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Study of high energy cosmic ray interactions and primary composition using mountain based detectors

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Abstract. We report new experimental results obtained by MSU-Waseda collaboration. Our detector is 60 cm thick lead X-ray emulsion chamber exposed to cosmic rays at Pamirs. We show that this experiment can detect cosmic rays in the wide energy range $10^{13} - 10^{17}$ eV. Using experimental data we discuss the primary cosmic ray composition and the features of hadron interactions in the region before and after the "knee".

1 Introduction

At present accelerators reached energy region that is overlapped with the one studied by cosmic rays experiments using X-ray emulsion chambers. Naturally the main interest turned to the problems of origin and propagation of highest energy cosmic ray particles. At the same time there has not been reached consistent understanding on the phenomena observed by experiments with X-ray emulsion chambers. There are many results that could not find explanation within framework of present models (Lattes et al., 1980; Baradzei et al., 1992; Hasegawa et al., 1996) Here we present analysis based mainly on collaborative work of Moscow State University and Waseda University groups (Waseda-MSU hereafter) on joint study of experimental data obtained by Pb chambers exposed at Pamir. We have started our work with the motivation to have clear understanding on the measurement procedure and detector response. Based on this we have developed underlying phenomenological picture of physics that lies behind the gamma hadron families observed in X-ray chambers. To check the conclusions and get better view we used simulation calculations, the UA5 model[1].

Before starting the classification of the observed events as anomalous we have to show how the general average picture of the physical object of interest looks like. We show that using simple quantities derived from experiment with mountain based X-ray chambers and a few assumptions on behaviour of hadron interactions (basically it is nearly constant inelasticity $< K >\sim 0.5$ in the energy region of our interest), we arrive to the conclusions that give consistent explanation to many observed family characteristics and shows the features of particle interactions in the fragmentation region at energies up to 10^{17} eV. Also our analysis reveals the qualitative view on composition of primary cosmic rays in wide energy region before and after the "knee".

2 Instrument description

In this work we use Waseda-MSU data from thick Pb X-ray chambers exposed at Pamir in 1988-1991. X-ray films of total exposure $ST = 57 m^2 year$ have been analyzed in Japan by joint Waseda-MSU team (Kopenkin et al., 1997). Pamir Pb chamber has homogeneous structure (Pb plates interleaved with RT6M Russian made X-ray films) that allows to study longitudinal profile of gamma rays and hadrons at every 1 cm interval. Large thickness (60 cm Pb) corresponds to ~ 3.5 m.f.p. and uniform hadron detection efficiency is close to 1. In our experiment we have made complete scanning and measurements of total available area, analyzing all showers (both, of single and family arrival) with $E_{th} = 4$ TeV. This type of study was not possible in another experiments.[2]

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[1]The UA5 program (Tamada , 1994) is a simulation code based on phenomenological model of multiple particle production observed by CERN pp collider by UA5 collaboration experiment (UA5 collaboration, 1987). The energy distribution of produced particles shows violation of Feynman scaling law.

[2]In Pamir carbon chambers there is no detailed information on longitudinal shower profile. In Chacaltaya experiment the chamber thickness is ~ 1 m.f.p. Also in previous set up of experimental study using Pb chambers of different thickness, the analysis has been performed either on single showers, or family showers, or both categories together, without their classification into two.

3 Average shower transition curve

First we show how our detector works in distinguishing showers of electromagnetic and hadron nature. Fig. 1 presents the average shower transition curve constructed over all observed single and family showers with $E_{th} = 4$ TeV.[3] The peak at small depths corresponds to the showers of gamma ray origin and the tail at larger depths reflects showers of hadron origin[4]. The value of attenuation of hadrons λ_{att} can be estimated from the exponential slope of the tail $\sim exp(-t/\lambda_{att})$. The experimentally observed λ_{att} obtained from the average $< D >$ transition curve is $248 \pm 30 g/cm^2$ and $343 \pm 40 g/cm^2$ for single and family showers respectively. Let us assume that majority of single showers are nucleons and majority of family showers are pions and apply well known formula that connects collision mean free path λ_{col} and λ_{att} given by $\lambda_{att} = \lambda_{col}/(1- < (1-K)^{\alpha} >)$, where K is inelasticity and α is the power index of the energy spectrum of hadrons incident upon the chamber.

The power spectrum of single hadrons in our experiment is $\alpha = 2.0 \pm 0.1$ and of family hadrons - $\sim 1.2 \pm 0.1$. If $< K >= 0.5$, then these values appear to be in agreement [5] with the ones from formula as can be seen in Table. 1.

