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Study of high energy cosmic ray interactions and primary composition at energies $10^{15} - 10^{17}$ eV using mountain based detectors

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abstract

We report new experimental results obtained by Waseda-MSU collaboration. Our detector is 60 cm thick lead X-ray emulsion chamber exposed to cosmic rays at Pamirs. General characteristics of cosmic ray hadron interactions at high energies are discussed. We show that mountain X-ray chamber experiment can detect cosmic rays in the wide energy range $10^{15} - 10^{17}$ eV. Using experimental data we show the features of hadron interactions and primary cosmic ray composition in the energy region before and after the “knee”.

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1 Introduction

Experiments with X-ray emulsion chambers have been carried out for more than 30 years at Mt. Chacaltaya (5,200 m, Brazil-Japan Collaboration), Pamir (4,300 m, Pamir Collaboration), Mt. Fuji (3,750 m, Fuji Collaboration), Mt. Kanbala (5,500 m, China-Japan Collaboration). The main objectives of these experiments is to study fragmentation region of hadron interactions and primary composition at energies $10^{15} - 10^{17}$ eV, overlapping region with current collider experiments.

In cosmic ray experiments the interpretation of hadron interactions involves consideration of the nature of primary particles. Because of exceedingly low flux, the primary cosmic ray particles of energy $\geq 10^{15}$ eV cannot be observed by direct methods. Naturally, at present

the main interest in experiments with emulsion chambers turned to the problems of origin and propagation of highest energy cosmic ray particles.

Nuclear electromagnetic cascade originated by primary cosmic ray particle in the atmosphere is detected in the chamber in the form of bundle of gamma rays¹ and hadrons called *a family*. The study of family characteristics is a main subject in experiments with emulsion chambers at mountain altitudes.

In spite of almost 30 years of investigation, there has not been reached yet consistent understanding on the physics of gamma hadron families observed by cosmic ray experiments with X-ray emulsion chambers. There are many experimental classes of events named as Centauros, Chirons, etc. that could not find explanation within framework of present models [1], [2], [3]. In addition, some unexpected results have been found in properties of particles inside of families: the anomalous long attenuation of hadrons in lead [4], [5], mini-clusters [3], extremely penetrating gamma ray showers² [6]. These experimental observations got their detailed morphological description, and individual events have been thoroughly examined, measured, and analyzed. In the present experiment, however, we do not find any evidence of such exotic events under their morphological definition.

Many of those anomalies were claimed by observing inconsistencies between the observed shower data and theoretical predictions under assumptions of hadron (nucleons and pions) and gamma ray origin. In most of the previous experiments, the studies were made with chambers of complex structure, and the response of the detectors to the incoming particles could not be examined in details. These experiments were always aiming at larger statistics and the design of chambers were mainly for larger exposures even sacrificing their qualitative sides.

Here we present the results of collaborative work of Moscow State University and Waseda University groups (Waseda-MSU hereafter) on joint study of the events recorded by thick Pb X-ray chambers of total exposure $ST = 57 m^2$ year during 1988 – 1991 at Pamirs.

The chamber is a thick pile of Pb plates and X-ray film layers, with total thickness as large as 60 cm of Pb. The structure is uniform and we are able to anticipate behaviour of showers of hadron and gamma ray origin with the help of the cascade theory. The comparison with the observational shower data shows that the showers in the chamber are well interpreted as those of hadron and gamma ray origin, and we find no room for exotic showers beyond the statistical fluctuations. At the same time, we are able to construct a procedure to estimate the shower energy and give the identification of shower origin.

The cosmic ray study has two aspects: the particle physics side through particle interactions and the astrophysics side through cosmic-ray origin of primary particles. Further, the observation is made at atmospheric depths of several nuclear interaction mean free paths, and the atmospheric diffusion obscures particle's original characteristics. These are the main reasons why cosmic-ray experiments could not remove ambiguities in their conclusion. But the situation is changing now.

The present chamber provides enough statistics of families with observed energy sum of a few hundred TeV, which can be a basis of the new cosmic ray study. The concerned family energy region corresponds to the primary particles of some 10^{15} eV or higher, after comparison of the flux value. This is just above the maximum collision energy available by the existing collider experiments. As a working hypothesis, we may assume no exotic nuclear interactions and assume simple extrapolation of the interaction model from the

¹ All particles of electromagnetic nature - electrons, photons, positrons are referred to as *gamma-rays* hereafter.

² Electromagnetic (electron-photon) cascades initiated by particles in the chamber are called *showers*.

accelerator experiments.

Thus, crucial point is the evaluation of the procedure of energy determination and identification of the origin of particles detected in the chamber. This is the basic point in the study of exotic phenomena.

Because of cosmic ray nature itself the features of hadron interactions are interrelated with the origin of primary particles. If an event has extremely large multiplicity or large hadron energy fraction, it would be considered a normal event in case of heavy primary particle or an exotic event in case of primary protons.

The spectrum of primary high energy cosmic rays has well known structure, with a significant change in slope around a few PeV, a region in the spectrum called the "knee" [7], [8]. It is believed that this break in the spectrum indicates either new mechanism of particle production or change of primary composition. Direct observations of cosmic ray primary spectrum (balloon experiments, such as JACEE[9], RUNJOB[10], MUBEE[11] and satellite experiments [12], [13]) work in the energy region up to $\sim 10^{15}$ eV/particle, that is just before the "knee". The region of the "knee" and above are studied mainly by indirect methods through air shower experiments at sea levels, or mountain altitudes, using large areas of detectors.

Comparing with direct balloon/satellite based and EAS experiments, mountain Pb chamber experiment covers the energy region before and after the "knee" using the same method. The determination of energy, shower identification and efficiency of Pb chamber are the same in the wide energy scale. Although the statistics in our experiment with Pb chambers is not so large, well established understanding of the detector performance and the method of shower detection and identification, will make it possible to get a picture on primary composition.

Therefore, we address both problems: the study of hadron interactions and primary composition in present paper.

The article will be organized as following.

In section 2, we explain the details of the experimental setup, detection and measurement procedure in Pamir experiment using thick lead X-ray emulsion chamber.

In section 3 we compare our Waseda-MSU data with experimental data obtained by previous Pamir experiment with Pb chambers [5],[14] in 1977-1988.

In section 4 we show how our detector works in distinguishing showers of electromagnetic and hadron nature. In addition, in Appendix, we present detailed explanation on used quantities and variables for description of hadron propagation through matter.

Section 5 describes phenomenological picture of gamma-hadron families. Using experimental data we establish basic parameters for simulation calculations.

In our consideration of gamma-hadron families we study pattern of energy flow represented by jets in Section 6.

In Section 7 with the concept of the leading shower in a family we reveal similarity of the pattern of families detected in various mountain chamber experiments.

