Chemical composition of the primary cosmic radiation observed at the Yakutsk array at energies above $3. \cdot 10^{17}$ eV

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Abstract

The composition of the primary cosmic radiation should be studied by various alternative approaches. A promising way is to exploit a dependence of the fraction of muons in an extensive air shower on the atomic number of the primary nuclei. A comparison of the fraction of muons at 600 m from the shower axis observed at the Yakutsk array in the vertical air showers at ultra-high energies with results of simulations in terms of QGSJET-II and Gheisha-2002d models carried out with the help of the CORSIKA 6.616 and GEANT4 codes showed rather heavy composition of the primary radiation. But some errors in these models should be taken into account. At last, one has to allow for the fact that signals in the surface and underground scintillation detectors of the Yakutsk array from various particles of extensive air showers are measured in different units. All these corrections taken together show the proton composition of the primary radiation in the energy region of $\sim 2. \cdot 10^{18}$–10^{19} eV. At lower energies a composition is heavier. The change from the heavy composition to the primary protons occurs in the energy interval of $9. \cdot 10^{17}$–$2. \cdot 10^{18}$ eV. It is not excluded that at energies above $1.1 \cdot 10^{19}$ eV the composition may be also heavier as illustrated by a trend of data.

1 Introduction

Studying the chemical composition of the primary cosmic radiation (PCR) in the region of ultrahigh energies is of extraordinary interest. The galactic cosmic rays are believed to end somewhere beyond the knee in the cosmic ray spectrum and the extragalactic PCR is expected at higher energies. The steep reduction in the PCR flux due to interactions of the primary protons with photons of the microwave relic radiation was predicted by Greisen [1] and Zatsepin and Kuz'min [2] at energies above $\sim 3. \cdot 10^{19}$ eV (the GZK effect).

In the model of uniformly distributed extragalactic sources with a power law spectrum of generation, the proton flux must first decrease (a dip), then increase (a bump) and drop steeply (the GZK effect) as it was shown in the "dip" scenario of the cosmic ray (CR) spectrum formation [3, 4]. Various scenarios of the CR energy spectrum formation have been suggested. The analysis [5] of the "dip" scenario [4] and the "ankle" scenario [6] showed a profound difference in the expected composition of CR. In the "dip" scenario [4] of the overall CR spectrum formation the galactic component produced by supernovae remnants dominates up to 10^{17} eV and then in the region 10^{17}–10^{18} eV a transition from galactic to extragalactic component occurs

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[5]. In this scenario the peak of rather heavy composition is predicted at energies $\sim 10^{17}$ eV followed by a sharp decrease of atomic number A within of the energy interval 10^{17}–10^{18} eV. It is regarded as a signature of the transition from galactic to extragalactic CR. The second peak of heavy elements in the atomic number distribution is predicted at energy $\sim 10^{19}$ eV. So a profound increase of heavy composition should be observed within the energy interval 10^{18}–10^{19} eV [5]. In the alternative "ankle" scenario [6] the extragalactic component dominates at energies above 10^{19} eV. The CR composition in this second scenario is considerably heavier at energies 10^{18}–10^{19} eV [5].

As a majority of conclusions about the primary composition exploits the dependence of the depth x_{max} of the shower maximum on the energy E it is very important to use some alternative method, e.g. measurements of a fraction α of muons in extensive air shower (EAS) at some distance from the shower axis. In this work, the results of calculations of the fraction α of muons in an EAS for the primary protons and iron nuclei are compared with data observed at the Yakutsk array (YaA), and conclusions are drawn on possible composition of the PCR in the energy region $3. \cdot 10^{17}$–$3. \cdot 10^{19}$ eV.

2 Calculation technique

Calculations of an individual EAS development in the atmosphere were carried out using the CORSIKA 6.616 package [7] in terms of the QGSJET-II [8] and Gheisha-2002d [9] models with the thinning parameter $\varepsilon = 10^{-8}$. The GEANT4 package [10] was used to estimate the signals from the EAS particles in the YaA surface and underground scintillation detectors and then a fraction α of muons. For the vertical showers at a distance 600 m from shower axes (within the ring with radii of 550 m and 650 m) mean densities $\rho_\mu(600, E_\mu \geq 1$ GeV) of muons with the threshold energy above 1 GeV and muon energy spectra within the interval 0.3 – 100 GeV were calculated for the primary protons in the energy range $3. \cdot 10^{17}$–$3. \cdot 10^{19}$ eV.