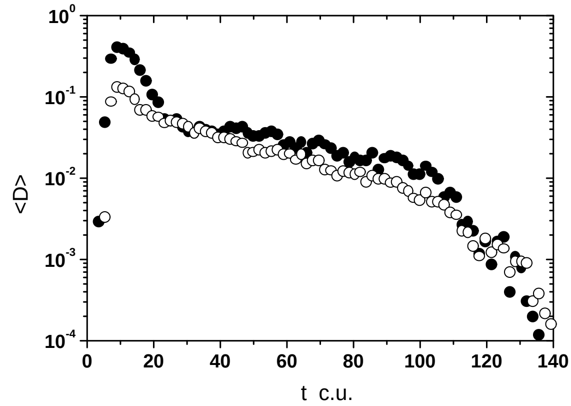

Fig. 1. Average shower transition curve ovel all observed single (open circles) and family (closed circles) showers with $E_{th} = 4$ TeV.

4 Hadrons in a family

The type of emulsion chamber used in Waseda-MSU experiment is particularly suitable for observation of hadron-gamma families. The comparison with the UA5 simulation results on hadron energy fraction in a family 100 TeV $\leq \Sigma E_{tot} \leq 1000$ TeV is shown[6] in Fig. 2. The observed energy of the shower $E_h^{(\gamma)}$ induced by a hadron of energy E_h depends on the energy fraction of the electromagnetic component produced in the interaction $k_\gamma = \Sigma E_\gamma / E_h$. The experimental distribution has a best fit if we assume $< k_\gamma >= 0.15$. As we can see, this value is consistent with $< K >= 0.5$, which results in $< k_\gamma >\sim 1/6$ assuming pion multiple production mechanism. We have used these experimental values as an input in our simulation of families detected in Pb chamber.

5 Lateral distribution of energy flow

The identification of showers as gamma rays or hadrons play a significant role in the study of families. There is an alternative way to describe the family development, using all showers without their identification as gamma rays or hadrons. In Fig. 3 we show the lateral distribution of energy flow of showers $d(\Sigma E_{tot})/2\pi R dR$ in the families from different energy regions: 58 families of $100 \leq \Sigma E_{tot} \leq 1000$ TeV from our Waseda-MSU experiment, 10 superfamilies 100 TeV $1000 \leq \Sigma E_{tot} \leq 7000$ TeV of $500\, m^2\, year$ exposure detected in deep Pb chambers of $40-110$ cm thickness (Arisawa et al., 1994) , 4 superfamilies $1000 \leq \Sigma E_{tot} \leq 5000$ TeV from Chacaltaya experiment (Hasegawa et al., 1996) , and the highest energy family Tajikistan (Ohsawa , 1997) ($\Sigma E_{tot} \geq 50000$ TeV) detected in deep carbon chamber in Pamir experiment ($\sim 2.7\, \lambda_{int}$). For comparison we show results of the UA5 simulation for proton primary. It is clear that the same energy density flow can be created either by primary proton or by primary nuclei of higher energy (respectively to mass number A).

No significant difference is seen between experimental data on families from Pamir and Chacaltaya experiment when we use the same energy intervals and showers are not classified into gamma or hadrons. It shows that in terms of energy flow, lateral and longitudinal behaviour of family development observed by X-ray chambers are basically the same. Because of the large halo area in the center, the energy flow density of Tajikistan family is presented by individual showers outside the halo region. We can notice similarity in behaviour of families in terms of energy flow of showers in a broad energy region from 100 TeV until ~ 50000 TeV in air and in the chamber[7].

[3] We use as E_{th} the value usually accepted by Pamir Collaboration. Our conclusions are the same if we use, for instance $E_{th} = 6.3$ TeV or $E_{th} = 10$ TeV.

[4] Sharp decrease after 100 c.u. is due to the limited chamber depth. $1 c.u. = 0.56$ cm Pb.

[5] Experimentally measured values on *short* mean free path of family hadrons (Arisawa et al., 1994) and on *long* mean free path of single and family hadrons together, (Rakobolskaya et al., 2000) were obtained with another methodical procedure using the shift of depth of shower maximum.

[6] $\Sigma E_{tot} = \Sigma E_\gamma + \Sigma E_h^{(\gamma)}$.

[7] If there were a fraction of exotic type of process that becomes dominant with increasing energy, then the signal would have appear in the behaviour of highest energy shower or family pattern.

