Features of UHE Hadronic Interaction in Fragmentation Region Inferred from the Analysis of MEC Families

Chen Jiangchuan, Lu Suiling, Zhu Qingqi, and Huo Anxiang

(Institute of High Energy Physics, The Chinese Academy of Sciences, Beijing, China)

With Mountain Emulsion Chamber (MEC) data obtained from Mt. Kanbala, the relation between family flux and the energy spectrum of showers in the family is investigated. A Monte-Carlo generator can reproduce the main features of families. It indicated that no global change appeared in the hadronic interaction at the fragmentation region in the energy region from 10^{14} to 10^{15} eV.

Key words: mountain emulsion chamber, family event, hadronic interaction.

1. INTRODUCTION

In recent years, accelerator experiments have covered the 10^{14}–10^{15} eV [1] energy region. However, accelerators working at the highest energy region are colliders and are usually good only for detection in the central region because it is difficult to measure particle features within the beam pipe. Up to now only a few physics quantities were measured in the fragmentation region by UA4 and UA7 groups in the CERN $S\bar{p}pS$ collier [2]. As to the MEC experiments, the main concern is the hadronic interaction characters in the fragmentation region, because they investigate the interaction between ultra-high-energy (UHE) cosmic ray particles and the rest target. Some characters of hadronic interaction in the energy region from 10^{15} eV to 10^{16} eV have been discussed with MEC families data [3] and it was impossible to draw a reasonable conclusion because there were many unknown factors.

Received on May 12, 1994. Supported in part by the National Natural Science Foundation of China.

It will be interesting to study the features of hadronic interactions in the overlapping energy region of collisions and MEC with the MEC experiment data. The characters of hadronic interaction in the central region have been known from the accelerator experiments, and in addition, the compositions of primary cosmic rays in this energy region have been detected directly by some experiments. These experimental facts provide the possibility of checking our Monte Carlo model and of research into the behavior of hadronic interactions in the fragmentation region. In this work, we investigate some features of hadronic interaction in the energy region from 10^{14} eV to 10^{15} eV (it overlaps the highest energy region of accelerators) with the new family data obtained on Mt. Kanbala (in Tibet, 5500 m above sea level, atmospheric depth 520 g/cm^2).

"Family" events can be observed in MEC, which consists of some parallel incident particles originating from a high-energy primary cosmic ray particle. The intensity of families and the spectrum indices of showers in the families relate closely to primary cosmic ray compositions and nuclear interaction characters. A reasonable Monte Carlo (MC) model should reproduce these basic features of families. But according to the Chacaltaya and Pamir Collaboration report, none of their models could reproduce both the intensity of families and the spectrum of showers in the families simultaneously with energy higher than 100 TeV [4]. These families were produced by the primary cosmic ray particles with energy of about 10^{15} eV. And they assume that it indicated some global changes in the characteristics of hadronic interaction beyond the energy region of the present accelerators. In this paper we will discuss this topic at the overlapping energy region in order to understand the family events at higher energy.

The following part of this paper consists of five sections. First we describe the procedure of the MEC experiment on Mt. Kanbala. Then we present the outline of our MC model and the simulation of our MEC detection efficiency in Sec. 3. The relation of family flux to the indices of the energy spectrum of showers in the families is shown in Sec. 4. The conclusions are presented in the last section.

2. EMULSION CHAMBER EXPERIMENT PROCEDURE

The emulsion chambers on Mt. Kanbala consist of alternately placed X-ray films and metal plates. Some of them include nuclear emulsions. Lead plate is used as an absorber and energy transformation material in this work. The area of an unit is 0.4×0.5 m^2 and the total thickness of lead is 30 radiation lengths (rl) in K9 chambers and 24 rl in K7 chambers. A box of the chambers contains six or eight units. Both K9 and K7 chambers are exposed for about one year, and the total exposure in this experiment is 21.8 (m^2/yr).

An incident particle can initiate an electromagnetic cascade shower, which is recorded as a series of black spots on X-ray films or nuclear emulsions in several layers of the chamber. The electromagnetic energy of the incident particle and its beginning point of an electromagnetic cascade can be inferred by measuring the optical density of shower spots on the X-ray films [5-7]. γ component of secondary cosmic rays can be separated statistically from the hadronic component by a shower beginning point in the emulsion chamber. The path for a hadron to initiate an electromagnetic cascade is the sum of the path of its nuclear interaction plus the path of $e^{\pm}$ pair production. Hence a hadron begins an electromagnetic cascade in a chamber more deeply than γ does on average. In this work, we take 6 rl as the criterion of the beginning point of electromagnetic cascade to distinguish the γ from hadrons. The probability of γ's beginning point less than 6 rl is about 99%, and the hadron's beginning point is about 30% in a lead chamber according to statistical calculation.