Section 8 describes picture of family in terms of energy density flow and presents the results of analysis of families in the whole energy region available for X-ray emulsion chambers.

Primary composition and primary spectrum are discussed in section 9.

Finally the conclusions are drawn in Section 10.

In Appendix we discuss in more details the attenuation and collision mean free paths of hadrons (A), analytical calculations (B,C) used in present analysis and also details of applied primary spectrum approximations (D).

2 Experimental setup

In this work we use Waseda-MSU data from thick Pb chambers exposed at Pamir in 1988-1991. In 1991, a Pamir mountain experiment group of Moscow State University and Laboratory of High Energy Physics of Waseda University proposed as a part of the Chacaltaya-Pamir Collaboration, joint study of cosmic ray phenomena by means of the homogeneous thick lead chambers. The detectors called thick lead chambers, which were developed by the group of Moscow State University, were constructed at the Pamirs (4370 m above sea level) in Tadjikistan in 1988-1991. The Pamirs mountains with such a high altitude is an ideal site for the observation of super high energy interactions of cosmic ray particles. After the processing of X-ray films in Russia they were shipped to Japan. X-ray films of total exposure $ST = 57 m^2 year$ have been analyzed in Japan by joint Waseda-MSU team [15].

2.1 The X-ray emulsion chamber

Pamir X-ray chamber has an area $10 m^2$ and consists of 20 units, each of $0.5 m^2$ size. The chamber is homogeneous in structure and uniform in detection efficiency of electron showers. 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 ~ 4 nuclear interaction mean free path. In this type of a detector the energy of incident particles is estimated by calorimetry method. X-ray emulsion chamber detects showers which are initiated by γ -rays and hadrons. Since there are γ -rays from decay of π^0 produced in nuclear collisions of incident hadrons, the emulsion chamber is sensitive both to electromagnetic and hadron components.

We also use in our analysis in present paper data of mountain chamber experiments which employed abother type of widely used X-ray chambers. For many years the Pamir experiment has employed X-ray emulsion chambers of different design, so called C chambers[16]. These chambers consist of 60-cm-thick blocks of carbon and several slabs of lead (in total 5 – 6 cm thickness) interspersed with sheets X-ray films. Covering a larger effective area, the C chambers provide greater exposure than Pb chambers, but are less efficient in hadron detection and less accurate in estimation of shower energy due to small number of X-ray film layers.

Japan-Brasil experiment that has been conducted since the beginning of 60th[17], employs X-ray chambers of a different design, made from bulk of carbon and lead plates interleaved with X-ray films and nuclear emulsions. Typical two-storey Chacaltaya chamber[18] consists of the upper chamber of 6 – 10 cm of Pb, the target layer of 20 – 30 cm carbon, the air gap (150 – 240 cm of air), and the lower chamber of 6 – 15 cm Pb. Some chambers, in addition to X-ray films, have nuclear emulsion plates in upper or/and lower parts of the chamber.

With different chamber structure design, all mountain experiments with X-ray chambers basically use the same observation techniques on electron showers.

2.2 The emulsion chamber techniques

When a bundle of high energy shower electrons propagates through the film material, it appears as a spot on the X-ray film, a cascade shower spot. These dark spots have sizes varying from a few tens to a few hundreds of microns. The optical density of each spot $D(E, t)$ can be measured by photometry and depends on the energy of the cascade E , and on the depth of its detection in the chamber, t . Comparing the observed value $D(E, t)$ for

each electron-photon cascade with theoretical predictions, the energy of the γ -ray, E_γ , that generates cascade, is estimated.

The energy of incident hadron E_h is estimated from the electromagnetic energy $E_h^{(\gamma)}$ released by the hadron as it traverses the chamber material. The observed energy of a shower induced by hadron $E_h^{(\gamma)}$, is proportional to the energy of an incident hadron, E_h : $E_h^{(\gamma)} = k_\gamma E_h$. k_γ is the energy fraction ($0 \leq k_\gamma \leq 1$) converted into electromagnetic component in the interaction of an incident hadron with a Pb nucleus. The energy detection threshold in Pamir experiment is $E_{th} \sim 4$ TeV.

An incident γ -ray generates electromagnetic cascade in the upper part of the chamber. A cascade of hadron origin may occur at arbitrary depth in the chamber. We denote as Δt the distance between the upper face of the chamber and the electron photon cascade vertex in units of radiation length, or cascade units (c.u.). An illustration of the determination of Δt , either for first interaction point, or for the shower maximum, is shown in Fig. 1.

Cascade showers detected in X-ray films can be categorized into single and family showers. Hadrons and γ -rays from primary and subsequent interactions in the atmosphere appear in the detector as a group of parallel showers, that is called a *family*. Since the interaction point of cosmic ray hadron is generally high in the air, cascade showers are spread out in the air and separated at distinguishable distances (up to 30 cm for their mutual distance) when they are recorded in X-ray films. Shower spots of families have similar pattern and coincide geometrically on successive layers of X-ray films. Family showers consist of γ -rays and hadrons.

If a shower detected in the chamber is not associated with any other parallel shower of energy above the detection threshold E_{th} , then it is called a *single* shower.

3 Experimental statistics

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

In our experiment we made complete scanning and measurements over 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 other experiments.³

We have made comparison of our experimental data (Waseda-MSU hereafter) using Pamir collaboration method of analysis, the same selection criteria for identification of gamma rays and hadrons⁴ and the same energy determination methods as in previous Pamir exposures with Pb chambers (we call it as MSU experiment) [5], [16]. The numerical data and comparison of family statistics and the observed hadron flux are given in Table 2.

In Fig. 2 we present differential energy spectra of gamma rays and hadrons in families $100 \text{ TeV} \leq \Sigma E_\gamma \leq 400 \text{ TeV}$ with $E_{th} = 4$ TeV from Waseda-MSU experiment and MSU experiment. As we can see there is good agreement between two experiments.

³ 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 (40-110 cm), the analysis has been performed either on single showers, or family showers, or both categories together, without their classification into these two groups.

⁴ Showers with $\Delta t \leq 6$ c.u. in this approach are considered to be gamma rays, and all other are hadrons. By this way of analysis Δt expresses shift of depth of the shower maximum from the expected position of pure electromagnetic cascade.

4 Average shower transition curve

Let us show how our detector works in distinguishing showers of electromagnetic and hadron nature. Fig. 3 presents the average shower transition curve constructed over all observed single and family showers with $E_{th} = 4$ TeV⁵. The peak at small depths corresponds to showers of gamma ray origin and the tail at larger depths reflects showers of hadron origin⁶. The value of attenuation of hadrons λ_{att} can be estimated from the exponential slope of the tail $\sim \exp(-t/\lambda_{att})$. Experimentally observed value of λ_{att} obtained from the average $\langle D \rangle$ transition curve is 248 ± 30 g/cm² and 343 ± 40 g/cm² for single and family showers respectively⁷.