We determine a fraction α of muons at some distance r from the shower axis as a ratio of the signal $s_\mu(600)$ in the underground detectors to the signal $s(600)$ in the surface detector

$$\alpha = s_\mu(600)/(s(600). \tag{1}$$

Here the both signals are measured in MeV. At the YaA the signals $s(600)$ and $s_\mu(600)$ were measured in the such relative units as VEM's (Vertical Equivalent Muon) [11] (slightly different VEM's for the surface and underground detectors were used). So, we multiply α by a factor f_1. Here f_1 is the ratio of the VEM units in the underground and surface detectors. It happened that muons with energies below the prescribed threshold energy $E_{th} = 1$ GeV can penetrate through the soil and strike a detector. The real signal was calculated and compared with signal caused by muons with the threshold energy $E_{th} = 1$ GeV. The difference may be taken into account with help of some coefficient k:

$$s_\mu(600) = k \cdot \rho_\mu(600, E_\mu \geq 1GeV). \tag{2}$$

3 Results

At the YaA the energy E of the primary particle which generates an EAS in the atmosphere is estimated with help of measurements of the Vavilov-Cherenkov radiation as function of the signal $s(600)$, as follows [12]:

$$E = (4.6 \pm 1.2) \cdot 10^{17} \cdot s^{0.98 \pm 0.03}(600), eV. \tag{3}$$

Our simulated estimate of the energy E of the primary particle may be found out as [13]:

$$E = (3. \pm 0.2) \cdot 10^{17} \cdot s(600), eV. \tag{4}$$

It should be noted that the experimental estimate (3) is by a factor 1.6 larger.

The ratio of intensity of the PCR observed at the YaA [12] to the intensity observed at the HiRes [14] presented in figure 1 shows that the coefficient in (4) could not be smaller. So the calculated fraction α could not be less than given with use of (4).

Unfortunately, the QGSJET-II model failed also to explain some very important data. The vertical muon intensities calculated in [15] in terms of the QGSJET-II model using the primary particle spectrum observed by the ATIC-2 [16] happened to be by a factor ~ 1.5 less than data [17, 18] in the impulse range of 10^2–10^5 GeV/c. It means that a number of muons are underestimated by a factor $f_2 \approx 1.15$. Besides, the Gheisha-2002d model predicts also by a factor $f_3 \approx 1.1$ lower muon density [19] than the model FLUKA [20] does. We find $k = 1.3$ and $f_1 = 1.03$. All these corrections taken together should lift the simulated magnitudes by a factor

$$f = f_1 \cdot f_2 \cdot f_3 = 1.3. \tag{5}$$

At last a dependence of the fraction α_f on the energy E should be estimated as we find out as follows

$$\alpha_f = f \cdot \alpha. \tag{6}$$

Here α_f is a measured value for nuclei. Results for protons and iron nuclei as solid and dashed lines with experimental data (points) are presented in figure 2.

One can see from this figure 2 the rather heavy composition at low energies. Then a profound decrease of the atomic number A starts at the energy $\sim 8.6 \cdot 10^{17}$ eV and ends at the energy $\sim 2.3 \cdot 10^{18}$ eV as the pure proton primaries. These pure proton composition elongates up to energies $\sim 1.14 \cdot 10^{19}$ eV. At energies above this value of $\sim 1.2 \cdot 10^{19}$ eV one can see some trend forwards higher composition though the error bars are too high. These results do not completely correspond to predictions [5] for the first scenario and contradict to the "ankle" scenario. The possible trend to the heavier composition at energies above $\sim 1.2 \cdot 10^{19}$ eV agrees with the results [21]. So, more sophisticated model of the CR spectrum formation should be developed.