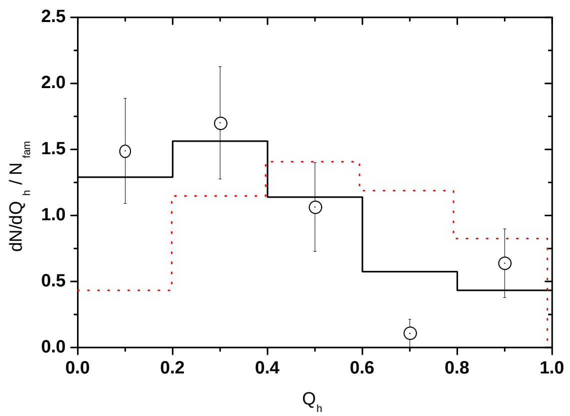

Fig. 2. Distribution of hadron energy fraction $Q_h = \Sigma E_h^{(\gamma)}/(\Sigma E_\gamma + \Sigma E_h^{(\gamma)})$ inside a family of $100 \le \Sigma E_{tot} \le 1000$ TeV. Marks are: open circles - experiment, solid line - simulation with $< k_\gamma >= 0.15$, dash line - simulation with $< k_\gamma >= 0.27$.

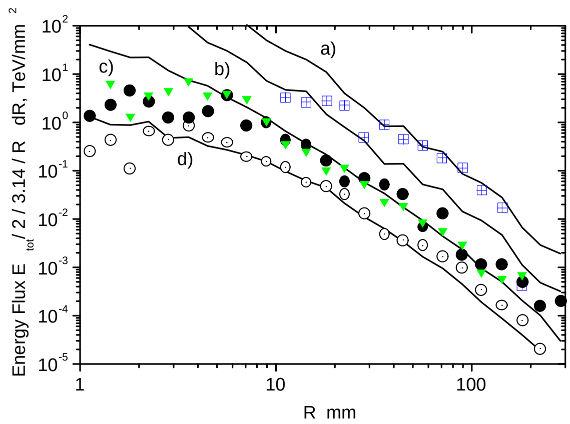

Fig. 3. Lateral distribution of energy flow density of showers ($E_{th} = 4$ TeV) in families. Marks are: open circles - family of $100 \le \Sigma E_{tot} \le 1000$ TeV (Waseda-MSU), closed circles - 1000-7000 TeV (MSU), squares - family Tajikistan, downward triangles - $1000 \le \Sigma E_{tot} \le 5000$ TeV (Chacaltaya). Solid lines - proton simulation (a) - $\Sigma E_{tot} = 200000$ TeV, b) - $\Sigma E_{tot} = 30000$ TeV, c) - $\Sigma E_{tot} = 3000$ TeV, d) - $\Sigma E_{tot} = 250$ TeV.

5.1 Halo phenomenon

We can notice that the halo formation naturally can find its explanation from this picture. Halo is created when the energy flow is reached certain threshold. From two particles of the same energy and different mass number (for instance proton and iron), the lighter one (proton) is more efficient for halo creation (high energy density in the center). High energy nuclei in turn will be more efficient in creation of multiple halo of small size (due to many nucleons). As can be seen from Fig. 3 the energy density of family ($R \le 10$) mm in interval $100 - 1000$ TeV is not enough to create sufficient condition for large halo formation, so halo is rarely observed. Superfamily region $\sim 1000 - 7000$ TeV is known for families with and without halo accompaniment. At very high energies, $E_{tot} \ge 10000$, TeV all families will be accompanied by halo in its center. These conclusions that follow from simple picture clarified by simulation, have found their confirmation in experimental observation (Pamir collaboration , 1991).

6 Total energy of family ΣE_{tot}

In order to study family characteristics in different energy intervals we have to use the same scale for family energy determination. The total energy of a superfamily with halo can be expressed as $\Sigma E_{tot} = E_{halo} + E_{out-halo}$.[8] The energy of halo [9] usually is estimated from the total track length as $E_{halo} = \epsilon * \int N_e(t)dt$, assuming the critical energy in Pb as $\epsilon = 7.4$ MeV

In experiment energy outside of halo region is determined as $E_{out-halo} = \Sigma E_\gamma + \Sigma E_h^{(\gamma)}$, with $E_{th} = 4$ TeV. Obviously, that halo region contains showers above and below this threshold E_{th}.

Comparing experimental and simulated lateral distribution of energy flow in the region outside of halo in a particular family, we can estimate the total energy of a family including halo region using the same energy threshold E_{th}. An upper limit on total energy of a family with $E_{th} = 4$ TeV is set by an experimental estimation of ΣE_{tot}, where halo energy E_{halo} is estimated from the raster scanning.

To choose between several variants we can use additional information on hadrons detected in the region outside of halo[10] From correlation on number of hadrons in a family N_h observed in the region $10 \le R \le 100$ mm (family can be either with or without halo) and the total energy of a family ΣE_{tot} shown in Fig. 4, the most probable mass number of primary particle, and correspondingly ΣE_{tot} can be estimated.