The power spectrum of single hadrons in our experiment is $s = 2.0 \pm 0.1$ and of family hadrons - $s = 1.2 \pm 0.1$. The spectra are shown in Fig.4. We can see that the difference in incident hadron spectrum is reflected by hadron attenuation behaviour. In Appendix we discuss in more details the attenuation and collision mean free paths of hadrons.

5 Family study

The behaviour of families in the energy region above 100 TeV have been already studied by many authors with the purpose to get information on hadron interactions.

It was already found that the concerned families are full of varieties in their properties, such as multiplicity of showers, lateral spread, relative content of gamma rays and hadrons, or family cluster structure.

Under the working hypothesis of the interaction model derived from the collider experiment, with weak scaling break extrapolation, this variety of family features are attributed to fluctuations in the atmospheric nuclear cascade process. We will present here the average properties of families and compare them with the predictions of our working model.

Under effect of diffusion in the development of atmospheric nuclear electromagnetic cascade, that is a stochastic process in its nature, we expect that the average behaviour of the family at the detector level will be with power energy spectrum and will reflect an exponential attenuation. The observation can confirm these points.

5.1 Hadrons in a family

The scatter plot of observed energy sum of gamma rays ΣE_γ and hadrons $\Sigma E_h^{(\gamma)}$ in families with $E_{tot} \geq 50$ TeV observed in Waseda-MSU experiment together with the result of the UA5 simulation⁸, assuming normal primary composition⁹, is shown in Fig. 5.

The type of Pb X-ray chamber used in Waseda-MSU experiment is particularly suitable for observation of hadrons. The comparison with the UA5 simulation results on hadron

⁵ We use as E_{th} the value usually accepted by Pamir Collaboration. Our conclusions would be the same if we use, for instance $E_{th} = 6.3$ TeV or $E_{th} = 10$ TeV.

⁶ Sharp decrease after 100 c.u. is due to the limited chamber depth. 1 c.u. = 0.56 cm Pb.

⁷ Experimentally measured values on *short* mean free path of family hadrons [14] and on *long* mean free path [4] of single and family hadrons together were obtained with another complicated methodical procedure.

⁸ The UA5 program[20] is a simulation code based on phenomenological model of multiple particle production observed by CERN pp collider by UA5 collaboration experiment [21]

⁹ Composition of the primary cosmic rays is considered to be normal at E_0 (eV) if relative abundances (%) of $p : He : CNO : Mg : Fe$ are 42 : 17 : 14 : 14 : 13. This composition is also called as proton dominant primary composition.

energy fraction¹⁰ in families $100 \text{ TeV} \leq \Sigma E_{tot} \leq 1000 \text{ TeV}$ is shown¹¹ in Fig. 6.

The observed energy $E_h^{(\gamma)}$ of the shower induced by a hadron of energy E_h depends on the energy fraction of the electromagnetic component produced in the interaction $k_\gamma = \Sigma E_h^{(\gamma)} / E_h$. The experimental distribution has a best fit if we assume $\langle k_\gamma \rangle = 0.15$. As we can see, this value is consistent with $\langle K \rangle \sim 0.5$, which results in $\langle k_\gamma \rangle \sim 1/6$ assuming charge symmetry in pion multiple production. We use these experimental values of k_γ and $\langle K \rangle$ as an input parameters in our simulation of families detected in Pb chamber using the UA5 model. The energy distribution of produced particles shows violation of the Feynman scaling law[22]¹².

6 Study of jets

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.

If the observed family has one collimated energy center it may be called a single "core" family [3]. This "core" can be either surviving leading nucleon from a surviving proton primary, high energy air cascade, or cluster of gamma and hadrons. On the other hand, if the family spread is wide, with many local energy centers (clusters of showers), it may be called a "multi-core" family [3] and a heavy primary nucleus would be the best candidate.

Such consideration can be formulated in the following way. By constructing jets we reveal the structure of the cascade complex and go "back" to the main interaction and to the primary particle. In our analysis we have applied the following algorithm for experimental and simulation events: 1) decascading of gamma rays to gamma clusters with parameter $Z_{dec} = 11.0 \text{ TeV mm}$ [23]; 2) jet-clustering of all showers, clusters, hadrons and gamma rays with parameter $Z_{jet} = 200 \text{ TeV mm}$; 3) normalizing jet energy by setting threshold $f'_{min} = 0.04$ for their fractional energy $f = E_{jet} / E_{tot}$. Parameters Z_{dec} and Z_{jet} reflect average transverse momentum in electromagnetic and strong interaction processes. In our analysis jet (in experiment and simulation) does not always represent the parent atmospheric interaction. It also includes successive interactions in the atmosphere by hadrons from parent interactions. Fig. 7 shows distribution of hadron energy fraction Q_h inside of a leading jet. This distribution is similar to the known correlation between Q_h and number of hadrons in a family N_h [2]. The peak near $Q_h \sim 0$ shows a case of a leading cluster of gamma showers or an old cascade from a family, started at high altitude. Another 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 a leading jet. Energy fraction carried by leading jet shows signature of primary particle origin and surviving nucleon in interaction. Fig. 8 gives distribution of the leading jet energy fraction $f = E_{lead} / E_{tot}$ in experiment (closed circles) and simulation

¹⁰ For this purpose we applied new method of identification of gamma rays and hadrons. This method takes into account the shape of transition curve together with $\Delta t = 6$ selection criterion. [19].

¹¹ $\Sigma E_{tot} = \Sigma E_\gamma + \Sigma E_h^{(\gamma)}$.

¹² This law postulates that the form of the distribution of secondaries is independent on the incident energy.

(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. 8. There is clear agreement between experiment and simulation based on primary proton dominant composition in energy region $E_0 \sim a\ few\ PeV$, near the "knee".

7 Analysis of families without identification of showers

The picture of hadron interactions obtained by the present experiment is different from those of other experiments, particularly Chacaltaya view with dominance of exotic families [1], [3],[18]. We will make the comaprison of their family data without identification of shower origin. It aims at comparison between the raw data eliminating possible effects of methodical effects, as much as possible.

7.1 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 applied methods of energy estimation and identification of shower. 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, which can be either gamma or hadron.

In Fig. 9 we show distribution of the leading shower energy fraction $E_{lead}/\Sigma E_{tot}$ in families of $100\ TeV \leq \Sigma E_{tot} \leq 1000\ TeV$ from Pamir Pb chambers, Pamir C chambers, and Chacaltaya experiment [3], [18] in comparison with the UA5 simulation results. Since we consider the energy ratio $E_{lead}/\Sigma E_{tot}$, this method is free from methodical details in each experiment. Fig. 9 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.

