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Observation of cosmic ray hadron interactions with Pamir 60 cm lead X-ray emulsion chamber

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Abstract. In present paper we analyze experimental data from collaboration work of MSU and Waseda University with 60 cm lead chambers of recent $57m^2$ year exposure at Pamirs. With new method of determination of energy and identification of origin of showers we study features of gamma hadron families, single hadrons and gamma showers. Our data are in agreement with previous results obtained by MSU group. General characteristics of cosmic ray hadron interactions at high energies are discussed.

1 Introduction

Experiments with emulsion chambers have been carried out for more than 30 years at Mt. Chacaltaya (5200 m, Brazil-Japan Collaboration), Pamir (4300 m, Pamir Collaboration), Mt. Fuji (3750 m, Fuji Collaboration), Mt. Kanbala (5500 m, China-Japan Collaboration). The main objective of these experiments is to study fragmentation region of hadron interactions and primary composition at energies $10^{15} - 10^{17}$ eV. This is overlapping region with current collider experiments.

Nuclear electromagnetic cascade originated by primary cosmic ray particle in the atmosphere is detected in the chamber in the form of bundle of gamma rays and hadrons called a family. The study of family characteristics is a main subject in experiments with emulsion chambers at mountain altitudes.

Our experimental data is a complete set of data obtained through investigation of total available experimental area of X-ray films of total exposure $ST = 57m^2 year$ collected with Pb chambers during 1988-1991 at Pamir. X-ray films were analyzed under joint research program between Waseda University and Moscow State University in 1990th. The statistics on single showers and families in present experiment is enough for a study on hadron interactions in exactly the overlapping region with the present collider experiments.

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Table 1. Experimental statistics on analyzed chambers

Item	Pb68	Pb69	Pb72	Pb73
Area (m^2)	8.5	7.5	10.	10.
Exposure ($year$)	1	1	2	2
Layers	58	58	59	59
Chamber (cm Pb)	60	60	60	60

On the basis of the detailed study of our experimental set of events we elaborate way of analysis that can describe clearly the physics behind the observed families.

2 Experimental setup

Pamir X-ray chamber has an area $10m^2$ and consists of 20 units, each of $0.5m^2$ size. The chamber is homogeneous in structure and uniform in detection efficiency of hadrons. Each unit of the 60 cm Pb chamber is a stack of 58 (59) X-ray emulsion films and 1 cm lead plates. The chamber thickness is ~ 3.5 nuclear mean free path. It allows detailed study of shower transition curve. The energy E of showers is estimated by measuring optical densities D at depths t and comparing with a calculation $D(E, t)$ based on the cascade theory.

3 Experimental statistics

We use in present analysis data from Pamir thick lead chambers $Pb68$, $Pb69$, $Pb72$, $Pb73$ of total exposure 57 m^2 year. The details are given in Table. 1.

4 Comparison with previous MSU data

We have made comparison of our experimental data (Waseda-MSU hereafter) using traditional method and the same selec-

Table 2. Experimental statistics on families

Family	Experiment ($m^2 year$) chamber type	Flux
$100 \le \Sigma E_\gamma \le 500$ TeV	Pamir (84)	($m^2 year$)
$E_{th} = 4$ TeV		(0.4 ± 0.1)
$N_\gamma = 10$	Pb 40 cm	
$\Delta t = 6$ c.u.		
$R_{max} = 150$ mm	Waseda-MSU (57)	(0.4 ± 0.1)
	Pb 60 cm	
$\Sigma E_\gamma \ge 100$TeV		($m^2 year$)
$E_{th} = 6.3$ TeV	MSU (160)	(0.4 ± 0.1)
$N_\gamma = 4$		
$\Delta t = 6$ c.u.	Pb 40,60,110 cm	
$R_{max} = 150$ mm		
	Waseda-MSU (57)	(0.5 ± 0.1)
	Pb 60 cm	

