

Composition of the primary cosmic radiation observed at the Yakutsk array at energies above 10^{17} eV

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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 scintillations detectors of the Yakutsk array are calculated using CORSIKA 6.99 code and GEANT4 software packages within the framework of QGSJET II, EPOS 1.99 and GHEISHA 2002 hadron interaction models and compared with experimental data. Suggestions to adjust the models of hadron interactions with the help of data on the vertical muon energy spectrum and on the calorimetric estimates of energy of the primary particles have been proposed. The simple method to estimate the vertical muon energy spectrum has been suggested. Simulations showed a deficit of muons in case of the QGSJET II model and a profound enhancement of muons in case of the EPOS 1.99 model. It is shown that a transition from a heavy primary composition to the proton primaries at energies $(1 - 2.6) \times 10^{18}$ eV might be observed.

Keywords: composition of the primary cosmic radiation, constraints of models.

1 Introduction

The Yakutsk array (YaA) [1] is placed ~ 50 km south from Yakutsk at the depth of 1020 g/cm^2 (100 m above the sea level). It started working in 1973 with 35 detector stations (surface detectors) covering $\sim 17 \text{ km}^2$ area. After reconstructions in 1990–1992 there are 49 detector stations covering $\sim 8 \text{ km}^2$ area, as a triangle mesh with a side of 500 m. Every station has 2 scintillation detectors with 2 m^2 area each. Inside the circle with the radius of 250 m there are 10 more such detectors which are not used in sampling of shower events. Such array allows to study cosmic rays in the energy interval $2 \times 10^{17} - 3 \times 10^{19}$ eV with the similar sampling of events inside all area. From the very beginning it was possible to measure also the Vavilov-Cherenkov radiation (VCR). As a light detector the PMT (FEU-49) with the 15 cm side was used. There are now 19 VCR detectors inside the circle with radius 1 km and 17 additional the VCR detectors inside the central circle with radius of 250 m. The signals from both the VCR detectors and (surface detectors placed inside the central circle are delivered to the special recorder which allows to study cosmic rays with energies $10^{15} - 10^{17}$ eV with the help of the VCR detectors.

Muons are measured at the YaA since 1976. There are 3 muon scintillation detectors with area of 20 m^2 each and the big detector with area of 180 m^2 . The depth of soil above detectors is equal to ~ 2.5 m. So, low energy electrons and gammas are absorbed. The threshold energy of muons are taken as $1.0/\cos\Theta$ GeV, but our calculations show some different value ($0.65/\cos\Theta$ GeV). The 3 Cherenkov differential detectors (CDD) working as a camera obscura have been constructed to study the longitudinal development of showers. At the ceiling of a camera there is a chink and some mosaik of the PMT are placed at the bottom. The mosaik of the PMT is arranged so that the various particular PMT detect the VCR generated at different

depth slants in the individual extensive air shower (EAS). So, it is possible to measure the depth of shower maximum. The time-space structure of the EAS is also studied with the help of the fast-acting VCR and scintillation detectors placed at points of the CDD.

The new electronics is also elaborated to measure more precisely the arrival directions of the primary cosmic ray particles and other parameters. The fiber optic cable would be used to share out information between stations and the central recorder.

As for interpretation of data it is also a lot have been elaborated [2]–[11]. First, only densities of electrons and muons have been calculated in terms of the Landau model [2]. Now we have the new level of interpretation.

Simulations of individual giant air showers with energies well above 10^{19} eV put forward very severe problems because of huge number of secondary particles. Our proposal exploits some basic observations. First, the fluctuations in a shower development are of primary importance. The random first interactions of the primary particle and the most energetic secondary particles contribute much to fluctuations in a shower development. Note, that a development of cascades with a large number of secondary particles does not contribute much to fluctuations in the longitudinal development of a shower. But fluctuations in number of particles which hit a detector at large distances from the shower axis are huge. The Coulomb scattering of the shower electrons and scattering of other particles in the inhomogeneous atmosphere is of importance. The signals, or responses of all detectors, to all shower particles should be calculated to allow a comparison with the experimental data. The signals shows the density of energy deposited in the 5 cm thick scintillator by shower particles for any distances from the shower axis.

