Estimation of depth of maximum by relative muon content in air showers with energy greater than 5 EeV measured by the Yakutsk array

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Abstract

Characteristics of muons with a threshold $\varepsilon_{thr} \geq 1$ GeV based on the air showers data in Yakutsk array were analyzed. Quantitative estimation of muons at different distance from the shower axis and the ratio of muon and charged particles at a distance of 600 m are obtained. An empirical relationship between the fraction of muons and longitudinal development – the depth of maximum development X_{max} is found. Calculations of the muon fraction are performed using the QGSjetII-04 for different primary nuclei, and compared with experiment. Mass composition of primary particles induced air showers of highest energies is estimated from the muon component.

Experimental data on muon component of air showers

Over 20 years of continuous observations, 1995-2015, more than 10^6 EAS events with data on the muon component and energies greater than $5\cdot10^{16}$ eV were recorded at the Yakutsk array. For the analysis, 802 showers with energies $E_0 \geq 5\cdot10^{18}$ eV and zenith angles $\theta \leq 60°$ were selected. 25 % of data consist of air showers with energies greater than 10^{19} eV. The sample of showers was formed according to the following criteria: showers' axes lie within a circle with a radius of 1000 m from the center of the array; there are measurements of muons in the range of distances of 300-800 m; The accuracy of determining the axis in showers was (10-20) m along the x_0 axis, and (15-25) m along the y_0 axis. The accuracy of determining the density of charged particles and muons at a distance of 600 m was ~ (10-15)%. In this case, approximately all data had the same conditions for the registration and accuracy of the main characteristics of the EAS. By measuring the flux of charged particles and muons, the classification parameters $\rho_{\mu+e}$ and were determined.

Air shower energy E_0 was determined by muons flux density ρ_μ according to equation (1).

$$\log_{10} E_0 = 18.33 + 1.12 \cdot \log_{10}(\rho_\mu(R = 600, \theta)) \qquad (1)$$

Estimation of the depth of maximum by muon component.

In individual showers, where the EAS Cherenkov light and muons were measured, the parameters ρ_μ, $\rho_{\mu+e}$, and X_{max} were found. Further, the correlation of the parameter $\rho_\mu(600) / \rho_{\mu+e}(600)$ and X_{max} was built for three zenith angles (Fig. 1). The figure also shows calculation based on the model Calculations based on the model QGSJetII-04 are also presented there for zenith angles <θ> = 18°, <θ> = 32° and <θ> = 58°.

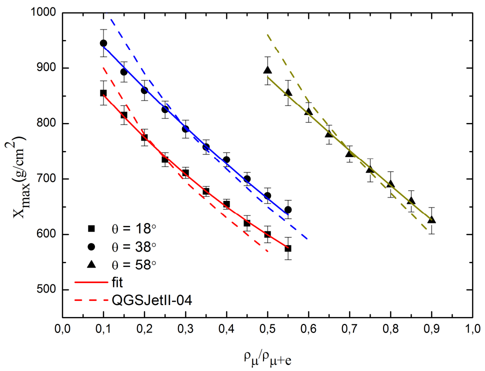

Fig. 1. Correlation of electromagnetic cascade depth of maximum with muon fraction $\rho_\mu(600) / \rho_{\mu+e}(600)$ at the distance 600 m from the air shower axis. Dashed lines are hadronic interaction model QGSjetII-04 for zenith angles <θ> = 18°, <θ> = 38° and <θ> = 58° respectively.

Fig. 1 show that model calculations, within the experimental errors, agree with the experimental data for the corresponding zenith angles. Using the data shown in Fig. 1 and the exponential function, an empirical relationship was established between $\rho_\mu / \rho_{\mu+e}(600)$ and X_{max} (2).

$$X_{max} = A_1 \cdot \left(-\frac{\rho_\mu / \rho_{\mu+e}}{t_1} \right) + y_0 \qquad (2)$$

Coefficients A_1, t_1 and y_0 were determined in the course of data approximation by function (2). As follows from the analysis, the coefficients in equation (2) depend only on the length of the muon track in the atmosphere. The generalized formula connecting X_{max} with the ratio $\rho_\mu(600) / \rho_{\mu+e}(600)$ is expressed as:

$$X_{max} = \left(535 + 2887\cdot(\sec\theta - 1)\right)\cdot \exp\left(-\left(\frac{\rho_\mu(600)}{\rho_{\mu+e}(600)}\right)_\theta / (0.521 + 3.980\cdot(\sec\theta - 1)) \right) + \left(386 - 2524(\sec\theta - 1)\right) \qquad (3)$$

Equation (3) was used for X_{max} estimation in individual showers by measured muon component.