4 Conclusion

The signals from particles of EAS in both the underground and surface scintillation detectors of the YaA are calculated using the CORSIKA 6.616 and GEANT4 software packages. The corrected ratios of these signals were compared with data in the energy region of $3. \cdot 10^{17}$–$3. \cdot 10^{19}$ eV. A comparison of the corrected calculated dependence of muon fraction α on the energy E with the data observed at the YaA shows that rather the proton primary composition dominates in the energy interval $2.3 \cdot 10^{18}$–$1.14 \cdot 10^{19}$ eV. The global trend of experimental point hints that heavy nuclei dominate at energy $E < 2.3 \cdot 10^{18}$ eV and possibly at ultra-high energies above $1.14 \cdot 10^{19}$ eV (but error bars are too high). The change of composition from the heavy nuclei to the protons occurs in the interval $8.6 \cdot 10^{17}$–$2.3 \cdot 10^{18}$ eV. A more sophisticated version of the model [5] should be developed to fit these results.

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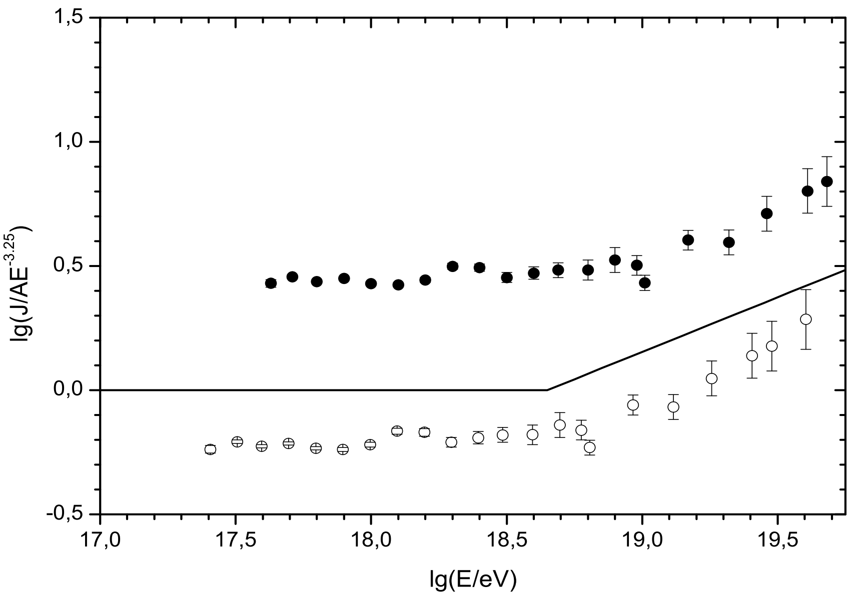

Figure 1: Ratio of intensities of the PCR observed at the YaA [12] estimated with help of (3) (solid circles) and with help of (4) (open circles) to the intensity observed at the HiRes [14] (solid line).

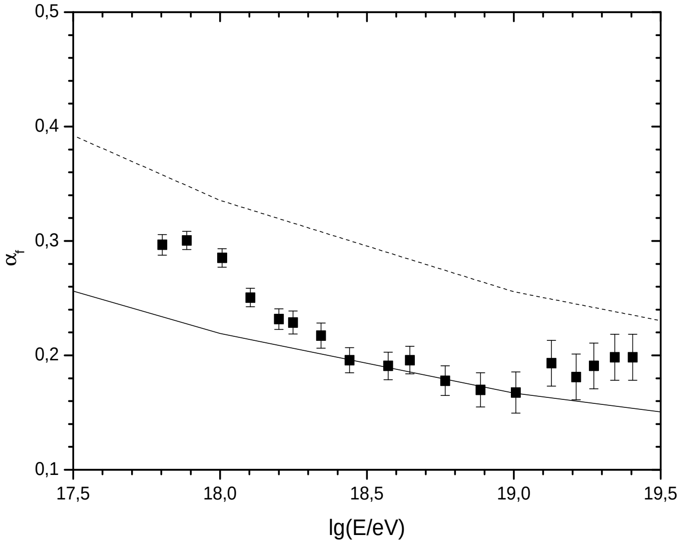

Figure 2: Dependence of the fraction α_f on the energy E for YaA. Solid line – protons, dashed line – iron nuclei, solid squares – [11].