A Relation Between Charged Particles and Muons With Threshold Energy 1 GeV in Extensive Air Showers Registered at the Yakutsk EAS Array

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Characteristics of muon component in EAS are analyzed together with their fluctuations. The aim of this analysis — a comparison of experimental data with computational results obtained within frameworks of various hadron interaction models for protons and iron nuclei and estimation of cosmic ray mass composition in the ultra-high energy region.

I. INTRODUCTION

The Yakutsk complex array for many years measures three main observables of extensive air showers (EAS): total charged component, muons with $\varepsilon_{\rm thr} \geq 1$ GeV and Cherenkov light [1]. Using these data we estimated the EAS energy with model independent quasi-calorimetric method [2] and determined the depth of maximum shower development (by measured Cherenkov light lateral distribution, using the parameter $p = \lg Q(200)/Q(550)$ and by the shape of Cherenkov light pulse, $\tau_{1/2}$) [3, 4]. Relative muon content at different core distances was measured [5, 6] and cosmic ray (CR) mass composition was estimated by various EAS characteristics [7–9].

In this paper we analyze muon component of EAS: mean characteristics, muon content and its fluctuations at fixed energy. The analysis is conducted within the framework of QGSJet II [10] and EPOS [11] hadron interaction models involving computations for primary particles of different masses using CORSIKA-6.900 code [12].

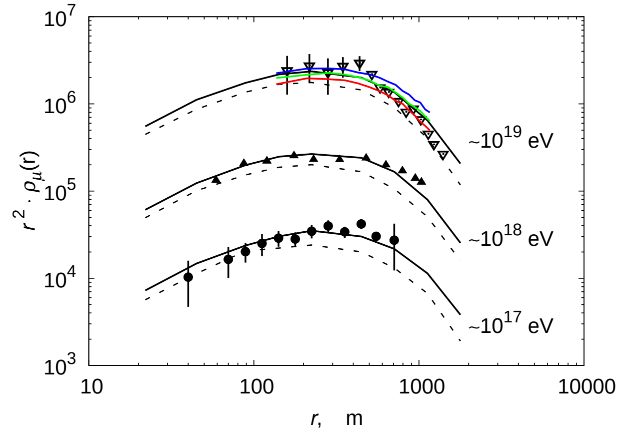

FIG. 1. Lateral distribution of charged particles for fixed energy values $10^{17}, 10^{28}, 10^{19}$ eV and zenith angle $\theta = 15°$. Symbols refer to the Yakutsk experiment. Solid lines denote computational results with QGSJet+FLUKA [13] for protons, dotted line — for iron, red line — EPOS+UrQMD [14] for proton, green — carbon, blue — iron.

II. MUON LATERAL DISTRIBUTION FUNCTION

On Figure 1 an example of mean lateral distributions for muons at different energies are displayed. Muon lateral distribution function (LDF) is significantly lower then that of charged component and can be effectively measured in individual events at $E_0 \geq 10^{17}$ eV within the core distance range $100 - 800$ m. Thus, as a classification parameter in this energy region, a parameter $\rho_\mu(600)$ could be used — the density of muon flux at 600 m from shower core.

Solid and dotted lines on the figure denote computational results obtained with QGSJet(UrQMD) models for proton (solid) and iron (dotted). It's seen from the Figure 1 that muon LDF from proton is more steep than one from iron nucleus and this difference is especially pronounced at large core distances. Qualitative comparison of computational results with the experiment reveals a better agreement with a heavier component of primary CR at $E_0 \leq 10^{18}$ eV and with lighter at $E_0 \sim 10^{19}$ eV. This feature could be stressed out if one puts parameter $r^2 \cdot \rho(r)$ on the y-axis of a plot instead of simple $\rho(r)$.

III. MUON PORTION AND ITS DEPENDENCE ON ANGLE, ENERGY AND THE DEPTH OF MAXIMUM EAS DEVELOPMENT

We considered the dependence of $\rho_\mu/\rho_{\rm ch}$ on the length of shower development after the maximum — $\Delta\lambda = x_0/\cos\theta - x_{\max}$. In highly inclined showers muon content increases proportionally to $x_0/\cos\theta$ value, where $x_0 = 1020$ g/cm^{2}for Yakutsk.

It is known fact that the depth of maximum EAS development differs significantly, depending on the kind of primary particle and, hence, this feature could be used in the analysis of the CR mass composition. For instance, by fixating the $\Delta\lambda$ parameter and studying the fluctuations of $\rho_\mu/\rho_{\rm ch}$ value. This technique is rather similar to one proposed by Atrashkevich et al [15].