Therefore, identification of showers as hadron or gamma or definition of an absolute energy scale in either of experiments could be the main source of differences in observation of exotic type of events. To study hadron characteristics in a family, it would be better to rely on analysis of data from the deep chamber with several mean free path thickness that allows good separation between showers of gamma rays and of hadrons.

8 Lateral distribution of energy flow

In Fig. 10 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 $100\ TeV \leq \Sigma E_{tot} \leq 1000\ TeV$ from Waseda-MSU experiment, 10 superfamilies, $1000 \leq \Sigma E_{tot} \leq 7000\ TeV$, of $500\ m^2\ year$ exposure detected in deep Pb chambers of 40 – 110 cm thickness [14], 52 families $100\ TeV \leq \Sigma E_{tot} \leq 1000\ TeV$ and 4 superfamilies $1000\ TeV \leq \Sigma E_{tot} \leq 5000\ TeV$ from Chacaltaya experiment [3],[18], and the highest energy family Tajikistan [24] ($\Sigma E_{tot} \geq 50000\ TeV$) detected in deep carbon chamber in Pamir experiment ($\sim 3.3\ \lambda_{int}$). 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 ¹³.

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 the family development observed by X-ray chambers is basically the same. Because of the large halo ¹⁴ area [25], [26] 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 ¹⁵.

8.1 Halo phenomenon

We can notice that the halo formation naturally can find its explanation from Fig. 10. Halo is created when the energy flow is reached certain critical value. From two primary 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 nucleus in turn will be more efficient in creation of multiple halo of small size (due to many nucleons). As can be seen from Fig. 10 the energy density flow in a family at $R \leq 10$ mm in energy 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, $E_{tot} \geq 10000$ TeV all families will be accompanied with halo in its center. These conclusions that follow from simple picture clarified by simulation, have found their confirmation in experimental observation [26]. In accelerator experiments halo phenomenon can not be observed, because there is absent "atmospheric thick filter" that is responsible for accumulation of nuclear electromagnetic cascades initiated by high energy primary particle.

8.2 Total energy of a 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 ¹⁶ $\Sigma E_{tot} = E_{halo} + E_{out-halo}$. The energy of a halo ¹⁷ 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 [24],[26].

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} .

¹³ The shower from a primary nucleus of energy E and mass A is equivalent to the sum of A nucleon showers of primary energy E/A .

¹⁴ Halo is a dark area of radius $\sim 0.5 - 3$ cm observed in X-ray emulsion films. It consists of large number of showers. Usually the area is so dark that is almost impossible to identify individual showers within halo area.

¹⁵ If there were a fraction of exotic type of process that becomes dominant with increasing energy, then the signal would have appeared in the behaviour of the highest energy shower or in the family pattern.

¹⁶ obviously, "ordinary" family without halo in energy interval $100 \leq \Sigma E_{tot} \leq 1000$ TeV has $E_{halo} = 0$.

¹⁷ 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.

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 halo¹⁸. From correlation on number of hadrons in a family N_h observed in the region $10 \leq R \leq 100$ mm (family can be either with or without halo) and the total energy of a family ΣE_{tot} shown in Fig. 11, the most probable mass number of primary particle, and correspondingly ΣE_{tot} can be estimated.

9 Primary composition

In our study of jets we have shown that families of 100-1000 TeV observed by emulsion chambers at mountain altitudes such as the Pamirs are induced mainly by protons. The atmosphere plays the role of a filter for heavy component. Our experimental data (Fig. 11) in this energy region agree with an 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 spectrum, 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 lines¹⁹ a) and 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. 11 the highest energy event Andromeda ($\Sigma E_{tot} \sim 20000$ TeV) detected in Chacaltaya experiment [25], and two highest energy events from Pamir $\sim 5000\ m^2\ year$ exposition - FIANIT [27] ($\Sigma E_{tot} \sim 30000$ TeV) and Tajikistan [24] ($\Sigma E_{tot} \sim 50000$ TeV). The energy of primary particle responsible for creation of these events (estimated by simulation) would be $E_0 \sim 10^{17} - 10^{18}$ eV. It is important to note that primary cosmic ray at these energies contain protons.

9.1 Family flux and primary spectrum

Fig.12 shows the integral spectra of the family energy in the form of energy of gamma rays ΣE_γ . Open circles with dots represent results of experiment with mountain based X-ray emulsion chambers exposed to cosmic rays at Pamirs. The hypothesis that all cosmic rays are protons can not explain experimental data. To accomodate the experimentally observed flux one have to consider enrichment of primary spectrum with heavy nuclei. The expected spectrum of the ΣE_γ obtained by simulation calculation using approximation of primary spectrum from [28] (see Appendix D). The agreement between experiment and simulation supports our conclusion on change of primary particle chemical composition from proton dominant to heavy dominant.

¹⁸ This is also important from the methodical point of view. Individual cascades form hadrons will be not masked by diffused dark halo area.

¹⁹ Lines reproduce function $N_h \sim A \times (E/A)^{0.8}$ (see Appendix C for details).

10 Discussion and Conclusions

Cosmic ray experiments undoubtedly produced many discoveries concerning the particle physics and the nature of particle interactions.

Also there have been numerous reports on observation of new phenomena observed by cosmic ray experiments with X-ray emulsion chambers. Without being confirmed by accelerators, these experimental observations stimulated new ideas, such as disoriented chiral condensate (DCC) [29], and helped in clarification of the present picture of hadron interactions.

Because of the cosmic ray nature itself the features of hadron interactions are interrelated with the origin of primary particles.

In order to interpret the data collected in experiments with emulsion chambers exposed to cosmic rays at mountain altitudes we have to know the characteristic features of particle interactions at very high energies and also to know the nature of primary particles.

One of the main long standing questions is whether particle physics is consistent with extrapolation of accelerator results at primary energy $E_0 \leq 1000$ TeV.

First we confirmed the validity of our new experimental data set comparing it with previous experimental observations using conventional methods for the data analysis. We get the same characteristics previously reported by Pamir collaboration.

To remove ambiguities associated with interpretation of experimental data, we have shown how the emulsion chamber detector in our experiment works in detection of gamma rays and hadrons.

With the concept of the leading shower in a family and energy flow density we reveal similarity of the pattern of families detected in various mountain chamber experiments in the whole energy region available to experiments with X-ray emulsion chambers.

In our consideration of the gamma-hadron families we studied pattern of energy flow represented by jets. Using the same algorithm of analysis and the same concept of jets in experiment and in simulation we conclude that general characteristics of cosmic ray families in the energy range 100 – 1000 TeV are compatible with predictions of simulation model (in our case this is the UA5 model) based on accelerator experiment extrapolation to higher energies.

