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Energy Distributions of Hadrons Registered in the Pamir Experiment and Mass Composition of Primary Cosmic Rays below the "Knee"

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The energy spectra of hadrons registered in carbon emulsion chambers have been obtained from the Pamir experimental data. The hadrons energy spectra from the Pamir and the other experiments have been compared.

The calculations simulating propagation of primary cosmic ray particles through the atmosphere to the mountain level have been made using CORSIKA program with QGSJET model. The comparison of the experimental data with the calculated spectra enables to state that primary cosmic ray for energies from 10^{13} eV up to $5 \cdot 10^{15}$ eV have light mass composition.

In the energy interval over 10^{15} eV primary cosmic ray have the following mass composition: over 50% of light nuclei (about 30% p and over 20% He) and about 14% Fe. Average logarithm of mass number $\langle \ln A \rangle$ varies from 1.57 for $E_o = 10^{13}$ eV up to 1.85 for $E_o = 5\ 10^{15}$ eV.

1. Experimental Data

The distributions of the energy of hadrons registered in the carbon emulsion chambers of the Pamir experiment at the altitude of 4300 m a.s.l. (600 g/cm^2) have been received. The results have been published in papers [1–3]. Presented distributions have been made for 7136 registered hadrons, among which 2539 particles with the energies of over $E_h > 17$ TeV. Having taken high energy hadrons, i.e. 109 particles, into account in the experimental data, the low energy part has been calculated with the corresponding weights. The number of hadrons with the energies of $E_h > 17$ TeV calculated with the statistical weights is 4855. The received energy distribution can be described with the following function:

$$\frac{dN}{dE_h} = \left(3.30 \begin{matrix} +0.46 \\ -0.40 \end{matrix}\right) \cdot 10^{-3} \left(\frac{E_h}{1TeV}\right)^{-3.23 \pm 0.04} \qquad \frac{1}{m^2 \cdot s \cdot sr \cdot TeV}$$

2. The Comparison with Other Experiments

Received results have been compared with the energy distribution of hadrons registered in the Pb chambers of the Pamir experiment [4, 5], Figure 1. This distribution was estimated in the interval of 20 – 300 TeV.

Taking the number of hadrons creating these distributions into account – over 2500 in C and around 800 from Pb chambers – the error values (not marked in the figure) are greater than the errors of the hadron distribution registered in the carbon chambers. The differences between the hadron distributions received for the data from different types of the chambers are within the limits of statistical errors. The energy distribution from the Pb chambers for $E_h > 100$ TeV is situated systematically above the points of the distribution from the carbon chambers but within the limits of statistical errors. Moreover, the number of particles in this part of the distribution is small.

Presented comparison shows the internal coherence of the data received from the C and Pb emulsion chambers of the Pamir experiment.

This result has been compared with the ones received in the ionization calorimeter of the Thien Shan and EAS – TOP experiments, which are situated in the mountains at the altitudes of 680 g/cm^2 and 820 g/cm^2 respectively [6–8]. These results are presented in Figure 2 for the various altitudes in the atmosphere (600 g/cm^2 – the Pamir experiment) without any recalculations of their intensity. It means that the streams of hadrons should be moved to each other by the value resulting from the average absorption length of the hadrons in the Earth atmosphere, presented in papers [2, 9].

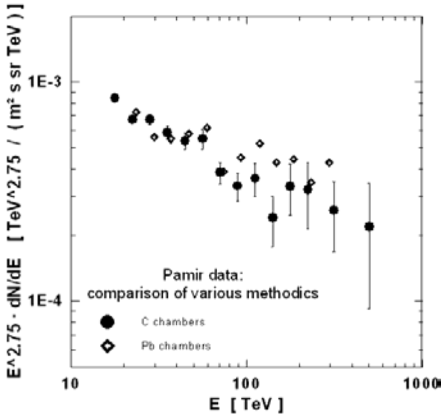

Figure 1. Comparison of the Energy Distributions Registered in C- and Pb-chambers of the Pamir Experiment

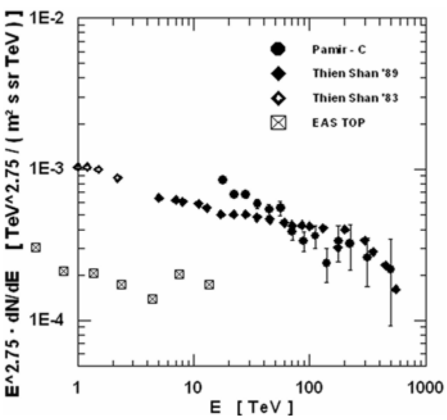

Figure 2. Comparison of the Energy Distributions Registered in C-chambers of the Pamir Experiment and in the Thien Shan and EAS – TOP Calorimeters

The data from the Thien Shan experiment is situated above the Pamir data for the energies 50 TeV and more. This effect is explained by the authors themselves [7] as one having methodical reasons.