Shower parameters calculated with CORSIKA code were modified by applying distortions according to experimental errors. Parameters measured in experiment (e.g. $\cos\theta, x_{\max}, \rho_{\rm ch}(r), \rho_\mu(r)$) for every shower were rolled with the normal distribution with σ parameter according to the experiment:

$$\sigma(\theta) = 3 \cdot \sec\theta;$$
$$\sigma(x_{\max}) = 40 \mathrm{g/cm}^2;$$
$$\sigma(\rho_r) = \sqrt{\rho_r^2 \cdot \left(0.025 + \frac{1.2}{s_{\rm det} \cdot \rho_r \cdot \cos\theta}\right)}$$

where $s_{\rm det}$ is area of the detector.

Figure 2 shows dependence of $\rho_\mu/\rho_{\rm ch}$ on the length of cascade development after the shower maximum compared with computational results. A strong correlation is observed between the muon content and the length of track in the atmosphere after the shower maximum. It is also seen that experimental data are in a good agreement with simulation results.

IV. MEAN CHARACTERISTICS

Figure 3 shows the energy dependence of $\rho_\mu(600)$ obtained in Yakutsk and MIA EAS experiments [16]. A good agreement is observed between the two.

Computational results obtained with EPOS and QGSJet01 from the work by Abu-Zayyad et al [16] are denoted with lines, dotted line represent our simulations with QGSJet II for protons and iron nuclei. A comparison of our computations with the results obtained by Abu-Zayyad et al [16] reveals that virtually there is no any difference between QGSJet01 and QGSJet II. A significant discrepancy is observed between EPOS and QGSJet II and it, as we see it, is associated with different amounts of muons generated by models. For example, $\rho_\mu(600)$ value calculated with EPOS for proton coincides with $\rho_\mu(600)$ obtained with QGSJet II for iron. Thus, a comparison of experimental data with model calculations result in controversial conclusions on CR mass composition. According to EPOS, at energies up to 2×10^{17} eV CRs consist of iron nuclei and above that energy, up to 10^{19} eV — of protons. In the energy interval $10^{17} - 3 \times 10^{18}$ eV QGSJet II computations agree with the experiment quite well if primary particles are iron nuclei and above 3×10^{18} eV the mass composition might be mixed with portion of protons and helium nuclei not less than $50 - 60\,\%$. More precise estimation of CR mass composition could be derived after improvement of theoretical models and selecting one, that describes experimental EAS data better then others.

V. FLUCTUATIONS OF $\rho_\mu/\rho_{\rm ch}$ RELATION ON THE GROUND LEVEL AT THE ENERGY $\sim 10^{18}$ EV

Showers initiated by different nuclei have differing altitudes of the maximum which in turn means that different numbers of muons are generated in these showers. It also means that they cover different paths in the atmosphere. By analyzing the tracks of muons that they pass in the atmosphere after the maximum of shower development we can try to estimate the composition of cosmic rays. With this aim in view, by choosing the mean zenith angle 36° (which corresponds to the track length after the maximum $\Delta\lambda = 500$ g/cm^2), let's normalize the values of muon content to this level and consider their fluctuations.

Results are presented on Figure 4. There are also shown the computational results obtained with QGSJet II and EPOS models for various nuclei. Measured values of fluctuations are presented in Table I. Obtained results have shown that within this method fluctuations of $\rho_\mu(600)/\rho_{\rm ch}(600)$ parameters don't allow to estimate the CR mass composition. However, mean values from different nuclei differ. Besides, QGSJet II hintnerats a heavier composition than that of EPOS: according to first one, the composition of selected showers shifts towards heavier nuclei; according to second one, showers correspond to nuclei of intermediate group. On the whole, both models argue for mixed composition.

However, if one takes into account gamma-photons generated in ground covering muon detectors, the mean value of $\rho_\mu(600)/\rho_{\rm ch}(600)$ relation decreases and composition shifts towards lighter nuclei (protons-helium-carbon) [18].

VI. CONCLUSIONS

Within the framework of QGSJet II and EPOS hadron interaction models using the CORSIKA code the values of muon portion $\rho_\mu/\rho_{\rm ch}$ at core distance $r = 600$ m were obtained. A relation between the muon portion and a distance to the depth of shower maximum $\Delta\lambda$ was also obtained. A comparison of the dependency with the experiment has shown that with account of experimental errors in the simulation data, a good agreement is observed between simulation and experiment.

A comparison of the muon portion distribution with computational results points towards mixed cosmic ray composition near $E_0 \geq 10^{18}$ eV. Large fluctuations of the muon portion prevent revealing of a single determined group of nuclei. A more detailed analysis is required, involving possible systematics of muon density measurement in the Yakutsk experiment.

