Estimation of CR mass composition in the energy range from 10^{17} to 10^{19} eV using multi-component analysis of EAS parameters measured with the Yakutsk array

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***Abstract*— Longitudinal and radial development parameters of extensive air showers measured with charged particle and air Cherenkov light detectors of the Yakutsk array are presented. To estimate the average mass composition of the primary particles, the two-dimensional spread of shower parameters is analyzed in comparison with cascade simulations using CORSIKA/QGSjet code. As a result, three fractions of the primary nuclei groups are estimated with the reconstruction error below 30% in the energy range $E_0 \in (10^{17}, 10^{19})$ eV.**

I. Introduction

Cosmic ray (CR) mass composition in ultra-high energy region remains unknown because of still insufficient event number of extensive air showers (EAS) detected. Several attempts have been made to determine the mean CR mass using measurements of the depth of shower maximum, $X_{\max}(E)$, or the muon content at the observation level, as a function of energy [1]. At present, there is some consensus for a composition becoming as if proton dominated around 10^{19} eV.

In order to improve the informativeness of data, other methods were proposed, mostly combining two or more shower parameters for multi-component analysis of the dataset [2]–[7]. For example, in papers [6], [7] a method was offered to evaluate the average mass composition using a combination of EAS parameters - $X_{\max}$ and the density of electrons and muons at the distance 600 m from a shower core, ρ_{600}.

This method allows to reliably distinguish showers initiated by primary protons and iron nuclei analyzing a distribution of the event rate on the plane $(X_{\max}, \rho_{600})$ supposed to be similar to that given by CORSIKA/QGSjet simulations.

Our aim here is to apply this method to the data of the Yakutsk array, namely $X_{\max}$ and ρ_{600} distribution in the energy range $E_0 \in (10^{17}, 10^{19})$ eV, in order to estimate the fractions of nuclei divided into three groups in the primary beam.

II. Method of analysis

In this work two-dimensional probability distributions of two experimental observables ($X_{\max}$ and ρ_{600}) are used. According to the procedure suggested in [7] normalized variables τ and ρ have been introduced instead of $X_{\max}$ and ρ_{600}:

$$\tau = \frac{X_{\max}}{\sigma(X_{\max})} - \left\langle \frac{X_{\max}}{\sigma(X_{\max})} \right\rangle \quad (1)$$
$$\rho = \frac{\lg \rho_{600}}{\sigma(\lg \rho_{600})} - \left\langle \frac{\lg \rho_{600}}{\sigma(\lg \rho_{600})} \right\rangle,$$

where σ denotes standard deviations and brackets mean the averaging.

Experimental data of the Yakutsk array are compared to the distributions obtained using CORSIKA code v. 6.0 employing QGSjet hadronic interaction model. We have generated 1500 artificial showers of fixed primary particle energies ($10^{17}, 10^{18}, 10^{19}$ eV) initiated by five type of nuclei: p, He, C, Si, Fe. For each of considered energy and kind of the primary nucleus two dimensional distributions of showers $f(\tau, \rho)$ were analysed.

As it was shown in [7], it is possible to distinguish zones on the (τ, ρ) plane, which allows to clearly separate showers initiated by light $(\mathrm{p} + \mathrm{He})$, medium (C) and heavy $(\mathrm{Si} + \mathrm{Fe})$ nuclei. This method was subjected to validation by simulation of experimental procedure of primary mass reconstruction assuming different models of composition. The error in reconstruction of light, medium and heavy nuclei fractions does not exceed 30% at $E_0 \in (10^{17}, 10^{19})$ eV.

III. Data analysis and discussion

Experimental data of the Yakutsk array are used to derive the $X_{\max}$ and ρ_{600}. Charged particle density at 600 m is an immediate output of our scintillation detectors while $X_{\max}$ is reconstructed basing on air Cherenkov light measurements [8].