It has been pointed out [30] that the interpretation of cosmic ray families detected at mountain altitudes has an ambiguity due to the poor understanding of two basic elements: the behaviour of inelasticity and the composition of primary cosmic ray particles.

In order to understand the behaviour of hadron interactions at higher energies we use family data sets from the whole available energy interval and apply the same method of analysis in experiment and simulation calculation.

The dynamics of particle multiple production can be well reproduced by the behaviour of inelasticity K which shows the fraction of incident energy transferred to secondaries. Since there is no information on inelasticity available from accelerator experiments, we have to rely on cosmic ray experiments.

We use a simulation calculation as a tool to check our experimental conclusions, taking into account numerical values on inelasticity derived from experiment.

Based on available information from our experiment, we show the consistency of results with an assumption of $\langle K \rangle \sim 0.5$ in hadron interactions in the energy region $10^{15} - 10^{17}$ eV²⁰.

²⁰ We have to mention that our earlier study of the inelasticity using the shape of transition curve of high energy hadrons produced similar result, $\langle K \rangle \sim 0.6$ [33]. several experiments have been conducted on

There were several papers on estimation of inelasticity based on data from emulsion chamber experiments [31],[32]. The value $\langle K \rangle \sim 0.5$ seems to be quite different comparing with other results ²¹. In our study the value of inelasticity is derived from the data obtained in experiment and is used as an input for simulation. Another studies used comparison of characteristics of families in model and experiment and used the model conclusion on inelasticity for interpretation of experimental data. The implications from our study are quite challenging. We can think of the analogy of Landau-Pomeranchuk-Migdal effect that changes the behaviour of electromagnetic cascades at super high energies, in the nuclear matter. The study on this subject is out of scope of present article.

We apply our method to the whole energy region studied by mountain chamber experiments and reveal the qualitative picture of primary cosmic ray composition before and after the "knee".

To understand the mechanism of origination, acceleration and propagation of particles in the Galaxy it is necessary to study the cosmic ray chemical composition.

The acceleration mechanism that works at the shock front of an expanding super nova remnants suggests the limit on the acceleration of particles proportional to the ZE_{max} [38].

If the origin of the "knee" is due to the acceleration limit, then the fraction of heavy component would become larger.

Our result indicate that the primary composition gradually becomes enriched with heavy nuclei with increasing energy ²².

At the end we would like to summarize the present status of exotic showers, exotic families and exotic interactions. We have shown that the showers observed in experiments with Pb X-ray chambers can be consistently classified into gamma ray origin and hadron origin. If some class of anomalous showers exist, then the upper limit would be within fluctuations.

Model of hadronic interactions with weak break of scaling can explain the average behaviour of families even at its highest energy end. The above conclusions do not necessarily rule out the existence of exotic particle origin of families. We know some families with outstanding features, for example, the original Centauro event[1] and the new Centauro-like event [39], [40] ²³. Thus, Centauro type events, has a flux comparable to $\sim 0.003 m^2 year^{-1}$

study of leading particles in dense matter. Fortunately, the difference between nuclear interaction mean free path and radiation length makes it possible to investigate the structure of cascade development. Since the theory of electromagnetic cascade processes is very well developed, it is possible to study the relation between experimentally observed cascade developed in dense material and parameters of elementary act of hadron nuclear interactions. In [34] it has been shown that in interval of $x_f \sim 0.3 - 0.9$ spectra of leading nucleons in proton-proton interactions are practically in agreement with spectrum of leading nucleons in *proton - Fe* interactions measured in cosmic rays at average energy $\sim 100 - 500$ GeV. The obtained value of $K_{tot} = 0.45$.

²¹ Study of inelasticity based on carbon emulsion chamber data[31] yields $\langle K \rangle = 0.65 \pm 0.08$, and study of all hadrons (without classification on single and family hadrons) from Pb chambers [32] produced $\langle K \rangle \sim 0.80$.

²² There have been reports [35], [36] that explained experimental data on lateral spread and integral spectrum of superfamilies detected in Chacaltaya experiment using set of simplest assumptions for the productions of secondaries and approximate scaling in the fragmentation region. This scenario requires a primary composition heavier than protons, with average mass number $\langle A \rangle = 7.3 \pm 0.9$. Observation of superhigh-energy halo events in superfamilies by the Mt.Fuji and Mt.Kanbala emulsion-chamber experiments [37] also suggested the heavy-nuclei dominance above the "knee" region.

²³ It is worth to note that the new Centauro like event has very low energy $\Sigma E_{tot} \sim 50$ TeV, with $E_{th} = 1$ TeV, and large lateral spread of showers, scattered at the region of ~ 20 cm. This event consists only of showers detected in the lower part of the chamber, thus excluding the problem of gamma-hadron identification. The original Centauro event has $\Sigma E_{tot} \sim 227$ with $E_{th} = 1$ TeV, has a few gamma-rays

at Chacaltaya experiment. There is no indication from experiment that such clear exotic type are increasing in frequency as we go to higher energies. Therefore, we may close the hypothesis of exotic type of interactions of increasing rate with energy.

The remaining is the possibility of exotic primary particles. There is no strong reason to believe that the primary particles are only known nuclei. In astrophysics, we may find a new circumstances where other kinds of particles or nuclei can be stable. The implications and study in this direction will be made elsewhere.

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according to original classification, and showers are concentrated mainly within $R \sim 1.5$ cm.

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Appendix

A Attenuation and collision mean free path of hadrons

A.1 Collision mean free path

Let us define the position of the first maximum in the development of the shower transition curve as Δt_1 . This distribution is shown in Fig. 13. In ideal case the point of the first maximum in shower transition curve is determined by collision mean free path of hadrons²⁴.

To study profile of hadron shower curve, we use detection threshold $E_{th} = 10$ TeV, for first interaction. The distribution of starting points Δt_1 of hadrons in lead chamber can be expressed as: $dN/d\Delta t_1 \sim N_0 \exp(-\Delta t_1/\lambda_{meas})$. From the slope of the curve we can estimate the measured collision length of cosmic ray hadrons as λ_{meas} which is proportional to the collision mean free path²⁵. Thus, λ_{col} in our experiment is $(160 \pm 30) \text{ g/cm}^2$.

A.2 Attenuation mean free path of hadrons

Change of the number of nucleons with depths follows the exponential decrease, different from the collision mean free path. As it has been shown above the exponential tail of the average shower transition curve expressed by average darkness $\langle D \rangle$ in the range of large values of shower starting points $\Delta t \geq 10$ c.u. is due to the attenuation of cosmic ray hadrons in lead.