In order to calculate signals in surface and underground scintillation detectors from various shower particles, we

employed the GEANT4 package [12]. In the calculations the surface and underground scintillation detectors were represented by some models. The database of scintillation detector responses was calculated by means of the GEANT4 package as signals generated by electrons, positrons, and photons in the energy range of 0.001–10 GeV and by muons in the energy range of 0.3–1000 GeV. All particles hit the detector at various zenith angles (within the range $0^\circ - 60^\circ$). The signals in the surface and in the underground scintillation detectors induced by the EAS particles at a distance r from the shower axis are calculated in the standard energy units (e.g., in MeV). At the same time, in practice, at the YaA the signals from the EAS were measured in some practical units such as the VEM's (Vertical Equivalent Muon). These quantities were measured in some calibration procedures. So, we have carried out calculations of signals in the surface and underground detectors respectively caused by the one near vertical muon. Thus, we suggested the multi-level scheme of simulations as a model of interpretation of giant air shower data. The relativistic equations have been suggested to be solved to take into account the spread of muons by the geomagnetic field.

In order to estimate the shower energies E and other parameters, we propose employing the new original method [6] that relies on evaluating matrices of signals in scintillation detectors for a large set of simulated showers. This set is used to interpret one observed event. The 5×5 km area in the plane of the detectors was separated into 201×201 squares with a side of 25 m. The CORSIKA code [13] allows for the calculation of a file with the parameters of particles in the plane of the detectors for each individual shower and the response database allows to estimate signals in each of the squares, which are treated as detectors. Thus, a set of 201×201 signal matrixes was calculated for each individual shower. The calculations were performed for events generated by each of the four types of the primary particles (protons, α particles, oxygen and iron nuclei). The minimum of the χ^2 function was sought with a step of 1 m in a square with a side of 400 m with the center at the shower axis position determined experimentally. As a result, new estimates were obtained for the shower energy, new coordinates x and y of the shower axis and other parameters.

In [10] a sample of 33 events with reconstructed energies above 2×10^{19} eV, zenith angles up to 45° , axis location inside the array and highquality muon data recorded was analyzed by the event-by-event method. For each of the events a library of showers (from 400 to 1000 showers) with different primary energies but with the same arrival direction as observed has been simulated in terms of various models. The sample of simulated showers with expected parameter $s(600)$ was used to obtain the probability distribution $f(\rho_\mu)$ to have $\rho_\mu(1000) = \rho_\mu$ in a simulated shower. Then the ratios $\eta(P, Fe) = \rho_\mu^{obs}/\rho_\mu(P, Fe)$ have been estimated. Assuming two component proton-iron composition the fraction of protons with energies above 10^{19} eV was found as $0.52 +0.19-0.20$ at 95% confidence level in terms of the EPOS 1.61 model [11].

The paper [10] showed clearly that the estimates of the primary cosmic ray composition depend severe on the models of hadron interactions used to interpret data. So, some additional testing of the models of hadron interactions is needed to make more plausible conclusions. In this paper we would like to show that the very reliable data [14, 15] on the vertical muon energy spectrum can

help to get more plausible conclusions about the primary cosmic ray composition at superhigh energies. Moreover models of hadron interactions can be also tested with the help of the energy estimates of showers observed by the calorimetric method with the use of the fluorescence light.

2 The vertical energy spectrum of muons

Some analysis of inclusive particle data taken at accelerators and now at the Large Hadron Collider (LHC) at the CERN laboratory is particularly interesting for constraining models of hadronic interactions. We would like to note that it is possible to carry out additional testing of these models with the help of very reliable data on the Vertical Energy Spectrum of Muons (VESM) in the energy range of $\sim 1 - 10^5$ GeV [14, 15]. The transport cascade equations for muons have been solved by the original method in [16] to estimate the VESM. We suggest a very simple procedure to calculate the VESM and to test the ability a various models used in simulations of EAS to produce a more correct number of muons in a shower.

First, the energy spectra of muons $F_{\mu P}(E_\mu, E)dE_\mu$ and $F_{\mu He}(E_\mu, E)dE_\mu$ in the energy range of $10^2 - 10^5$ GeV were calculated for the proton and He nuclei primaries with various fixed energies E in the range of $10^2 - 10^7$ GeV with the help of the CORSIKA-699 package [13] in terms of tested models. Then for the primary proton spectrum $F_P(E)dE$ and the He nuclei spectrum $F_{He}(E)dE$ the estimated muon energy spectrum $F_\mu(E_\mu)dE_\mu$ can be expressed as follows

$$F_\mu(E_\mu)dE_\mu = \left(\int dE \times F_P(E) \times F_{\mu P}(E_\mu, E) + \int dE \times F_{He}(E) \times F_{\mu He}(E_\mu, E) \right) dE_\mu, \quad (1)$$

As for the primary proton and He nuclei spectra we have used the Gaisser-Hillas (GsH) approximation [17].