In order to minimize systematic uncertainties the following data selection criteria were applied: i) shower axes are within the array area; at $E_0 < 10^{18}$ eV an additional cut was

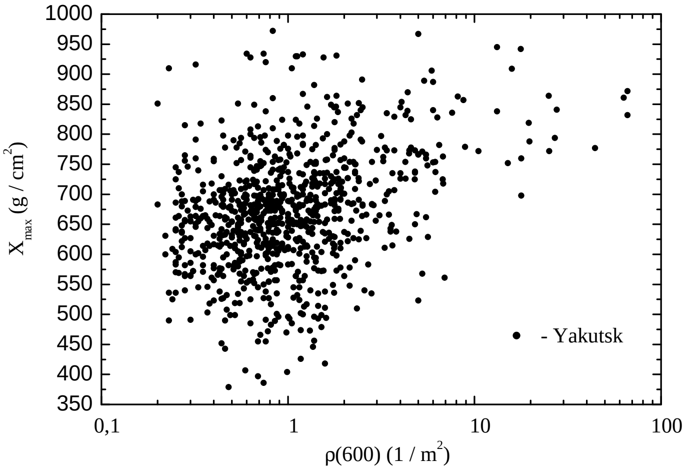

Fig. 1. A distribution of the depth of shower maximum, $X_{\max}$, and the charged particle density at 600 m from the shower core, ρ_{600}, observed at the Yakutsk array.

applied for showers with axes close to the array periphery; ii) shower detection efficiency is greater than 0.9; iii) zenith angle doesn't exceed the Cherenkov light detector aperture; iv) light extinction in atmosphere is less than 0.41 at $\lambda = 420$ nm. As a result, 587 showers with primary energy above 10^{17} eV observed during the period of 1993-2005 were selected.

In Fig. 1 the two-dimensional distribution of showers in the plane ($X_{\max}, \rho_{600}$) is shown. Here $X_{\max}$ characterizes a maximum depth of individual showers and ρ_{600} is the density of particles at the observation level. One can see from Fig. 1 that there is some obvious correlation between the shower maximum and the charged particle density.

According to the analysis of probability distributions $f(\tau, \rho)$ reconstructed using the simulated showers database [7], we roughly divide the final spot by two lines m_1 and m_2 into three zones corresponding to primary particle type at fixed primary energy. In the first and third zones light ($\mathrm{p + He}$) and heavy ($\mathrm{Si + Fe}$) nuclei initiated showers respectively are well separated from each other with the probability $\sim 90\%$. In the medium zone showers initiated by different nuclei are strongly intermixed. Our calculations [7] based on different assumptions about primary composition show that in medium zone the fraction of carbon-initiated showers is $\sim 50\%$.

Fig. 2 presents the results of multi-component analysis of (τ, ρ) distribution derived from the Yakutsk array data. The analysis was carried out in three energy bins with average energies 2.4×10^{17} eV, 9.8×10^{17} eV and 4.8×10^{18} eV. Lines represent borders of the above mentioned zones. Namely, line m_1 is dividing light and medium nuclei initiated showers, and m_2 is between medium and heavy nuclei zones. As it is seen from Fig. 2, the points are spread over zones non-uniformly. The main part is located in the first and the second zones. In percentage, the zone-2 sample is twice larger than that of zone-1.

We assume that carbon nuclei are responsible for a half of all events in the second zone. Significant contribution to this

