# Extensive comparison of emulsion chamber data at high mountains with CORSIKA simulations

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### Abstract

Experimental data obtained by emulsion chambers at Pamir and Chacaltaya are compared with simulation calculations using CORSIKA program employing several models for high energy nuclear interactions. Although those models are considered to be based on modern theory and are widely accepted as standard simulation codes, it is shown that no models can explain many of characteristics, hadron-gamma correlation, shower-clusters of small spread, penetrating cascades and so on, observed in the experiment.

## 1 Introduction

We have been studying very high energy nuclear interaction by analysing high-energy cosmic-ray families, a bundle of electromagnetic particles and hadrons produced in nuclear and electromagnetic cascade process in the atmosphere originating from single primary cosmic-ray particle, observed by Pamir and Chacaltaya emulsion chamber experiments [1, 2, 3, 4]. The cosmic-ray families give valuable informations about particle production in the forward most angular region yet unexplored in the present collider experiments. The cosmic-ray family is, in general, originating from superposition of a number of nuclear interactions during passage through the atmosphere, and it is not straightforward to get nature of the interaction directly from the observations. In order to clarify the characteristics of the atmospheric nuclear interactions, therefore we need to compare experimental data with simulation calculations assuming models extrapolating accelerator data into higher energy and smaller angular region according to reliable theory of particle production.

CORSIKA[5], a detailed Monte Carlo program for extensive air-showers developed for KASCADE experiment, is now widely accepted as a standard simulation code for cosmic-ray experiments. In the present paper, we use CORSIKA code for calculations of ordinary high energy cosmic-ray families. Comparing experimental data with simulation calculations, we demonstrate extraordinary characteristics seen in the high-energy cosmic-ray families.

## 2 Hadron and gamma families

### 2.1 Experimental data

We use following experimental data for the comparison with simulation calculations.

1) Pamir joint carbon chambers ($720m^2year$)[1, 3]
2) a part of Pamir chambers ($530m^2year$)[4]
3) Chacaltaya two-storey chambers ($300m^2year$) [1, 2, 3]

Among detected families in those chambers, events with total observed energy,$\Sigma E_\gamma + \Sigma E_h(\gamma)$, larger than 100 TeV, where detection threshold energy was set to be 4 TeV both for electromagetic particles (abbreviated as 'gamma-rays') and hadrons, were selected out for the analysis.

### 2.2 Simulation calculations

We use air-shower simulation program CORSIKA5.20 employing three different models for high energy hadronic interactions; i.e., HDPM, VENUS and QGSJET incorporated in the program. Another phenomenological model is also used employing UA5 algorithm[6] for nuclear interaction and algorithm formulated by Niihori et al. [7] for atmospheric propagation.

Sampling 40,000 primary cosmic-rays of $E_0 \geq 1,000TeV$ from the spectrum formulated by Nicolsky [8] (transparency No.5) for each of the four different models, we calculate nuclear and electromagnetic cascade in the atmosphere until energy of all hadrons and electromagnetic particles falls below 2 TeV or they arrive at the chamber.

In emulsion chambers we can detect hadrons as hadronic showers when those hadrons interact with chamber materials. Hadron energy, $E_h$, is transformed into visible energy, $E_h(\gamma)$, using $k_\gamma$-distribution in hadron-carbon interaction, which are calculated using above hadronic interaction model. Although detection probability of hadrons in carbon-chamber is different chamber by chamber, here we assumed it to be 0.7. Errors of energy estimation of $E_\gamma$ and $E_h(\gamma)$ in the experiment is also taken into considerations by assuming Gaussian-type error distribution, depending on the energy, e.g., 20 % for E=10TeV.

### 2.3 Smaller family flux

Integral spectrum of gamma-ray component of family energy, $\Sigma E_\gamma$, is shown in transparency Nos.6 and 7. Experimental data gives family intensity as $I(\Sigma E_\gamma \geq 100TeV) \sim 0.37m^{-2}y^{-1}sr^{-1}$. Although family intensity depends on used simulation code, all the simulated data gives still $3 \sim 4$ times higher intensity than observations. The result indicates that the energy dissipation in the experimental atmospheric families is stronger than that in the simulation calculations.