The attenuation mean free path shows the change of the number of hadrons above certain energy threshold at different depths in the chamber. The attenuation mean free path is equal to the distance at which intensity of hadrons of the same power spectrum decreases in e times.

The attenuation mean free path is always greater than collision mean free path.

In the basis of all methods for determination of attenuation of hadrons there is a simple relation $N_X = N_0 \exp(-X/\lambda_{att})$ between the incident number of particles N_0 at the top of the material with thickness X and the number N_X after passage of the material.

Based on this relation one can determine the attenuation length from relation λ_{att} : $\ln(N_0/N_X) = X/\lambda_{att}$.

A.3 Attenuation of hadrons in lead

Following the above considerations, the simplest way to estimate the attenuation length in experiment with X-ray Pb chamber would be to count the number of hadron shower spots above certain threshold of darkness D_{th} at two depths in the chamber separated with enough thickness of material.

In case of lead chamber with many X-ray films for shower detection our task is easier, because in this case we construct the distribution of number of showers spots detected at every layer²⁶.

In our experiment we have two categories of showers - single showers and family showers. Applying the same procedure - counting the number of shower spots at every layer for single

²⁴ Collision mean free path is a distance which hadron travels without interactions.

²⁵ $\lambda_{meas}/\lambda_{col} = 1.16$ for incident family hadrons with power index $s = 1.2$ and $\lambda_{meas}/\lambda_{col} = 1.19$ for hadrons with power index $s = 2.0$ [42]

²⁶ This procedure is similar to our construction of average shower transition curve.

and family showers, we can see the difference, if it exists, in attenuation behaviour between two groups of showers.

Fig.14 illustrates the situation. The correction has been made for the arrival zenith angle θ , so attenuation can be expressed in cascade units.

A.4 Attenuation of hadrons in air

In this case the atmosphere works as a target and X-ray chamber detector is used for determination of the energy of particles. If one knows the intensity of hadrons (nucleons) at the top of the atmosphere $N_0(E, 0)$, the atmosphere thickness at the level of the detector x , and the intensity of observed hadrons $N(E, x)$, one can determine Λ and σ from equation $\Lambda = 1/\sigma n = \ln(N_x/N_0)$.

The arrival zenith angle (θ) distribution of cosmic ray hadrons detected in X-ray chamber can be approximated as [17],[14]:

$$N = h(\leq \cos(\theta)) = N(\theta = 0)(2\pi/m)\cos(\theta)^m, \quad (1)$$

where $m = t/\Lambda + 2$, and t is the atmospheric depth (for Pamir it is 594 g/cm^2).

The slope of the curve fit gives the attenuation length of hadrons in the atmosphere $\Lambda = 105 \pm 7 \text{ g/cm}^2$. This result is in agreement with previous analysis of MSU experimental data [5] $\Lambda = 105 \pm 5 \text{ g/cm}^2$.

A.5 Attenuation and collision mean free paths of hadrons in heterogeneous chamber

A big gamma-hadron family Tajikistan with total energy of showers $\Sigma E_{tot} \sim 50000 \text{ TeV}$ was detected in the deep carbon X-ray emulsion chamber exposed at Pamirs [24]. Because of the large number of hadrons, this event is particularly suitable to discuss the issue of hadron interactions with carbon and lead materials.

We present details on chamber structure, statistics of observed showers and numerical parameters used for calculation in Tables 3-4.

The total number of hadrons with $E_{th} = 10 \text{ TeV}$ observed at the top of the hadron block H2 is 95. Among these hadrons 20 has continuation and observed after block H2. Also there are 36 new hadrons that are detected in block H2. Two hadrons are observed from the top until the bottom of the chamber. We have the following equation: $\exp(-T/\lambda_{att}) = 58/97$. Substituting $T = 1.39 \lambda_{col}$, we get $\lambda_{att} = (2.70 \pm 0.55) \lambda_{col}$.

B Analytical expression of attenuation mean free path

We express the attenuation mean free path by

$$\exp \left[-\frac{\mu}{\lambda_N} t \right]$$

where

$$\mu_N(s) = 1 - \langle (1 - K)^s \rangle \text{ for nucleon, and}$$

$$\mu_\pi(s) = \xi [1 - (1 - b) \langle (1 - K)^s \rangle - \phi(s)] \text{ for pion}$$

(0) We assume that

$$\xi \equiv \frac{\lambda_\pi}{\lambda_N} = \frac{1}{1.1}$$

(1) Inelasticity

We assume that the total inelasticity is distributed uniformly between $-1 < K < 2$ and 1. That is,

$$g(K)dK = \frac{dK}{2(1 - \langle K \rangle)}$$

by which the average value of the inelasticity is $\langle K \rangle$.

$$\begin{aligned} \langle (1 - K)^s \rangle &\equiv \int_{-1}^1 (1 - K)^s g(K) dK \\ &= \frac{[2(1 - \langle K \rangle)]^s}{s + 1} \end{aligned}$$

(2) Pion production

We assume the energy spectrum of *charged* produced pions is given by [41]

$$\begin{aligned} \varphi(E_0, E)dE &\equiv \varphi(x)dx = Da \frac{(1 - a'x)^4}{x} dx \\ (x &= \frac{E}{E_0}, D = \frac{5}{3}) \end{aligned}$$

We know that $a = a' = 1$ at low energies (the scaling function). $a > 1$ and $a' > 1$ indicate the scaling violation.

(3) Charge exchange of the surviving pion

There is a channel that the incident charged pion becomes the surviving neutral pion after the collision. The process is important because the charged pion disappears after the collision. We assume the probability is b .

(4) Ratio of collision mean free path and attenuation mean free path.

Taking into account the above considerations and described parameters we can plot the ratio of collision mean free path and attenuation mean free path as a function of power energy spectrum of incident hadrons. Fig.15 shows the result of comparison of analytical calculations for different values of inelasticity, $\langle K \rangle = 0.5$ and $\langle K \rangle = -0.75$, and several parameters $b = 0.3$, $a = 1, 3, 5$, with experiment. Open circles with dots show data on Waseda-MSU family and single showers, solid circle - hadrons from Tajikistan family (power index of spectrum is $s = 1.1 \pm 0.1$).

C Dimensional analysis on atmospheric diffusion problems

The cosmic ray family is a product of development of nuclear and electromagnetic cascades in the atmosphere initiated by arrival of a primary cosmic ray particle. This problem can be formulated and solved in analytical way [17], applying the formalism on diffusion problems. But the results can be valid only on the average behaviour of families, and individual families are full of fluctuations particularly in the nuclear cascade.

Let us take a proton with energy E_0 and consider a family produced at atmospheric depth t . We are looking for a number of hadrons, $f_h(E, t)dE$, and gamma-rays $f_\gamma(E, t)dE$ with energy $(E, E + dE)$.