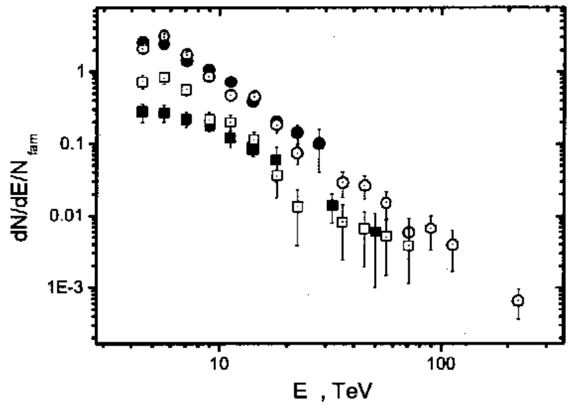

Fig. 1. Differential energy spectra of gamma rays and hadron in a family 100 TeV $\le \Sigma E_\gamma \le 400$ TeV with $E_{th} = 4$ TeV. Marks are: open circles (gamma rays) and squares (hadrons) in Waseda-MSU experiment, solid circles and squares - gamma rays and hadrons from MSU experiment.

tion criteria for identification of gamma rays and hadrons[1] and the same energy determination method as in previous Pamir and MSU experiments (Pamir collaboration , 1983; Rakobolskaya et al., 2000). Showers observed in X-ray chamber are classified into single that are not accompanied by any shower with energy above detection threshold E_{th} and family showers - bundle of parallel showers with the same zenith angle arrival direction. For family showers the energy-weighted center is determined, and energy of all γ-rays and hadrons within a circle of $R \le R_{max}$ radius is calculated. The numerical data and comparison of family statistics are given in Table 2.

In Fig. 1 we present differenetial energy spectra of gamma rays and hadrons in families 100 TeV $\le \Sigma E_\gamma \le 400$ TeV with $E_{th} = 4$ TeV from Waseda-MSU experiment and MSU experiment (Rakobolskaya et al, 2000). As we can see there is good agreement between two experiments. Experimental characteristics on hadrons are presented in Table. 3. The observed hadron flux in present experiment is in agreement with the one previously reported by MSU group. Investigation of zenith angle distribution gives an attenuation mean free path of hadrons in the air for Pamir altitude as $105 \pm 6 g/cm^2$. This result is consistent with various studies made so far. The absorption of single and family hadrons in Pb using position of the hadron shower curve maximum Δt at depths $22 - 78$ c.u. is in good agreement with extensive study made with 110 cm Pb chamber.

[1]Showers with $\Delta t \le 6$ c.u. are considered to be gamma rays, all other are hadrons. Δt expresses the shift of depth of the shower maximum from the expected position of pure electromagnetic cascade.

5 Family study

The behaviour of families in the energy region above 100 TeV have been carefully studied by many authors with the purpose to get new information on hadron interactions. For example, families with $\Sigma E_{tot} = \Sigma E_\gamma + \Sigma E_h^{(\gamma)}$ in the range $100 - 1000$ TeV provide information on hadron interactions and primary cosmic ray composition at primary energy $E_0 \sim 10^{15} - 10^{17}$ eV. Families are often classified into specific groups by their appearance or by their prominent features , such as content of gamma or hadron component ("gamma reach of hadron reach"), lateral spread ("wide or narrow"), multiplicity of showers ("large multiplicity or small multiplicity"), presence of clusters or halo ("family with halo, double core" and so on). Each family represents a certain pattern of showers. Once the feature of the family has been chosen, the pattern acquires its evaluation.

5.1 Leading shower in a family

To compare experimental data on gamma hadron families from different mountain experiments we have to choose some algorithm that would be almost free from experimental biases such as the altitude of the experimental site, details of the chamber structure, parameters of X-ray films and nuclear emulsions used, and the applyed methods of energy estimation and identification of showers. Taking into account the same trigger conditions for the selection criteria, let us consider the behaviour of the highest energy shower in a family, or leading shower, it can be either gamma or hadron.

In Fig. 2 we show distribution of the leading shower energy fraction $E_{lead}/\Sigma E_{tot}$ in families of $100 \le E_{tot} \le 1000$ TeV and $E_{th} = 4$ TeV from Pamir Pb chambers, Pamir Carbon chambers, and Chacaltaya experiment (Semba , 1983; Hasegawa et al., 1996) in comparison with the UA5 simula-

Table 3. Experimental statistics on hadrons

Item	MSU	Waseda-MSU
Exposure $m^2 year$ Hadron flux $\times 10^{-10}$ $cm^2\ sec\ str$ $E_{th} = 6.3$ TeV (single and family)	30.5 (1.8 ± 0.2)	57 (1.8 ± 0.2)
Attenuation in air (g/cm^2) (single and family) $E_{th} = 6.3$ TeV	(105 ± 7)	(105 ± 6)
Absorption in Pb (g/cm^2) (single and family) $E_{th} = 6.3$ TeV) $22 \leq \Delta t \leq 78$ c.u.	(212 ± 19)	(219 ± 13)

