# Mass Composition of Primary Cosmic Ray below the "Knee" Deduced from Analysis of Energy Distribution of Hadrons Registered in the Pamir Experiment

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**Abstract**

Energy spectra of hadrons registered in carbon emulsion chambers have been obtained from the Pamir experimental data. Calculations simulating propagation of primary cosmic ray particles through the atmosphere to the mountain level have been done with the use of the CORSIKA program with QGSJET model.

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 above $10^{15}\,eV$ 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 $< lnA >$ varies from 1.57 for $E_o = 10^{13}\,eV$ up to 1.85 for $E_o = 5 \cdot 10^{15}\,eV$.

## 1. Experimental Data

Distributions of energy of hadrons registered in 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 the papers [1]. This data has a very good statistical background ($N(E_h > 17.7\,TeV) = 2275$). Received the experimental distribution were described by the power law function (results in $[m^{-2}s^{-1}sr^{-1}]$):

$$I(> E_h) = (2.79 \pm 0.06 \pm 0.85) \cdot 10^{-6} \cdot \left(\frac{E_h}{17.7TeV}\right)^{-2.01 \pm 0.04} \qquad (1)$$

The results are in accordance with energy distribution of hadrons registered in the Pb-chambers of the Pamir experiment and with the results of other experiments which has been shown in paper [2].

pp. 135–138 

## 2. Calculations and Analysis

The calculations using CORSIKA program and QGSJet model have been done [3, 4] to be able to draw conclusions about primary spectrum, from which hadrons observed in the experiment come. As shown in paper [3] these calculations enabled to find answers to the following questions. How much the intensity of secondary hadrons at the Pamir level decreases in comparison with intensity of primary spectrum for the assumed primary composition and particles with what primary energy give the observed spectrum of secondary particles.

**Table 1.** Percentage fraction of nuclei in primary cosmic ray assumed for calculations for two exemplary energies $E_o$ of primary particles.

| $E_o$ / Assumptions | $10^{13}\,eV$ | $3 \cdot 10^{15}\,eV$ |
|---|---|---|
| light mass composition | 40 % p, 21 % He<br>14 % N, 13 % Si, 12 % Fe | 31 % p, 23 % He<br>17 % N, 16 % Si, 14 % Fe |
| heavy mass composition | 20 % p, 10 % He<br>10 % N, 10 % Si, 50 % Fe | 14 % p, 10 % He<br>11 % N, 11 % Si, 54 % Fe |
| mutable mass composition | 40 % p, 21 % He<br>14 % N, 13 % Si, 12 % Fe | 13 % p, 10 % He<br>7 % N, 7 % Si, 62 % Fe |

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

Results received for pure mass composition assumed in the calculations 100% of p or 100% of Fe show the tendencies in the changes of spectrum observed at the mountain level with participation of light and heavy nuclei in primary cosmic ray composition. Results of these calculations are shown in the Figure 1 - left and have been presented in paper [3].

Experimental data and data from calculations are shown in Figure 1. Distribution of energies of hadrons registered in the Pamir experiment, data from experiments registering particles of primary cosmic ray above the atmosphere - satellite data Proton and Sokol and balloon data JACEE and RUNJOB are also shown. The lines in the figures represent results of simulations. In the upper part of the left figure the lines show primary spectrum assumed for calculations (they are related to indirect experimental data for $E_o = 10\,TeV$). In the lower part of the figure (at the mountain level) spectra of hadrons at the Pamir level received from simulations with assumptions described earlier.