When a common property of f_h and f_γ is discussed, we will simply write it down as $f(E, t)$. In this type of formalism we can approximate the solution as $f(E, t)dE = A \exp(-t/\lambda_{att}(s))(E_0/E)^s dE/E$, where s is called "age of cascade".

The result of stochastic process of development of nuclear electromagnetic cascade in the atmosphere follows exponential attenuation and power spectrum.

A is a slowly varying function of E_0, E , and t . The attenuation mean free path λ_{att} is a function of age s , which can be calculated under the assumed simple model ²⁷.

C.1 Lateral spread of hadrons in a family

The three dimensional diffusion is a complicated problem which is beyond the scope of present paper. The distribution of product of energy E ²⁸ and distance R , $z = \ln(ER)$, can be approximately expressed by Gaussian function,

$$\psi(z)dz = \frac{1}{(\sqrt{2\pi}\sigma)} \exp\left(-\frac{(z - z_0)^2}{2\sigma^2}\right),$$

where $z_0 = \langle \ln ER \rangle$. This expression is shown in Fig.16 together with experimental data on hadrons.

Let us express the energy spectrum of hadrons as $dN_h/dE \sim (E/E_{th})^{-(s+1)}$, where E_{th} is the detection threshold. Assuming constant transverse momentum ER and taking into account that $\ln(ER)$ follows to Gaussian distribution, we have expression for dN_h/dR as :

$$dN/dR \sim \frac{1}{R} \left(\frac{E_{th}R}{\exp(z_0 - s\sigma^2/2)} \right)^s \sim R^{(s-1)}$$

where power spectrum index $s = 1.2$, and σ and $z_0 = \langle \ln E_h^{(\gamma)} R \rangle$ can be taken from Fig. 16.

C.2 Lateral energy density flow

The lateral distribution of energy flow ρ_E in a family (Fig. 10) is expressed as :

$$\frac{\langle E \rangle (dN/dR)}{2\pi R},$$

where $2\pi R$ is perimeter, and $\langle E \rangle$ is the average energy. Thus, taking into account that $E \sim 1/R$, we have $\rho_E \sim R^{(s-3)}$. Because of the energy threshold, there is a deviation from this law at large distances ²⁹.

²⁷ Analytical calculations assume scaling in particle production, inelasticity $\langle K \rangle \sim 0.5$, and the similar collision mean free path for nucleons and pions.

²⁸ $E = E_h^{(\gamma)}$

²⁹ The radius threshold value $R_{th} \sim z_0/\exp((s\sigma^2)/2)/E_{th}$

C.3 Correlation of the number of hadrons and total energy of family

We can write down the following relation between the number of hadrons N_h and measured hadron energy E as $N_h \sim (E)^{-s}$, where $s = 1.2$. In terms of incident hadron energy E_0 the expression is $N_h \sim (E_0/E)^s$, thus $N_h \sim (E_0)^s$.

The relation between total family energy ΣE_{tot} and primary particle energy E_0 is the following: $\Sigma E_{tot} \sim (E_0)^\beta$. In the energy interval under consideration $\beta \sim 1.5$ as can be seen from ³⁰ Fig. 17.

Thus, $N_h \sim (E_0)^s \sim (\Sigma E_{tot})^{s(1/\beta)}$, with $s/\beta = 1.2/1.5 = 0.8$, and we get the relation between the number of hadrons N_h and the total energy of family ΣE_{tot} presented in Fig. 11.

C.4 Family energy spectrum

If primary particle spectrum has a power index α and expressed as $E_0^{-\alpha}$, then measured spectrum of families would be $N_{fam} \sim ((\Sigma E_{tot})^{1/\beta})^{-\alpha}$. Then, with $\beta = 1.5$, and $\alpha = 1.8$ we get $N_{fam} \sim (\Sigma E_{tot})^{-1.2}$.

Taking into account the relation between energy of gamma rays in a family ΣE_γ and total family energy ΣE_{tot} presented in Fig. 17, we can obtain the power index of family spectrum as $\sim 1.25 \pm 0.10$ in Fig. 12. This result is in agreement with experimentally measured slope of ΣE_γ family spectrum [2].

D Primary spectrum

There are several approximations of primary cosmic ray spectra [28], [43] that take into account results of direct measurements [9], [11], [13]. Approximation of primary cosmic ray spectrum from [28] is expressed as:

$I(> E) = 8.04(10^{-4})(E/0.1)^{-1.70}[B_p(1 + 610^{-4}E)^{-0.4} + \Sigma_A B_A(E/0.1)^{(\Delta(\gamma))_A}](1 + 0.01A^{-1}E)^{-4}cm^2sec^{-1}str^{-1}$, where $B_p = 0.41, B_4 = 0.22, B_{26} = 0.14, B_{51} = 0.10$, and $\Delta(\gamma)_p = 0.$, for $A = 1, 4, 15, 26, 51$ - $\Delta(\gamma)_4 = 0.0, \Delta(\gamma)_{15} = 0.04, \Delta(\gamma)_{26} = 0.04, \Delta(\gamma)_{51} = 0.04$. Power indexes of helium and proton spectra are 1.7, and other nuclei spectra have spectrum power indexes 1.66 before the "knee". After 1.6 PeV there is 0.4 increase of power spectrum of protons. Change of power spectra of nuclei happens at energy 100 TeV/nucleon. To get an impression of different approximations we show the result in Fig. 18 and Fig. 19 in comparison with direct and indirect measurements. Spectrum of all nucleons is obtained from all particle spectrum in assumption that nucleons are packed in nucleus and interact independently.

³⁰ The accumulation effect of gamma ray component related to the creation of halo at higher energies also can be deduced from this figure.

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
Thickness (cm Pb)	60	60	60	60

Table 2 Experimental statistics on families and hadrons in Waseda-MSU experiment

Family	Experiment ($m^2 year$) chamber type	Flux
$100 \leq \Sigma E_\gamma \leq 500$ 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	
$\Sigma E_\gamma \geq 100$ 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	
Hadron flux $\times 10^{-10}$	MSU (30)	(1.8 ± 0.2)
$cm^2 sec^{-1} str^{-1}$	Pb 110 cm	
$E_{th} = 6.3$ TeV	Waseda-MSU (57)	(1.8 ± 0.2)
(single and family)	Pb 60 cm	

Table 3 Structure of the three storeyed carbon-Pb X-ray chamber

Item	Thickness cm	Thickness m.f.p	X-ray films
Upper Carbon block	5.0	0.08	
Gamma (Γ) block Pb	6.0	0.43	2
Hadron (H1) Carbon block	60.0	0.96	
Hadron (H1) Pb block	6.0	0.43	2
Hadron (H2) Carbon block	60.0	0.96	
Hadron (H2) Pb block	6.0	0.43	3

Table 4 Summary on shower observation in Tajikistan family.