The energy distribution was also compared with the data of the EAS-TOP calorimeter [8], presented in Figure 2. Experimental data of the Pamir experiment after recalculation to the level of 820 g/cm^2 for the average absorption length of the hadrons in the atmosphere ~104 g/cm^2 [9], has intensity about twice as high as data from the EAS – TOP experiment.

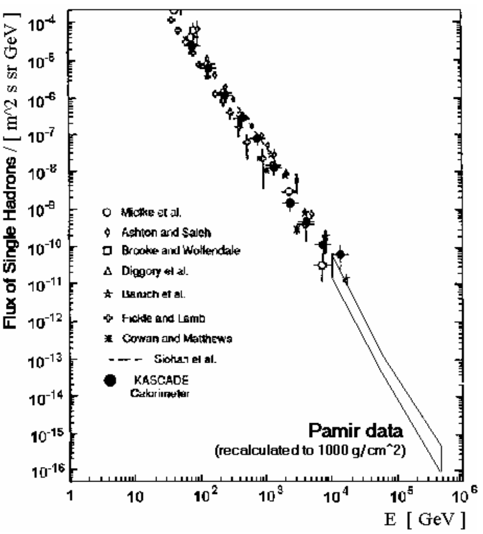

Figure 3. Comparison of the energy distributions registered in C-chambers of the Pamir experiment and in the KASCADE calorimeter

The comparison of the energy distribution of hadrons registered in the KASCADE calorimeter and the carbon chambers are presented in Figure 3. This comparison was presented in paper [1]. The intensities from the Pamir experiment were recalculated to the depth of 1000 g/cm^2 in the Earth atmosphere, what corresponds to the location of the KASCADE experiment. The comparison of this data is presented in the original figure from paper [10]. This comparison suggests a very good correspondence of both distributions.

2. Calculations and Analysis

The calculations using CORSIKA program and QGSJET model [11] have been made to be able to draw conclusions about primary spectrum, from which hadrons observed in the experiment come. As shown in papers [3, 9] these calculations enabled to find answers to the following question. How much the intensity of secondary hadrons at the Pamir level decreases in comparison with the intensity of primary spectrum for the assumed primary composition and particles with which primary energy give the observed spectrum of secondary particles.

Calculations have been made for five different primary nuclei (H, He, N, Si, Fe). The simulations cover the energy range of 10^{13} eV – 10^{17} eV with slope $\gamma_H = 2.68$, $\gamma_{He} = 2.62$, $\gamma_N = 2.60$, $\gamma_{Si} = 2.60$ and $\gamma_{Fe} = 2.60$. Spectra of all particles above the "knee" have slopes = 3.2. Table 1 gives percentage of different nuclei in the mass composition taken to the simulation for chosen E_0.

Table 1. Percentage Fraction of Nuclei in Primary Cosmic Ray Assumed for Calculations for Two Exemplary Energies E_0 of Primary Particles

E_0 / Assumption	10^{13} eV	$3 \cdot 10^{15}$ eV
light mass composition	40% p, 21% He 14% N, 13% Si, 12% Fe	31% p, 23% He 17% N, 16% Si, 14% Fe
changeable mass composition (mutable)	40% p, 21% He 14% N, 13% Si, 12% Fe	13% p, 10% He 7% N, 7% Si, 62% Fe
heavy mass composition	20% p, 10% He 10% N, 10% Si, 50% Fe	14% p, 10% He 11% N, 11% Si, 54% Fe

The energies of primary particles, E_0, and secondary particles at registration level created by them, E_{sec}, are known from calculations. An energy distribution of particles which come from primary particles from selected E_0 interval has been made. Further, an energy E_{sec} distribution for all primary particles has been made. The ratio of the number of secondary particles from the distribution for chosen E_0 interval to the number of secondary hadrons from the distribution for all E_0 (later as 'Eff') has been estimated for particular E_{sec} intervals. The value of Eff ratio estimated in such way informs, what part of secondary particles at registration level comes from primary spectrum from taken E_0 interval (see Table 2). It can be seen that hadrons observed at the mountain altitude come from PCR particles with energies 10 TeV – 5 PeV.