The criteria for family identification are as follows: (1) the energy of every shower, $E_i \geq 4$TeV, where E_i stands for the observed energy, includes only the electromagnetic component energy for a hadronic shower; (2) the number of showers in a family is $N_\gamma \geq 4$; (3) the total observed energy of a family is $\Sigma E_i \geq 20$ TeV. In the measurement, in order to reduce the leakage of showers that are far away from the center of the family and the leakage of hadron showers that appear at the deep part of

Table 1
List of emulsion chamber exposed at Mt. Kanbala in this work.

Series Name	Units Number	Area (m^2)	Exposure Time (d)	Exposure Amount (m^2yr)	Family Number
K9	72	14.4	429	16.9	92
K7	25	5.0	358	4.9	43
Total	97	19.4		21.8	135

a chamber in the families, we scanned all showers on every film and drew their target figures for every unit. In a target figure, the tracks of showers in a family are parallel to each other and their zenith angles are the same, so they are identified easily. Table 1 is the list of emulsion chambers exposed on Mt. Kanbala in this work.

3. MONTE CARLO SIMULATIONS

We have carried out a Monte Carlo simulation for UHE cosmic ray propagation in the atmosphere and a simplified simulation for determining the detection efficiency of the UHE shower in the emulsion chamber. The multiparticle production from a hadron-nucleus (h-A) and the primary cosmic ray energy spectrum are key points for the simulation of UHE cosmic ray propagation in the atmosphere. Our multiparticle production model consists of an SD dissociation component, a soft component of NSD, and a hard component from a QCD minijet; hence it is called an SD-SH model. It is based on accelerator data and specifically on the smooth extrapolation of inclusive interaction results of the CERN ISR and S$\bar{p}$pS to a higher energy region [10]. It has an approximate Feynman scaling behavior in the fragmentation region. The primary proton energy spectrum has a bending point of 100 TeV, with an index -2.74 below and -3 above this energy, respectively. We assume that the bending point of the energy spectrum of primary cosmic ray components other than protons is determined by a rigidity cut-off in the magnetic field of the galaxy. The flux of primary protons with energy larger than 70 TeV is 3.6×10^{-5} ($m^{-2}sr^{-1}sec^{-1}$). The relative abundance of primary protons, helium, and others at 70 TeV/nucleus is assumed to be 0.31, 0.25, and 0.44, respectively, which is compatible with JACEE's recent results [8]. The SD-SH model has been used to interpret successfully the MEC γ family phenomena at total observed energy more than 100 TeV [9]. In this work, the energy region we study is lower than that in Ref. [9].

The shower detection efficiency in MEC is determined by the following simplified simulation model: (a) For pure electromagnetic showers inside the emulsion chamber, the detection efficiency is close to 1.0 if its path in the emulsion chamber is more than 10 rl (a path of at least 10 rl is the requirement for scanning a shower and measuring its energy in the experiment). In this case it is not necessary to simulate γ shower developing in the emulsion chamber. However, more than 20% of energy measuring error may affect the observed energy spectrum, so its effect has been taken into account. (b) For hadrons, the mean nuclear interaction length in the emulsion chamber is taken as 30 rl of lead for a nucleon and 36 rl for a $\pi^{\pm}$ meson; the inelasticity k follows an approximate distribution, $P(k) = 0.4 + 1.2\,k$ within (0,1), and it has a mean value of 0.6. The energy fraction for secondary π^0 is one-third that of inelasticity. For a hadronic shower, if the distance from its entry to the cascade beginning point in the chamber is less than 6 rl, it will be treated as a γ. For a shower, if the path from its cascade beginning point to the exit point in the chamber is less than 10 rl, it is treated as an unmeasurable object and is taken away. The criteria for a family are identical for experimental data and Monte Carlo samples.

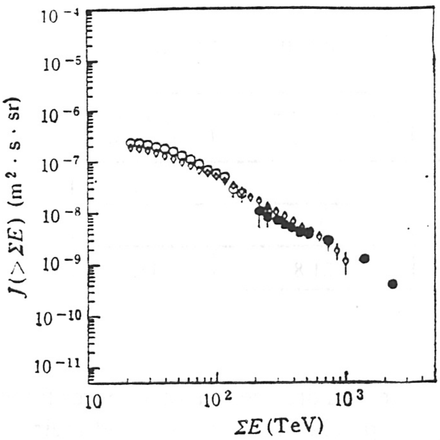

Fig. 1
γ family intensity at Mt. Kanbala altitude. The symbol ○ stands for data in this work, ● is the result in Ref. [3], and ◇ represents Monte Carlo sample.