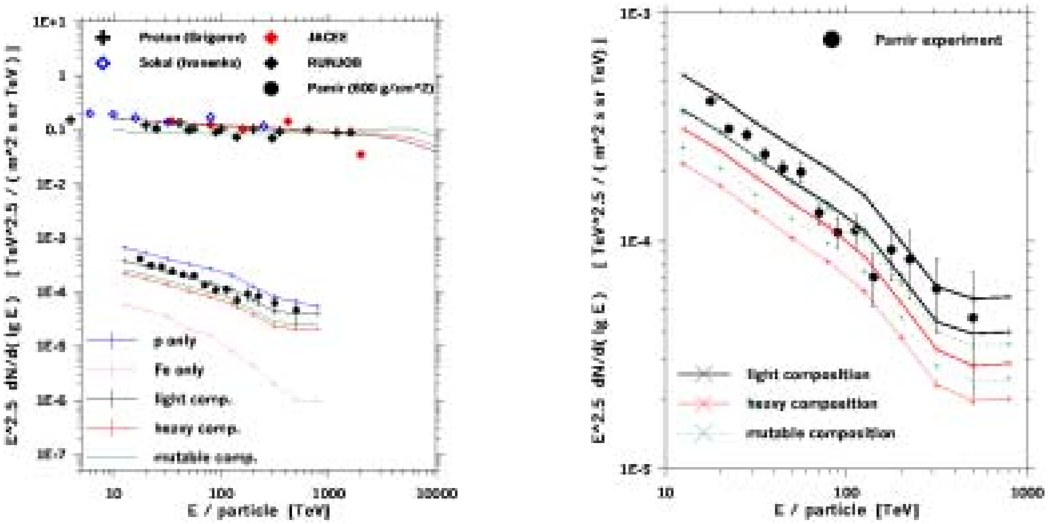


**Fig. 1.** Energy distributions of primary cosmic ray particles (symbols) and hadrons registered in the Pamir experiment (black dots) and energy distributions received from the calculations (lines).

Figure 1 - right presents more precisely results from the lower part of the left one. Black dots represent results of the Pamir experiment. The lines show distributions received from calculations for different assumptions. Because intensities of primary cosmic ray registered in various experiments conducted above Earth atmosphere differ from each other up to 50 %, primary spectrum assumed in calculations was related to given verge values. It can be seen in Figure 1 - right as two different curves representing the same mass composition taken for calculations.

Black solid curves are distributions of energy of hadrons produced by primary spectrum with light composition. It can be seen that experimental data is inside the area limited by lines obtained for light mass composition. $E_h$ distributions for heavy mass compositions of primary comic ray, red in the figure, are below experimental data in the distance larger than the spectrum estimation error. It means that primary cosmic ray with light mass composition is responsible for the spectrum observed at the mountain level. Results received with the assumption the mass composition changes from light to very heavy, mutable composition, are illustrated by green lines. Part of energy distribution in interval $E_h$ from 60 to 150 $TeV$ is not consistent with others. Data from this part of distribution goes beyond the area representing light composition and places itself between the areas of light and heavy composition (good estimated by mutable).

The question is, for which energies $E_o$ of primary comic ray presented conclusions about light mass composition are binding. In the paper [3] it has been shown that primary particles with energies $E_o > 1\,PeV$ produce about 40 % of secondary hadrons observed at the Pamir level with energies $E_h \sim 50\,TeV$, 55 % - with $E_h \sim 100\,TeV$ and 75 % - with $E_h \sim 300\,TeV$. It can be concluded that light mass composition goes up to so called "knee" i.e. $(3 \div 5) \cdot 10^{15}\,eV$.

It can be expected that observed irregularity for spectrum of registered hadrons with $E_h$ from 50 to 150 TeV will give the picture of subtle structure of primary comic ray for $E_o$ hundreds TeV after the close analysis. We can expect that this area of primary comic ray is richer in iron.

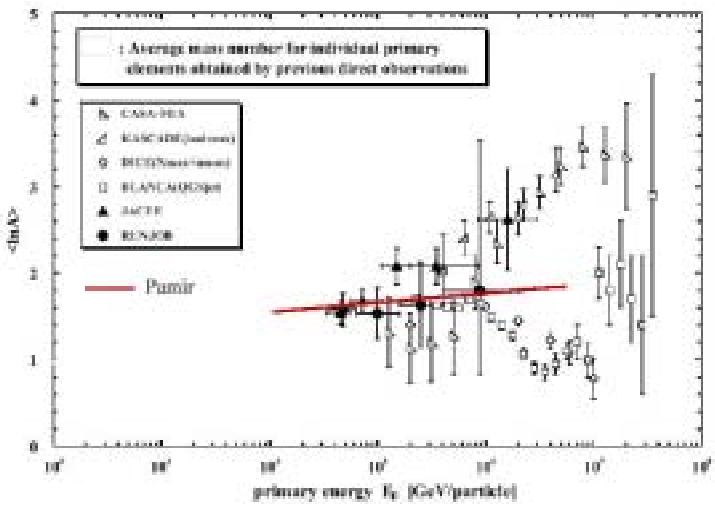


**Fig. 2.** Average values ln(A) for mass composition of primary cosmic ray received in various experiments. Solid red line shows the result of the Pamir experiment received and described in this paper. (This figure has been copied from the paper [6]).

## 3. Conclusions

Comparison of energy distributions of hadrons registered in the Pamir experiment with the results of calculations allow to conclude that primary cosmic ray for energy $E_o$ from $E_o = 10^{13}\,eV$ to $E_o = 5{\cdot}10^{15}\,eV$ has light mass composition.

In the energy interval above $10^{15}\,eV$ 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 $< lnA >$ varies from 1.57 for $E_o = 10^{13}\,eV$ up to 1.85 for $E_o = 5 \cdot 10^{15}\,eV$.

## 4. References


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