

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.

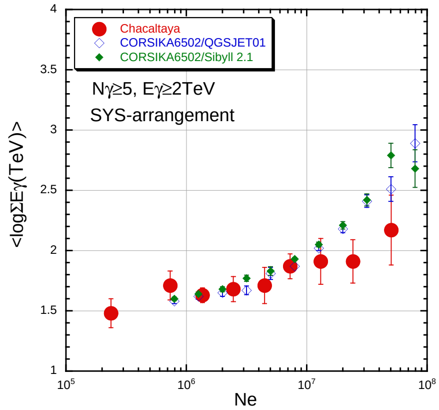

Figure 1: Diagram on air-shower size, N_e, and average energy sum, $< log \sum E_\gamma >$, of accompanied families.

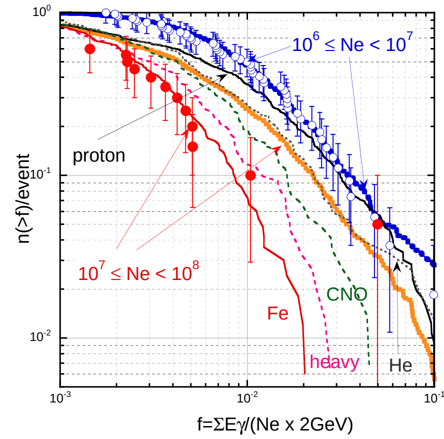

Figure 2: Distribution of family energy normalized by $Ne \times 2$ GeV, $f \equiv \sum(E_\gamma + E_h(\gamma))/(N_e \times 2$ GeV). Circles are for the experimental data and lines are for simulated events. Open circles and line are events of $10^6 \leq N_e < 10^7$ and solid circles and dotted line for $10^7 \leq N_e < 10^8$. Thick lines are for the case of proton-dominant composition shown in Table 1.

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 log-average of accompanied family energy $< \log \sum E_\gamma >$. It is seen that the average family energy of the experimental data is clearly smaller than that of simulated data in the shower-size region of $N_e \geq 10^7$. There is no considerable difference between the two interaction models in the simulations.

Energy of primary particle, E_0, is roughly proportional to the shower size, N_e, and is given by $E_0 \approx N_e \times 2$ GeV at Mt. Chacaltaya. In Fig.2 we show a distribution of family energy normalized by primary energy given by above equation, $f \equiv \sum E_\gamma/(N_e \times 2$ GeV), for the events with shower size $10^6 \leq N_e < 10^7$ and $10^7 \leq N_e < 10^8$ respectively. The distribution of experimental data is well described by simulations for the events with $10^6 \leq N_e < 10^7$, The distribution, however, is very different from simulations for those with $10^7 \leq N_e < 10^8$. In the figure, also shown are thouse for the air-showers accompanying families with $10^7 \leq N_e < 10^8$ for 5 different natures of primary particles. As is naturally expected and is seen in the figure, if the primary particle is heavier, the f value becomes smaller. The distribution of the experimental data of $10^7 \leq N_e < 10^8$ is very close to that of iron nuclei. It is seen as if all the primaries are iron nuclei for the experimental data of $10^7 \leq N_e < 10^8$, i.e., $E_0 \approx 10^{16} - 10^{17}$ eV.

Lateral spread of EAS-triggerd families

Fig.3 shows a distribution of average lateral spread, defined by $< r \equiv \sum E_\gamma R_\gamma / \sum E_\gamma >$, of families 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

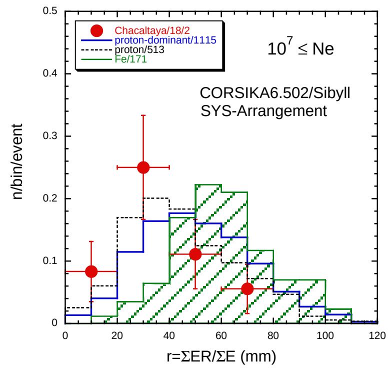

Figure 3: Distribution of average lateral spread $< ER >$ of γ-rays in the families associated with air-showers of $10^7 \leq N_e < 10^8$. Circles are experimental data and lines are simulated data for proton primaries (dash-dotted), iron-primaries (shaded) and all particles with spectrum.

by heavy primaries. The experimental distribution agrees more or less with simulations assuming proton dominant primary composition shown in Table 1, 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.

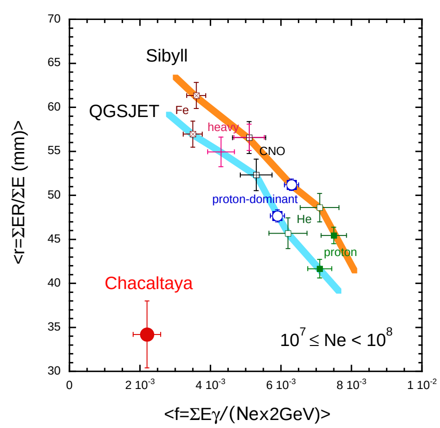

Figure 4: Diagram on average family energy normalized by shower size and average lateral spread, for the events with $10^7 \leq N_e < 10^8$.

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. 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.

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