7 Primary composition

In our study of jets we have shown that of the families of 100-1000 TeV observed by emulsion chambers at mountain altitudes such as the Pamirs are induced by protons. The atmosphere plays the role of a filter for heavy component. Our experimental data (Fig. 4) in this energy region agree with

[8]obviously, "ordinary" family without halo in energy interval $100 \le \Sigma E_{tot} \le 1000$ TeV has $E_{halo} = 0$.

[9]The darkness D for every element in density matrix obtained after scanning of halo area is converted into electron density ρ by the characteristic curve of the X-ray film ($D = D_0(1 - exp(-\alpha\rho))$, The lateral distribution of electron density is integrated for every level to obtain the total number of electrons N_e in the halo.

[10]This is also important from the methodical point of view. Individual cascades form hadrons will be not masked by diffused dark halo area.

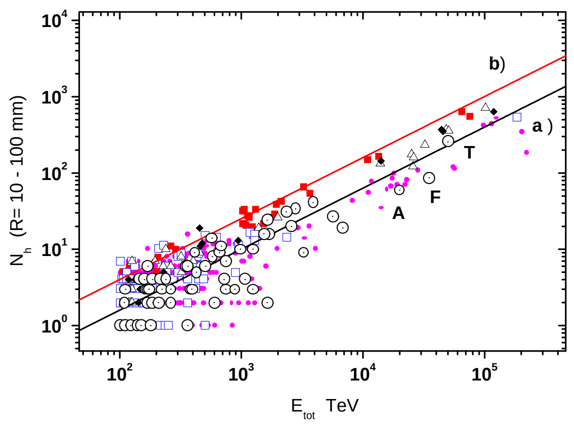

Fig. 4. Correlation of number of hadrons N_h in the region $10 \leq R \leq 100$ mm from the family center , and total family energy ΣE_{tot} with $E_{th} = 4$ TeV in simulation and experiment. Marks are: open circles - Waseda-MSU, closed circles - MSU, circle with A - family Andromeda (Yamashita , 1984), circle with F - family FIANIT (Pamir collaboration , 1984), circle with T - family Tajikistan, dots - proton, squares - Fe, open triangles - CNO, rhombuses - Mg. Line a) - $\sim A \times (E/A)^{0.8}$ for A=1, Line b) the same for $A = 56$.

assumption of normal chemical composition. These families are originated by cosmic rays with average primary energy $E_0 \sim a\, few$ PeV that is just near the "knee" region.

If the fraction of heavy nuclei increases in primary sepctrum, then the relative number of families originated by protons decreases. It can be seen that the relative number of families originated by nuclei (area between line[11] a) and line b)) increases with ΣE_{tot} and at higher energies (in emulsion chambers it corresponds to superfamilies of ($\Sigma E_{tot} \sim 1000 - 7000$,) TeV after the "knee" the primary composition becomes heavier, enriched with nucleus. We also show in Fig. 4 highest energy event Andromeda ($\Sigma E_{tot} \sim 20000$ TeV) detected in Chacaltaya experiment, and two highest energy events from Pamir $\sim 5000\, m^2\, year$ exposition - FIANIT ($\Sigma E_{tot} \sim 30000$ TeV) and Tajikistan. The energy of primary particle responsible for creation of these events (estimated by simultion) would be $E_0 \sim 10^{17} - 10^{18}$. It is important to note that primary cosmic ray at these energies contain protons.

8 Discussion and Conclusion

Using all available information from our experiment, we show the consistency of results with an assumption of $< K >= 0.5$ in hadron interactions in the energy region $10^{15} - 10^{17}$ eV[12]. We use a simulation calculation (using the same ¡K¿) as a tool to check our experimental conclusions. We apply our method to the whole energy region studied by mountain chamber experiments and reveal the qualitatiove picture of primary cosmic ray composition before and after the "knee".

[11] lines reproduce function $N_h \sim A \times (E/A)^{0.8}$

[12] We have to mention that our study of the inelasticity using the shape of transition curve of high energy hadrons produced similar result, $< K > \sim 0.6$ (Augusto , 2000).

Table 1. Attenuation mean free path of hadrons with $E_h^\gamma \geq 4$ TeV. λ_{col} is assumed to be 190 g/cm^2 .

Hadron category	Spectrum index α	λ_{att} g/cm^2	λ_{att} $(< K >= 0.5)$ g/cm^2
Single	2.0 ± 0.1	248 ± 30	253
Family	1.2 ± 0.1	343 ± 40	320

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