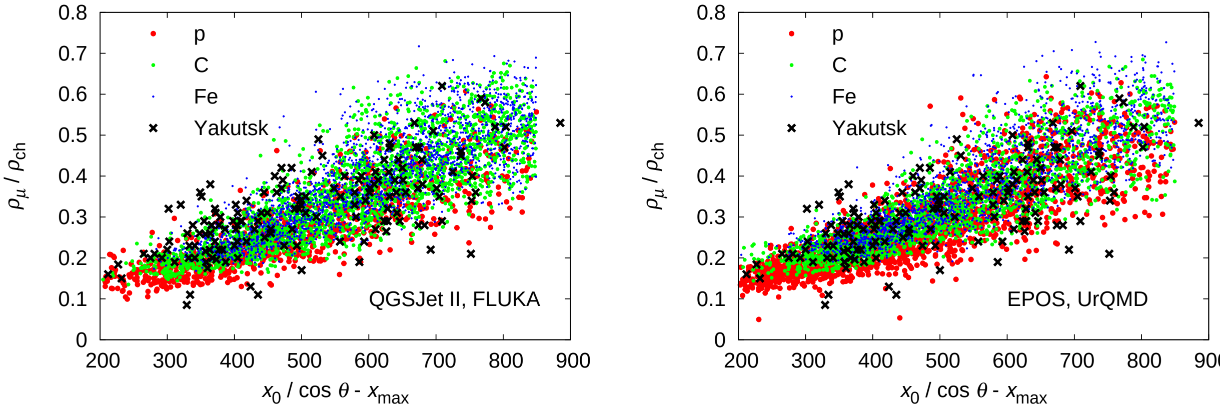

FIG. 2. A dependence of muon portion with $\varepsilon_{\rm thr} \geq 1$ GeV on the length of track in the atmosphere for individual showers with $\theta = 0 - 50^{\circ}$ and energy 10^{18} eV. On the left — results obtained with QGSJet II model, on the right — with EPOS model.

TABLE I. Fluctuations of $\rho_\mu/\rho_{\rm ch}$ relation, normalized to the length of track 500 g/cm^2

			QGSJet II, FLUKA			EPOS, UrQMD		
	Yakutsk	Yakutsk[a]	p	C	Fe	p	C	Fe
$\langle\rho_\mu/\rho_{\rm ch}\rangle$	0.3145	0.2768	0.2687	0.3025	0.3193	0.2893	0.3170	0.3381
σ	0.0747	0.0657	0.0517	0.0541	0.0536	0.0563	0.0511	0.0539

[a] With respect to contribution from gammas generated in the shielding of detector (Dedenko, 2010)

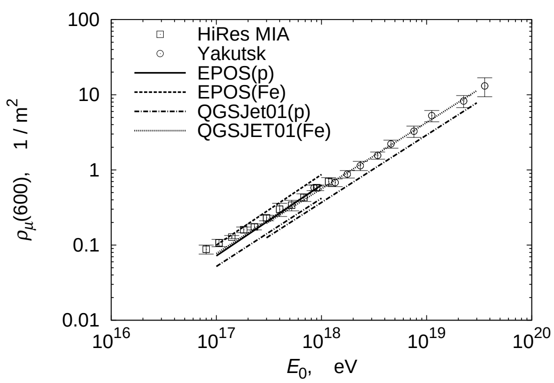

FIG. 3. Muon density $\rho_\mu(600)$ measured in Yakutsk experiment as a function of primary energy compared to model calculations.

ACKNOWLEDGMENTS

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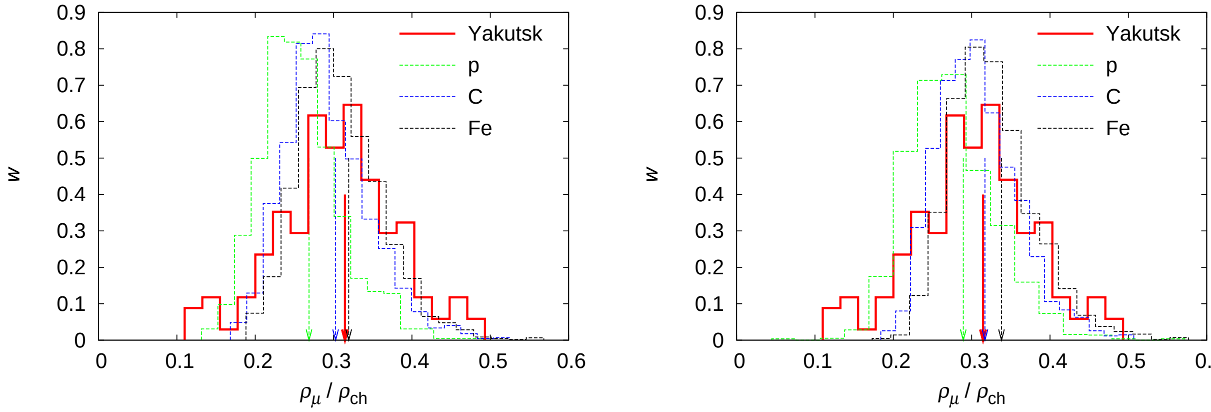

FIG. 4. A distribution of the ρ_μ/ρ_{ch} relation, normalized to the track length 500 g/cm^2. On the left — according to models QGSJet II(FLUKA), on the right — according to EPOS(UrQMD).

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