Dependence of X_{max} from E. Estimation of mass composition.

Using a sample of showers with energies above 5 EeV and data on the muon component, in each shower, the fraction of muons at a distance of 600 m from the shower axis was determined and, using formula (3), the depth of the EAS development maximum X_{max} was determined. The data were divided into several energy intervals and the average $\langle X_{max} \rangle$ was determined. The results are shown in Figure 2, as red triangles. Since only some of the showers with muons were considered, the result obtained can be regarded as preliminary. For comparison, Fig. 2 shows the data of the Yakutsk setup for other components: surface detectors, EAS Cherenkov light and radio emission. In addition, the figure shows the data of the Auger, Telescope array, and LOFAR experiments and model calculations QGSJETII-04, Sibyll 2.3c, EPOS-LHC. The results of all experiments within the measurement errors are in a good agreement with each other and reflect the uneven X_{max} change with increasing energy.

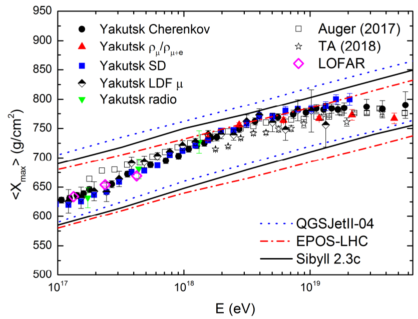

Fig. 2
Dependence of air shower depth of maximum on energy. It shows results of small and large air shower experiments. Lines show hadronic model calculations for proton and iron nuclei.

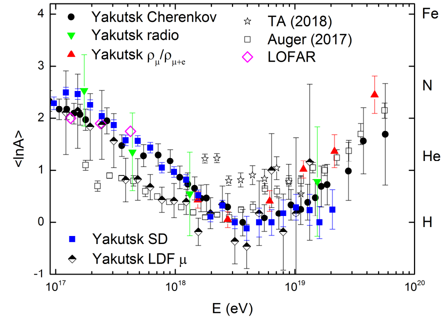

Fig. 3
Mass composition of cosmic rays with ultra-high energies.

Estimation of cosmic rays mass composition <lnA> was performed by interpolation (4).

$$\langle lnA \rangle = \frac{X^{exp}_{max} - X^{p}_{max}}{X^{Fe}_{max} - X^{p}_{max}} \cdot lnA_{Fe} \qquad (4)$$

Yakutsk array results on <lnA> are obtained by four components of air showers (Fig. 3). It can be seen from the figure that in energy region 5 EeV value of <lnA> is starting to increase, which indicates heavier mass composition. In Fig. 3 for comparison other experiments Telescope Array, Auger, and LOFAR are shown. It can be seen that the results of the Telescope Array and Auger arrays according to X_{max} coincide with the results of the Yakutsk installation in the region $E_0 \geq 5$ EeV, including the results obtained for muons. The uncertainty associated with uncertainty of the real model of the development of extensive air showers (by the example of muons), as can be seen from Fig. 3, cannot influence the conclusion about an increase in heavy nuclei in the cosmic ray flux, starting with energies of 10 EeV.

Conclusion

Based on the results obtained from the analysis of the fraction of muons in this work, and the results of other experiments, it can be concluded that the composition of cosmic rays consists of protons and nuclei with low atomic weight in the energy range of 5-10 EeV (Fig. 3). For energies above 30 EeV, the mass composition of cosmic rays begins to change towards heavier elements - CNO and iron nuclei.

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