Estimation of the mass composition of ultra-high energy cosmic rays by muon fraction in extensive air showers

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Abstract: The signals from particles of extensive air showers in the energy region of $10^{17} - 10^{20}$ eV in both the surface and underground scintillation detectors of the Yakutsk array are calculated using the CORSIKA 6.616 and GEANT4 software packages and compared with experimental data. It is shown that a transition from a heavy primary composition to proton primaries at energies $(1 - 2.6) \times 10^{18}$ eV and from primary protons again to heavy primaries at energies above 1.3×10^{19} eV might be observed.

Keywords: Extensive air showers, CR mass composition

1 Introduction

Studying the chemical composition of primary cosmic radiation (PCR) in the region of ultrahigh energies is of extraordinary interest. In the case of the protonic composition of PCR at energies above $\sim 3 \times 10^{19}$ eV, a steep reduction in the PCR particle flux due to interactions of primary protons with photons of the microwave relic radiation (the GZK effect) was predicted by Greisen [1] and Zatsepin and Kuz'min [2]. In the model of uniformly distributed sources with a power law spectrum of generation, the proton flux must first decrease (dip), then increase (bump) and drop steeply (the GZK effect) [3, 4]. In the case of a heavy nuclear (e.g., iron) composition of PCR particles, the flux reduction (if it takes place) cannot be explained by the GZK effect, and we must find other reasons for it (e.g., the value of the maximum energy E_{max} of particle generation in sources could be low).

In the work [5], the two scenarios of the resulting energy spectrum generation are considered. In the first scenario, the galactic component produced by supernovae remnants dominates up to 10^{17} eV and in the region $10^{17} - 10^{18}$ eV a transition from galactic to extragalactic components occurs. In the second scenario, the extragalactic component dominates at energies above 10^{19} eV and the extragalactic component is produced by supernovae remnants up to the energy 3×10^{18} eV.

The mass composition expected in these two scenario's significantly differs: in the first case, the mean logarithm of the CR atomic number $\langle \ln A \rangle$ at $10^{17} - 10^{‘18}$ eV abruptly drops from the value $\langle \ln A \rangle = 2.5$ to $\langle \ln A \rangle = 1$. Hence, the reliable experimental determination of the CR mass composition in energy region $10^{16} - 10^{19}$ eV would enable finding the transitional region between galactic and extragalactic components in the CR spectrum.

Investigations of the chemical composition of PCR particles in the region of ultrahigh energies are at present possible generally on the basis of the dependencies of either the depth x_{max} of the maximum of an extensive air shower (EAS) or the fraction of muons on the energy E of the shower. The role of decay processes in cascade development in the atmosphere declines with an increase in particle energy, so some EAS parameter associated with muons (e.g., the muon density $\rho_{mu}(600)$ with energy E_μ above some threshold $E_{\text{thr.}}$ at a distance of 600 m from the shower axis) depends on energy E of the primary particle:

$$\rho_\mu(600) = a \cdot E^b, \tag{1}$$

where a and b are constants, and $b < 1$. This means that within the bounds of the superposition hypothesis [6], an additional factor A^{1-b} appears for a primary nucleus with the atomic number A in the analogous dependence. In the case of the exact accounting of nucleus-nucleus interactions, the exponent c in the dependence A^c can differ from $(1 - b)$, but the inequality $c > 0$ will still hold true. This means that the magnitude of the muon density $\rho_\mu(600)$ for primary nuclei will exceed the analogous magnitude for primary protons at the same energy E of the PCR particle.

In this work, the results from calculating the fraction of muons in an EAS for primary protons and iron nuclei are compared with data from the Yakutsk array (YaA), and conclusions on the possible composition of PCR particles in the energy region $10^{17} - 3 \times 10^{19}$ eV are drawn.

2 Calculation technique

Calculations of individual EAS development in the atmosphere were performed using the CORSIKA 6.616 package [7] within the bounds of the QGSJET II [8] and Gheisha 2002 [9] models with the thinning parameter $\epsilon = 10^{-8}$. The GEANT4 package [10] was used to estimate the signals from EAS particles in YaA surface and underground scintillation detectors. In the case of underground detectors, the propagation of EAS particles falling to the soil from the atmosphere and through a stratum of soil that varied from 2.3 to 3.2 m for different detectors, was considered using this package. The chemical composition and specific weight of the soil were taken into account. For vertical showers at the distance 600 m from axes (within the ring with radii 550 m and 650 m) mean densities of muons $\rho_{mu}(600)$ with the threshold energy above 1 GeV and muon energy spectra within $0.3 - 100$ GeV were calculated with the use of CORSIKA 6.616 code for primary protons in energy range $10^{17} - 10^{20}$ eV. The dependence of signal $s(600)$ in surface detectors on energy E of the shower can be approximated by the formula [11]