Table 2. What Part of Secondary Hadrons Comes from PCR Particles with Selected E_0 Range for Chosen E_{sec} (Eff)

E_{sec} [TeV] / Eff, for E_0	50	125	316	501
< 1 PeV	0.61	0.45	0.24	0.34
> 1 PeV	0.39	0.55	0.76	0.66
< 3 PeV	0.83	0.76	0.59	0.48
> 3 PeV	0.17	0.24	0.41	0.52

As shown in paper [9], all primary protons contribute to the hadron spectrum observed at the mountain level. Primary Fe nuclei must have energies at least 1 PeV so that the hadrons with the energies of tens of TeV appear in the observed spectrum. A strong decrease of number of protons in the primary spectrum for the energies of PeV and an increase in the Fe nuclei must result in a significant intensity decrease of hadrons observed at the mountain level already from the energy of 10 TeV, what can be seen in Figure 4.

3. Conclusions

Experimental data and data from calculations are shown in Figure 4. Black dots represent results of the Pamir experiment. The lines show distributions received from the calculations for different assumptions. Intensities of primary cosmic ray registered in various experiments conducted above the Earth atmosphere differ from each other by up to 50%, when primary spectrum assumed in the calculations was related to the given verge values, what can be seen in Figure 4 as two different curves representing the same mass composition. Black solid curves are the distributions of energy of hadrons produced by primary spectrum with light composition. The results received with the assumption that the mass composition changes from light to very heavy, marked as 'changeable' or 'mutable' composition, are illustrated with green, broken lines. The results for heavy mass composition for all energies E_0 have been marked with red, dotted lines in Figure 4.

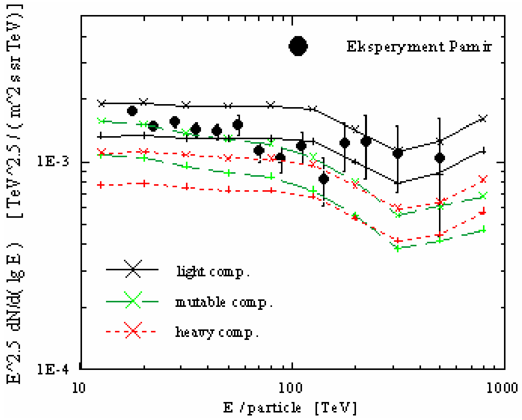

Figure 4. Energy Distributions of Hadrons Registered in the Pamir Experiment (black dots) and Energy Distributions Received from the Calculations (lines)

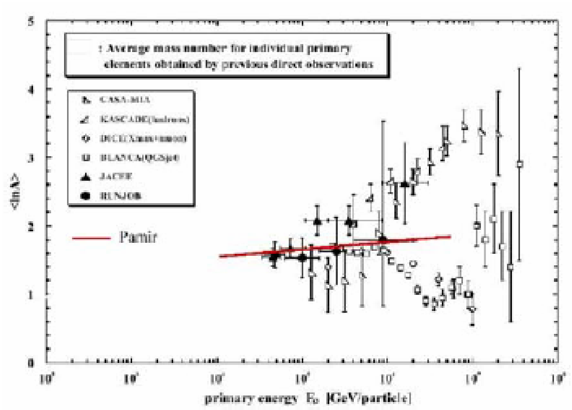

Figure 5. Average Values ln(A) for Mass Composition of Primary Cosmic Ray Received in Various Experiments. Solid red line shows the result of the Pamir experiment described in this paper

It can be seen that experimental data is inside the area limited by the lines obtained for light mass composition. It can be concluded that light mass composition goes up to the so called "knee" i.e. $3 - 5 \cdot 10^{15}$ eV.

In the energy interval above 10^{15} eV primary cosmic ray has the following mass composition: over 50% of light nuclei (about 30% p and over 20% He) and about 14% Fe. Average logarithm of mass number <lnA> varies from 1.57 for $E_0 = 10^{13}$ eV up to 1.85 for $E_0 = 5 \cdot 10^{15}$ eV. Figure 5 presents the values of average logarithm of the mass number of the primary cosmic ray nuclei for several experiments and for C-chambers presented in this paper. Figure 5 has been copied from paper [12].

4. References

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