X denotes the place of hadron identification. (Collision m.f.p. in Carbon 62.5 cm.
Collision m.f.p. in Pb 14.0 cm.)

Shower identification	Spot detection	Number of showers ($E \geq 10$ TeV)
	Γ H1 H2	
γ	X - -	293
hadron	X X -	28
hadron	X X X	2
hadron	- X -	75
hadron	- X X	20
hadron	- - X	36
Total	- - -	454

Fig. 1 Schematic view of the determination of the shower starting point Δt in the Pb X-ray chamber. Δt_1 is a shift of the first shower maximum D_{max-1} from the theoretical average curve of gamma ray. Δt_{max} is a shift of the shower maximum D_{max} from the theoretical average curve of gamma ray.

Fig. 2 The differential energy spectra of gamma rays and hadrons in a family $100 \text{ TeV} \leq \Sigma E_\gamma \leq 400 \text{ TeV}$ with $E_{th} = 4 \text{ TeV}$. Marks are: open circles (gamma rays) and squares (hadrons) in Waseda-MSU experiment, solid circles and squares - gamma rays and hadrons from MSU experiment.

Fig. 3 The average shower transition curve over all observed single (open circles) and family (closed circles) showers with $E_{th} = 4 \text{ TeV}$.

Fig. 4 The differential energy spectra of single hadrons (solid circles) and hadrons in families $\Sigma E_{tot} \geq 50$ TeV (open circles with dots) in Waseda-MSU experiment.

Fig. 5 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. 6 The distribution of hadron energy fraction $Q_h = \Sigma E_h^{(\gamma)} / (\Sigma E_\gamma + \Sigma E_h^{(\gamma)})$ inside a family of $100 \leq \Sigma E_{tot} \leq 1000$ TeV. Marks are: open circles - experiment, solid line - simulation with $\langle k_\gamma \rangle = 0.15$, dash line - simulation with $\langle k_\gamma \rangle = 0.27$.

Fig. 7 The 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. 8 The 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.

Fig. 9 The 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).

Fig. 10 The lateral distribution of energy flow density of showers ($E_{th} = 4$ TeV) in families. Marks are: open circles - family of $100 \leq \Sigma E_{tot} \leq 1000$ TeV (Waseda-MSU), closed circles - $1000 \leq \Sigma E_{tot} \leq 7000$ TeV (MSU), squares - family Tajikistan, upward triangles with dots - $100 \leq \Sigma E_{tot} \leq 1000$ TeV (Chacaltaya), downward triangles - $1000 \leq \Sigma E_{tot} \leq 5000$ TeV (Chacaltaya). Solid lines - proton simulation (a) - $\langle \Sigma E_{tot} \rangle = 200000$ TeV, b) - $\langle \Sigma E_{tot} \rangle = 30000$ TeV, c) - $\langle \Sigma E_{tot} \rangle = 3000$ TeV, d) - $\langle \Sigma E_{tot} \rangle = 250$ TeV.

Fig. 11 Correlation of number of hadrons N_h in the region $10 \text{ mm} \leq R \leq 100 \text{ mm}$ from the family center, and total family energy ΣE_{tot} with $E_{th} = 4 \text{ TeV}$ in simulation and experiment. Marks are: open circles - Waseda-MSU, closed circles - MSU, circle with A - family Andromeda [25], circle with F - family FIANIT [27], circle with T - family Tajikistan, dots - proton, squares - Fe, open triangles - CNO, rhombuses - Mg. The line *a*) represents function $\sim A \times (E/A)^{0.8}$ for $A=1$, and the line *b*) the same for $A = 56$.

Fig. 12 The integral spectra of the gamma ray energy of a family ΣE_γ and primary flux. Open circles with dots represent Waseda-MSU experiment (families $50 \text{ TeV} \leq \Sigma E_\gamma \leq 1000 \text{ TeV}$ of $57 \text{ m}^2 \text{ year}$ exposure), Pamir experiment (of $\Sigma E_\gamma \geq 1000 \text{ TeV}$ of $\sim 500 \text{ m}^2 \text{ year}$ exposure) and high energy families from Pamir experiment FIANIT and Tajikistan ($\sim 5000 \text{ m}^2 \text{ year}$ exposure). The solid line shows the primary flux of cosmic rays.

Fig. 13 The distribution of Δt_1 (a shift of the first shower maximum D_{max-1}) for single (closed circles) and family (open circles) showers in Waseda-MSU experiment.

Fig. 14 The distribution of number of shower N_s spots with $D \geq 0.1$ detected in X-ray films at every depth in the chamber (t is expressed in cascade units). This procedure is similar to our construction of the average shower transition curve $\langle D \rangle$. Marks are: single showers (closed circles) and family showers (open circles).

Fig. 15 The ratio of collision mean free path and attenuation mean free path $\lambda_{col}/\lambda_{att}$ as a function of hadron incident spectrum s in experiment and analytical calculations for different values of inelasticity, $\langle K \rangle = 0.75$ (lines a), b), c), d)) and $\langle K \rangle = 0.50$ (lines e), f), g), h)). Marks are: open circles with dots - Waseda-MSU family and single showers, solid circle - hadron from Tajikistan family. The solid lines a) and e) are for nucleons. The dot-dash lines d) and h) - pions ($a = 1$, scaling), the dot lines c) and g) - pions ($a = 2$, scaling violation), and the dash lines b) and f) - pions ($a = 5$, scaling violation). In calculations charge exchange is assumed to be $b = 0.3$.

Fig. 16 The distribution of $\ln(E_h^{(\gamma)} R)$ in families $100 \text{ TeV} \leq \Sigma E_{tot} \leq 1000 \text{ TeV}$ from Waseda-MSU experiment. Solid line shows Gaussian function.

Fig. 17 The relation between observed family energy ΣE_{fam} and primary particle energy E_0 . Marks are: solid line - family energy of hadrons ΣE_{tot} , dash line - family energy of gamma rays, and dot line - total energy of family ΣE_{tot} .

Fig. 18 The proton and helium summary spectra from direct (stars - JACEE [9], closed circles - RUNJOB [10], open squares - MUBEE [11], closed squares - Ryan spectrum[44]) and indirect (triangles - CASA-BLANKA [45], rombuses - HEGRA [46], open circles - review from [47] experiments in comparison with approximations by [43] - solid line (1), and by [28] - dashed line (2).

Fig. 19 The spectrum of all nucleons. Marks are: open squares - JACEE experiment, closed squares - MUBEE experiment, solid curve - approximation from [43], dash line - from [28]

Fig. 1

Fig. 2

Fig. 3

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Fig.18

Fig. 19