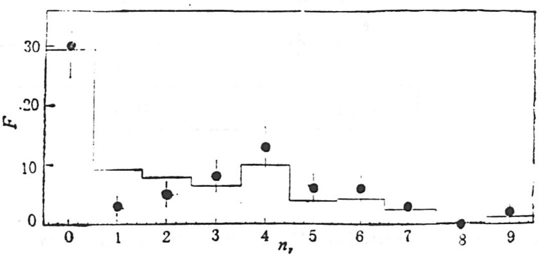

Fig. 2
Multiplicity distribution of shower near center of families (R < 1.25 cm). n_γ is shower number of every family, F is the frequency of family with n_γ. Symbol ● represents experimental data, and the histogram stands for MC samples produced by primary hadrons.

4. RESEARCH ON SOME MAIN FEATURES OF FAMILIES

The flux of families is sensitive to the composition and energy spectrum of primary cosmic rays and to the nuclear interaction model in the Monte Carlo simulation. The flux of experimental families and MC simulation are shown in Fig. 1. It can be seen that the flux of our MC samples is consistent with both our experimental result and the data in Ref. [3]. The family events attenuate in accordance with the rule of $\exp(-x/\lambda)$ in the atmosphere, where x is the height of observation (x = 520 g/cm^2 at Mt. Kanbala) and λ is the attenuation length. The attenuation length of families in the atmosphere is an important quantity of the family phenomena and can be inferred from the zenith angle distribution of the families. The attenuation lengths are (106 $\pm$ 22)g/cm^2 obtained with the experiment data and (112 $\pm$ 10)g/cm^2 obtained with the MC samples. The multiplicity distribution of showers near the center of the family is shown in Fig. 2, and it is related to the scaling behavior feature in the fragmentation region. The multiplicity distribution of showers near the center of the family would decrease quickly if the scaling rule was violated. The comparisons of some features of families between experimental data and MC samples in the energy region from 20 TeV to 100 TeV are listed in Table 2. According to the Monte Carlo simulation, more than 90% of these families were produced by primary cosmic ray particles with energy in the region from 3×10^{13} eV to 10^{15} eV. In addition, compositions of primary cosmic rays with energy below 10^{14} eV have been detected directly. It can be seen from Figs. 1 and 2 and Table 2 that our MC simulation coincides with experimental data. This means that the hadronic interaction parameters used in our MC model are reasonable.

It is well known that lateral spread of families relates closely to the transverse momentum of secondary particles in the hadronic interactions and to the electron-emitting angle in electromagnetic cascades, so the lateral spread of secondaries in MEC data can provide us with some information about the hadronic interaction model. The differential distribution of average lateral spreads $<ER>$ and $<R>$ of families is shown in Figs. 3(a) and (b), respectively, where E is single shower energy and

Table 2
Mean features of families.

	Families Number	Attenuation Length (g/cm²)	Shower Multiplicity	Center Shower Fraction
EXP. data	77	106±22	6.1±0.8	0.36±0.06
MC sample(h)	475	112±10	6.1±0.3	0.30±0.02
MC sample(γ)	88	79±16	7.4±0.8	0.98±0.02

R is the distance from the shower to the center of the family; $<ER>$ is the average value of $E \times R$.

5. RELATION BETWEEN FLUX OF FAMILIES AND ENERGY SPECTRUM OF SHOWERS IN THE FAMILY

The energy spectrum of showers in the family, as well as the flux of families, is sensitive to the parameters of the nuclear interaction model. In principle, these features should be reproduced by a reasonable MC generator. We have shown in the last section that an SD-SH generator can reproduce many features of families. To compare the experimental data and our simulation results, the indices of energy spectra of showers with energy from 10 TeV to 50 TeV in the families are calculated by the least square method. To carry out a global investigation, we calculated the spectra indices distribution

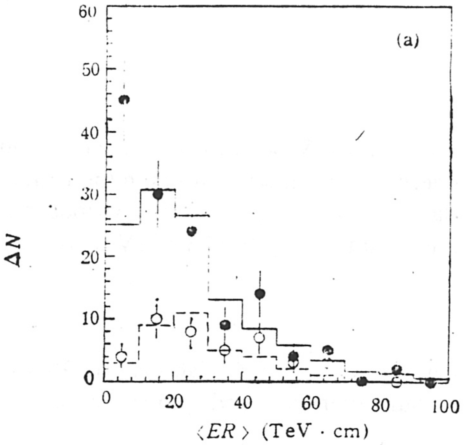

Fig. 3 (a)
The differential distribution of lateral spread $<ER>$ of families.