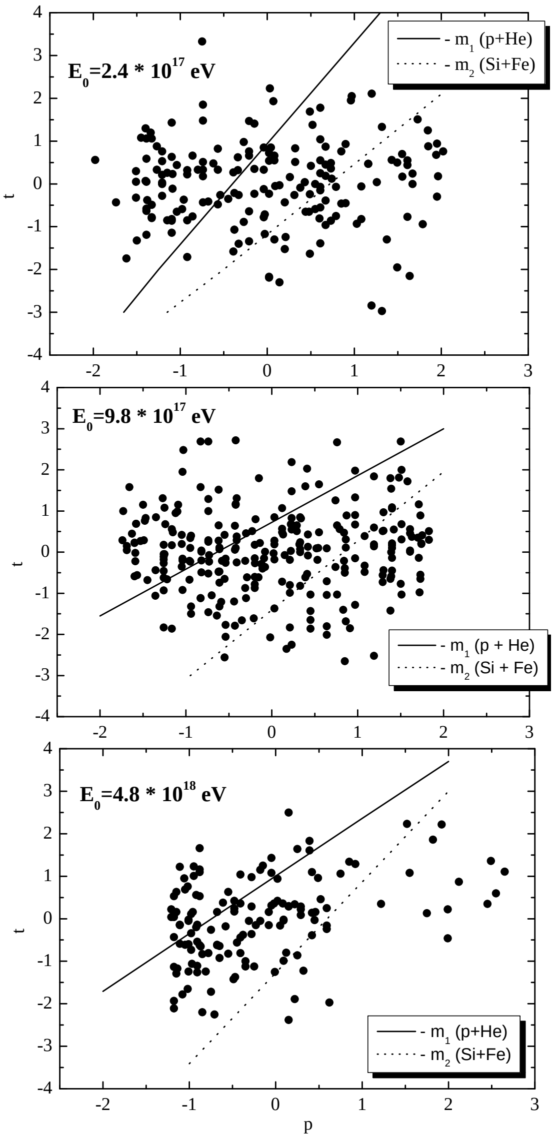

Fig. 2. Normalized experimental data (τ, ρ) in different energy bins. m_1 is a borderline between light and medium nuclei initiated shower groups ($\mathrm{p + He}$ and C), while m_2 is a borderline between medium and heavy nuclei groups (C and $\mathrm{Si + Fe}$). Average energies are indicated for each energy bin.

zone is made by nuclei of the first group (up to 30%) and by nuclei from the third group ($\sim 15\%$). The remaining part of the set ($16 - 27\%$) falls into the zone-3 where the heavy nuclei (silicon and iron) induced showers are concentrated.

In the Table 1 the shower samples are given in the energy bins and three zones. In the last column the average logarithm of the primary nuclei mass is given. The fraction of light nuclei increases from 50% to 53%, and a fraction of medium nuclei is increasing with energy from 23% to 31%. At the same time, the fraction of heavy nuclei decreases from 27% to 16% in the primary CR flux. These changes result in the average composition, $\langle \ln A \rangle$, changing from a heavy to lighter mix as the energy increases, as it is seen from the last column.

All these conclusions are inferred under the necessary condition of similarity of observed and simulated distributions

TABLE I

EAS EVENT NUMBER

$\langle E_0 \rangle$, eV	n	Light	Medium	Heavy	$\langle \ln A \rangle$
$2.4 \cdot 10^{17}$	177	$89/0.50$	$40/0.23$	$48/0.27$	2.05 ± 0.61
$9.8 \cdot 10^{17}$	266	$133/0.50$	$70/0.26$	$63/0.24$	1.95 ± 0.59
$4.8 \cdot 10^{18}$	144	$77/0.53$	$44/0.31$	$23/0.16$	1.68 ± 0.50

in the (τ, ρ) plane. The recognition error of the nuclei groups in the whole energy range $E_0 \in (10^{17}, 10^{19})$ eV does not exceed 30% in this case.

The results obtained here using multi-component analysis of $X_{\max}$ and ρ_{600} distribution are in qualitative agreement with our previous conclusion (derived by other methods) concerning the fraction of protons and helium nuclei in the primary beam increasing with energy [5], [9]–[11].

The further improvement of this technique could be implemented as suggested in [12], [13] involving in multi-component analysis another observables sensitive to primary mass, for example, mean square radius of lateral distribution of electrons/charged particles or some other parameter. This will be the subject of our forthcoming publication.

ACKNOWLEDGMENT

This work is partially supported by RFBR (grants #06-02-16973, #05-08-50045 and NSh-#7514.2002.2) and INTAS (grant #03-51-5112).

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