### 2.4 Existence of hadron-rich events

Hadron-rich nature of the events are well seen in a correlation diagram on the number of detected hadrons, $N_h$, and energy fraction of hadron component in a family, $Q_h \equiv \Sigma E_h^{(\gamma)}/\Sigma(E_\gamma + E_h^{(\gamma)})$ (see transparency No.8). Hadron- rich events (Centauro-species[2, 9]) which are distributed in the region of $N_h \geq\sim 10$ and $Q_h \geq\sim 0.6$ in the experimental data are scarcely seen in the simulated events. The other three models give results almost same to QGSJET. Thus we can conclude that the Centauro-like events are not due to superposed fluctuation of ordinary nuclear interactions during passage through the atmosphere.

### 2.5 Unusual shower-clusters

#### 2.5.1 Mini-clusters

Correlation between hadrons and gamma-rays is seen in a form of a distribution on relative distance, $R_{min}$, between a hadron and its nearest neighbouring showers in a family (transparency No.9). One can see that there exists a clear excess in the experimental data over simulated almost flat distribution in the region of $R_{min} \leq 1mm$. This anomalous correlation between hadrons and gamma-rays is often seen as very collimated shower-clusters, named 'mini-clusters' [10, 11], in which both hadrons and gamma-rays are included. Average spread of constituent showers in the mini-cluster is $< Er >\sim 2 - 3GeV \cdot m$. It is too large to interpret it due to a local nuclear interaction at zinc roof which is located $\sim 1m$ above the Chacaltaya chambers and is too small to interpret due to an atmospheric interaction of several hundreds of meters or more above the chamber. Thus 'mini-clusters' are indicating an existence of particle production with very small $p_t$, $< p_t >= 10 \sim 20MeV/c$.

#### 2.5.2 Giant mini-clusters

We observe another type of very high energy shower-clusters with very small lateral spread, several mm in radius. The characteristics is seen that almost all family energy is carried by the cluster of small lateral spread. In transparency No.14 we shows a distribution on $\chi \equiv \Sigma E(R < 1cm)/E_{tot}$, where $\Sigma E(R < 1cm)$ is energy sum carried by showers inside radius 1 cm from family center and $E_{tot}$ is the total family energy. We can see a clear excess of the event with large $\chi$ value in the experimental data over simulated events. Those shower clusters are accompanied by either none of surrounding showers or a small number of low energy showers around it. In order to demonstrate how small the lateral spread of those events, we show a distribution of lateral spread, $R_E$, of a family defined by $R_E = \Sigma ER/\Sigma E$ (transparency no.15). Again we can see a clear excess of the events with small $R_E$ over simulation calculations. We put nickname 'giant mini- clusters"[1, 3] for those shower-clusters.

## 3 EAS-triggered families

In the experiment combined with emulsion chamber and EAS array [12], which has been carried out on Mt. Chacaltaya, we can detect both atmospheric families and air-showers at the same time. We have calculated, for the combined experiment, atmospheric families and accompanied air-shower size, $N_e$, using above four simulation codes. Transparency no.19 shows a diagram on $N_e$ and average energy sum, $< \Sigma E_\gamma >$, of associated atmospheric families. Here the average is calculated for the events of $\Sigma E_\gamma \geq 10TeV$. Detection threshold energy is taken to be 2 TeV. As is seen in the figure, $N_e$-dependence of family energy in the four simulation calculations are almost identical. The experimental data, however, shows systematically smaller family energy than simulated data in the region of $N_e \geq 5 \times 10^6$. The result again indicates that the energy dissipation is much strong in the atmospheric interactions than expected in the assumed nuclear interactions. The identical experiment which has been carried out at Tien-Shan also gives almost same results[13].