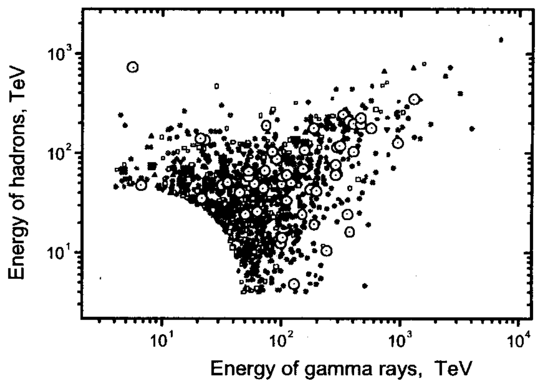

Fig. 3. Scatter plots of observed energy of hadrons $\Sigma E_h^{(\gamma)}$ and gamma rays ΣE_γ in Waseda-MSU experiment (open circles) and the UA5 simulation. Marks are: dots - proton, open squares - He, upward triangles - CNO, downward triangles - Mg, closed squares - Fe.

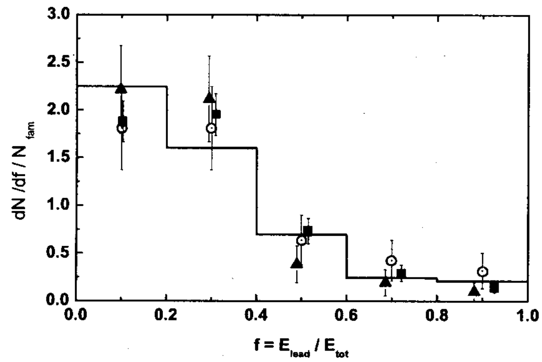

Fig. 2. Distribution of leading shower energy fraction in a family with $100 \leq \Sigma E_{tot} \leq 1000$ TeV. Marks are: open circles - Waseda-MSU experiment, triangles - Chacaltaya experiment, squares - Pamir carbon chamber experiment, solid line - UA5 simulation (normal primary composition).

6 Study of jets

To make arguments in a quantitative way let us express the pattern of energy flow of a family in terms of jet clusters, using step by step information on individual gamma rays and hadrons [2]. The scatter plot of observed energy of gamma rays ΣE_γ and hadrons $E_h^{(\gamma)}$ in families with $E_{tot} \geq 50$ TeV observed in Waseda-MSU experiment together with the result of the UA5 simulation, assuming normal primary composition, is shown in Fig. 3.

If the observed family has one collimated energy center it may be called a single core family. This core can be either surviving leading nucleon from proton primary, high energy air cascade, or cluster of gamma and hadrons. If the family spread is wide, with many local energy centers, it may be called a multi-core family and the heavy primary nucleus would be the best candidate.

By constructing jets we reveal the structure of the cascade complex and go "back" to main interaction and to the pri-

[illegible]

for experimental and simulation events: 1) decas gamma showers to gamma clusters with parame = 1000 TeVmm (Bayburina et al., 1981); 2) jet of all showers, clusters, hadrons and gamma rays meter $Z_{jet} = 200$ TeVmm; 3) normalizing jet en etting threshold $f'_{min} = 0.04$ for their fractional $= E_{jet}/E_{tot}$. Parameters Z_{dec} and Z_{jet} reflect ansverse momentum in electromagnetic and strong n processes. In our analysis jet (in experiment and n) does not always represent the parent atmospheric

is purpose we applied our new method of identification rays and hadrons (Fujimoto , 2000). This method takes nt the shape of transition curve and does not depend on ı. selection criterion

the ratio of energies E_{lead}/E_{tot}, this method is free from methodical details in each experiment. Fig. 2 shows that data from different experiments are consistent with each other and with simulation. It means that the average pattern of a family is similar in terms of showers in Chacaltaya and Pamir experiment.

Identification of showers as hadron or gamma or definition of an absolute energy scale in either of experiments could bring the very well known differences in observation of particular type of events with special characteristics. To study hadron characteristics in a family, it would be better to rely on analysis of data from the deep chamber with several m.f.p thickness that allows good separation of showers on gamma rays and hadrons.