$$s(600) = \Delta E E(3 \times 10^{17} \text{ eV}), \tag{2}$$

where the magnitude of the signal from one muon was taken as equal to $\Delta E = 10.5$ MeV, and the value of $s(600)$ is expressed in MeV. Using known values of muon density $_{\mu}(600)$ and the signal $s(600)$, their ratio can be determined as:

$$\alpha = k \Delta E \rho_{\mu}(600)/s(600), \tag{3}$$

the magnitude ΔE is defined above, and the coefficient k allows us to consider the distinction between the actual signal and the one calculated.

3 Results

Our calculations show that in dependence (1), the exponent $b = 0.895$. This means that for primary iron nuclei, the fraction α is $A^{0.105} = 1.53$ times as much as the calculated value for protons within the bounds of the superposition hypothesis [6]. If we allow for the actual nucleusnucleus interactions, the value of this coefficient could be somewhat less. Our approximate calculations for the signal in underground detectors show that coefficient k is equal to 1.15, due both to the development of cascades from the muons in the soil and the decline of the real energy E_n of the muon registration threshold ($\sim 15\,\%$).

A comparison of the values of coefficient α, calculated by formula (3) for primary iron nuclei and protons, with the results from the experiment (the dots with errors [12], the ordinates of which were raised by $\sim 3\,\%$ by allowing for cascades in the soil) for almost vertical showers ($\cos\theta \geq 0.9$)

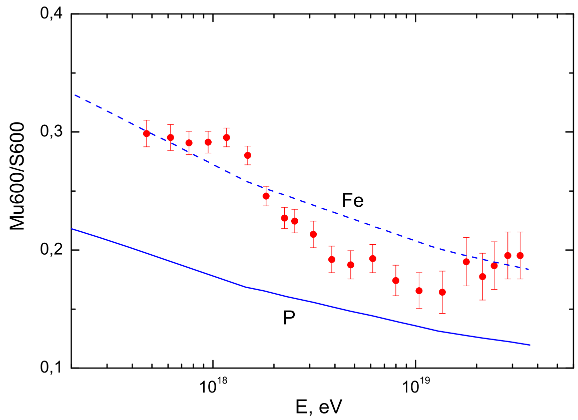

Figure 1: The dependence of muon fraction $\rho_{\mu}(600)/s(600)$ at a distance of 600 m from the shower axis in vertical EASes. Dots with errors are from [12]. The solid line represents protons; the dotted line — iron nuclei.

is presented in Fig. 1. Energy was estimated by $s(600)$ with the use of the dependency obtained at the Yakutsk array [13] (calorimetric method). Experimental data are located near the curve representing computational results for iron nuclei with some points even above it. It is quite possible that the model weakly predicts the muon fraction and doesn't suite well for accurate estimation of the CR mass composition. As for relative change with the energy, then in energy range $10^{18} - 10^{19}$ eV a rapid decrease of the muon fraction is observed. Therefore, it is possible to conclude, that CR mass composition becomes lighter at $E \sim 10^{18}$ eV. This conclusion agrees with the HiRes data [14]. At $E > 10^{19}$ eV the muon fraction grows pointing out increasing fraction of heavier nuclei. The similar result was obtained by Pierre Auger collaboration [15].

4 Conclusion

The signals from particles of extensive air showers in the energy region of $10^{17} - 10^{20}$ eV in both the surface and underground scintillation detectors of the Yakutsk array are calculated using the CORSIKA 6.616 and GEANT4 software packages and compared with experimental data. It is shown that the density of muons with energy above $E_{\text{thr.}} = 1$ GeV in vertical showers is proportional to the shower energy to 0.895: $\rho_{\mu}(600) \propto E^{0.895}$. According to the model of superposition, the muon density in iron-induced showers should be higher by factor 1.53. It was demonstrated that accounting both muons propagation in soil and their energy spectra leads to increased signal in underground scintillation detectors by factor 1.15 compared to the signal accepted for surface detectors.

A comparison of the calculated dependence of muon fraction α on signal value $s(600)$ with the data obtained at the Yakutsk array shows that the model is inaccurate and predicts too low values since several data points give mass composition heavier than iron nuclei. The global trend of experimental point hints that heavy nuclei dominate at energy $E < 10^{18}$ eV, in the region of $10^{18} - 10^{19}$ eV the portion of lighter nuclei increases and at ultra-high energy $E > 10^{19}$ eV the dominance of heavy nuclei is possible again.

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