## 4 Summary

Characteristics of atmospheric families are compared with simulation calculations assuming four different interaction models. Although simulation program CORSIKA is accepted as a standard simulation code for cosmic-ray experiment, none of simulation calculations satisfactorily explain the experimental characteristics of the observed atmospheric families, that is,

1) Intensity of atmospheric families is $3 \sim 4$ times smaller than expected.

2) Average family energy in EAS-triggered events is systematically smaller than expected in the range of shower-size $Ne \geq 5 \times 10^6$.

The above two indicate energy dissipation in experimental families is much sever than that in calculations. Changes of chemical composition in primary cosmic-rays can give smaller family intensity. But changes of chemical composition alone can not explain the above result 2) of EAS- triggered families. Therefore it is necessary to introduce changes of nuclear interaction from assumed ones in the simulations.

3) Existence of hadron-rich events are not due to superposed fluctuations of ordinary hadron interactions but are possibly due to new-type of nuclear interaction, Centauro-like interaction.

4) Extraordinary shower-clusters are observed, one is 'mini-cluster', composed of very collimated hadrons and gamma-rays, and the other is 'giant mini-cluster', in which most of family energy is carried by a number of collimated hadrons and gamma-rays. Those shower-clusters indicate an existence of particle production with small transverse momentum, $< p_t(\gamma) >\sim 10 - 20 MeV/c$. It might be connected to the observation of muon bundles of extremely high multiplicity in CosmoLep experiment (though observed frequency of 'mini-clusters' and 'giant mini-clusters' is much smaller in emulsion chamber experiment), also to "halo" events, which are extremely high energy events observed by emulsion chamber experiments.

The author would like to express his sincere thanks to CORSIKA development group for free use of the simulation codes. The calculation was carried out using IBM RS/6000 SP at the Computer Center of Kinki University.

## References

[1] Chacaltaya and Pamir Collaboration (L.T.Baradzei et al.), *Nucl. Phys. B370*(1992) 365.

[2] C.M.G.Lattes, Y.Fujimoto and S.Hasegawa, *Phys. Rep.65* (1980) 151; S.Hasegawa, *ICR-Report-151-87-5* (presented at FNAL CDF seminar; 1987, Inst. for Cosmic Ray Research, Univ. of Tokyo)

[3] S.Hasegawa and M.Tamada, *Nucl. Phys. B474* (1996) 141

[4] Pamir Collaboration (S.G.Baybrina et al.), *Trudy FIAN 154* (1984) 1 [Nauka, Moscow (in Russian); S.A.Slavatinsky, *Nucl. Phys.52B (Proc.Suppl.)*(1997) 56

[5] J.Knapp, D.Heck and G.Schats, *Nucl. Phys.52B (Proc. Suppl.)* (1997) 136, 139 ; *FZKA report 5828* (1996, Forschungszentrum Karlsruhe, GmbH Karlsruhe)

[6] UA5 Collaboration (G.L.Alner et al.), *Nucl. Phys. B291* (1987) 445.

[7] Y.Niihori, T.Shibata, I.M.Martin, E.H.Shibuya and A.Trutelli Jr., *Phys. Rev. D36* (1987) 783.

[8] S.I.Nicolsky, *Proc. Int. 3rd Symp. on Cosmic Rays and Particle Physics* (Tokyo, 1984) 507.

[9] Pamir Collaboration and Chacaltaya Collaboration, Phys. Lett. B190(1987) 226

[10] Brasil-Japan Collaboration, proc. AIP Conf. no.85(1981) 500 ; *proc. 20th Int. Cosmic-Ray Conf. Vol.5*(Moscow, 1987) p.326

[11] Y.Funayama and M.Tamada, *J. Phys. Soc. of Japan Vol.55 No.9*(1986) 2977, 2996

[12] K.Honda et al., *Phys. ReV. D56* (1997) 3833

[13] S.B.Shaulov, Proc. Int. Workshop on Very High Energy Nuclear Interaction(Tokyo, 1991) (Inst. for Cosmic Ray Research, Univ. of Tokyo) p.228; Proc. AIP Conf. no.276(1992) 94