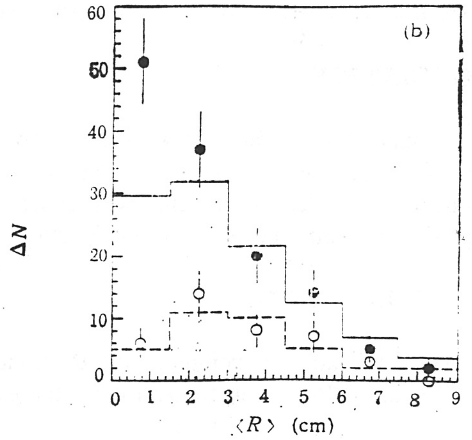

Fig. 3 (b)
The differential distribution of lateral spread $<R>$ of families.

The symbols ○ and ● stand for the distribution of γ family and hadron family of experimental data (a γ family is a family that has some hadrons or no hadrons; a hadron family is a family has some hadrons). Solid lines and dotted lines are the distributions of the γ family and hadron family of the MC sample, respectively, produced by primary hadrons.

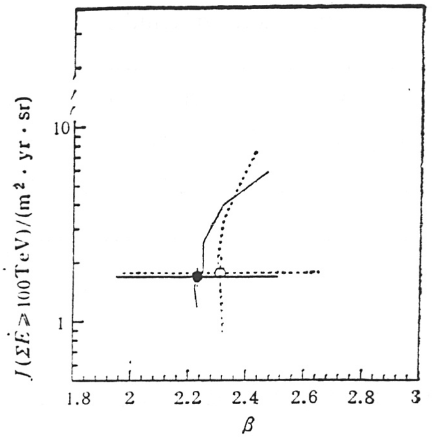

Fig. 4

The relation between family flux J and the indices β of energy spectra of showers in the families. The solid line and dotted line stand for the MC simulation and experimental data with family energy threshold from 20 TeV to 150 TeV, respectively. Symbols ○ and ● stand for the value of J and β of the family, respectively, with energy threshold 100 TeV; horizontal lines stand for the statistical error of β at this value.

of showers in the family for various threshold energy levels of the family from 20 TeV to 150 TeV. Combining the preceding results, the relations between family flux and energy spectrum indices of showers in the family are shown in Fig. 4. In this figure, it can be seen that our MC simulation is consistent with experimental data in statistical error.

6. CONCLUSION

By analyzing the families with energy from 20 TeV to 200 TeV obtained in emulsion chamber on Mt. Kanbala, the relation between family flux and energy spectrum of showers in the family was studied, and our MC results agree with experimental data. Our results imply that no global change appeared in hadron interaction at the fragmentation region with energy from 10^{14} eV to 10^{15} eV.

ACKNOWLEDGMENT

We thank all the members of Mt. Kanbala Emulsion Chamber Collaboration Group. We especially thank Prof. Ren Jingru for his earnest help in our experiment and data analysis.

REFERENCES

[1] UA5 Collab., G.J. Alner *et al.*, *Phys. Rep.*, **154** (1987) p.247; UA5 Collab., R.E. Ansorge *et al.*, *Z. Phys.*, **C34** (1989) p.357; T. Alexopouos *et al.*, *Nucl. Phys.*, **A498** (1989) p.181C; N. Amos *et al.*, *Phys. Rev. Lett.*, **63** (1989) p.2784.

[2] UA4 Collaboration, *Phys. Lett.*, **198b** (1987) p.583; UA7 Collab. et al., Proc. 20th ICRC **5** (1987) p.23.

[3] J.R. Ren *et al.*, *Phys. Rev.*, **D38** (1988) p.1404; J.R. Ren et al., *Phys. Rev.*, **D38** (1988) p.1417.

[4] Chacaltaya and Pamir Collaboration, ICRR-Report-254-91-23.

[5] J.R. Ren, *College Periodical of Shandong University*, **3** (1982) p.76.
[6] M. Akashi *et al.*, *Nuovo Cimento*, **A65** (1981) p.355.
[7] M. Amenomori *et al.*, In 8th International Cosmic Ray Conference, Bangalore. Conference Papers (Tata, Institute of Fundamental Research, India, 1983), Vol. 2, (1983) p. 57.
[8] K. Asakimori *et al.*, Proc. 23rd ICRC **2** (1993) p.25.
[9] Q.Q. Zhu *et al.*, *J. Phys.*, **G16** (1990) p.295; Zhu Qinqi et al., *High Energy Phys. and Nucl. Phys.*, (Chinese ed.), **14** (1990) p.296.
[10] J.G. Rushbrook, in Proc. of Europhys. Conf. on High Energy Phys. Bari, Italy, (1985) p.839; C. Geich-Gimbel, *Int. J. Mod. Phys.*, **A4** (1989) p.1527, and references therein.