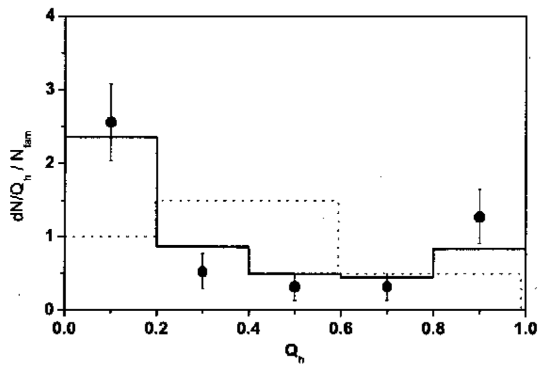

Fig. 4. Distribution of the hadron energy fraction Q_h inside of leading jet. Marks are: closed circles - experiment; solid line - proton simulation, dash line - Fe simulation.

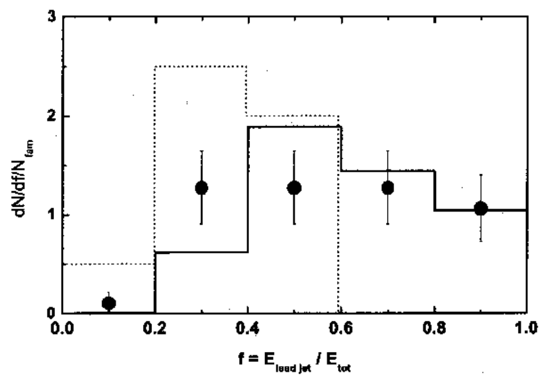

Fig. 5. Distribution of the leading jet energy fraction $f = E_{jet}/E_{tot}$. Marks are: closed circles - experiment; solid line - proton simulation, dash line - Fe simulation.

interaction. It also includes successive interactions in the atmosphere by hadrons from parent interactions.

Fig. 4 shows distribution of hadron energy fraction Q_h inside of leading jet. This distribution is similar to the well known correlation between Q_h and number of hadrons in a family N_h. The peak near $Q_h \sim 0$ shows leading cluster of gamma showers or old cascade from a family started at high altitude. One peak is situated near $Q_h = 1$ and represents leading cluster of hadron nature or surviving nucleon. Families of experiment and simulation agree well and show that jets we have constructed are close to the initial stage of a family.

6.1 Leading jet

The main stream of energy flow in the atmospheric nuclear electromagnetic cascade is represented by leading jet. Energy fraction carried by leading jet shows signature of primary particle origin and surviving nucleon in interaction. Fig. 5 gives distribution of leading jet fractional energy $f = E_{lead}/E_{tot}$ in experiment (open circles) and simulation (proton - solid line and heavy - dash line). Value $f > 0.6$ corresponds to the families with clear energy center. The rest of the distribution shows families with several energy centers. Proton primary families show substantially large number of families with clear energy center. Families of heavy origin show absence of collimated energy concentration as we can see in Fig. 5. There is clear agreement between experiment and simulation based on primary proton dominant composition (normal composition) in energy region $E_0 \sim a\,few$ PeV, near the "knee".

7 Discussion and Conculsions

We show validity of our experimental data using conventional methods and get the same characteristics previously reported by MSU. With the concept of highest energy shower in a family we find no difference in a family pattern observed by X-ray chambers. In our consideration of families we studied pattern of energy flow represented by jets. We can conclude that general characteristics of cosmic ray families in the range 100-1000 TeV are compatible with predictions of simulation model based on accelerator experiment extrapolation to higher energies.

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References

Pamir collaboration, Proc. 18th ICRC, Bangaloure, Vol. 5, p.420, 1983.
Rakobolskaya, I.V. et al., Peculiarities of super high energy hadron interactions, MGU press, Moscow, p.256, 2000.
UA5 collaboration, Nucl. Phys. B, 29, 445, 1987.
Fujimoto, Y. et al. , Nucl. Phys. Proc. suppl. 97: 154, 2001.
Semba, H. , Prog. of Theor. Phys., Vol. 75, 111, 1983.
Hasegawa, S. et al., Nucl. Phys. B 474, 141, 1996.
Bayburina, S.G. et al. , Nucl. Phys. B 191, 1 , 1981.