Figure 1 shows ratios R of the ATIC 2 cosmic ray intensity [18] to the GsH approximation for the primary protons as the solid points and for He nuclei as the open points. This figure 1 displays that the ATIC 2 data are (10 – 15)% less than the approximation GsH in the energy range of $10^2 - 10^3$ GeV, nearly coincides with GsH for the interval $10^3 - 10^4$ GeV and (20 – 30)% above GsH for energies above 10^4 GeV. So, in calculating (1) with the ATIC 2 data some compensation is possible.

Figure 2 shows ratios R of the VESM calculated in terms of the EPOS 1.99 model [19] as solid triangles and in terms of the QGSJET II model [20] as stars with the help of the formula (1) to data [14] (before 10^3 GeV) and to data [15] (above 10^3 GeV). It is obviously seen from figure 2 that the intensity of muon spectrum calculated in terms of the EPOS 1.99 model is higher by a factor ~ 1.5 up to energy 10^3 GeV and by a factor ~ 1.8 up to energy 10^4 GeV comparing with data [14, 15]. As it was stated in [16] the model QGSJET II predicts the intensity which is by a factor ~ 1.5 less than data [14, 15].

Our simulations of the VESM were carried out with the help of the original formula (1). Our method is very simple and very easy to be executed. Calculations were carried out in the logarithmic scale with 8 points for the interval of $10^2 - 10^3$ GeV and with 4 points per a decade at higher energies up to 10^7 GeV. Our results for the QGSJET II

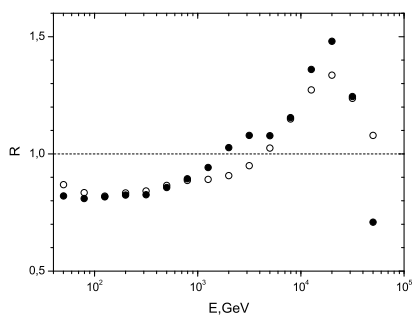


Fig. 1: Ratios R of the ATIC2 cosmic ray intensity [18] to the GsH approximation [17] for the primary protons (solid circles) and He nuclei (open circles).

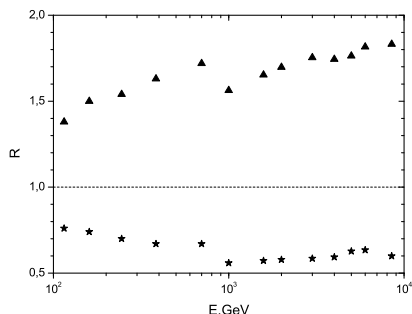


Fig. 2: Ratios R of the vertical muon energy spectra calculated in terms of the models [19] (triangles) and [20] (stars) to the data [14] before 10^3 GeV and to the data [15] above 10^3 GeV .

model [20] are (5 – 10)% less than obtained with the ATIC 2 spectrum [18] in [16]. But we have used the GsH approximation [17] as the primary particle spectrum which differs slightly from the ATIC 2 data (see Fig. 1 and a text above). Thus, the very simple formula (1) has been suggested to test an ability of models of hadron interactions to predict the correct number of muons at least at energies below 10^{16} eV. At higher energies there is also a possibility to constrain models of hadron interactions. All models used for the EAS simulations should provide the correct estimates of energy of showers. Just now it is not the case. The experimental estimate of the energy E of the primary particle is by a factor 1.6 larger than simulated one in terms of the QGSJET II model [20] for the YaA. For the Telescope Array (TA) simulated estimate is by a factor 1.27 larger than the observed one with the help of the fluorescence light [22]. For the Pierre Auger Observatory (PAO) the simulated estimates are also considerably larger by (30 – 50)% [23]. Thus, all models of hadron interactions should be adjusted so to fit data both on the vertical muon energy spectrum and on the energy estimates observed in calibration procedures with the help of the fluorescence light. But in advance before such fitting it is possible to use some simple correction factors f to take into account this adjusting [21, 24].

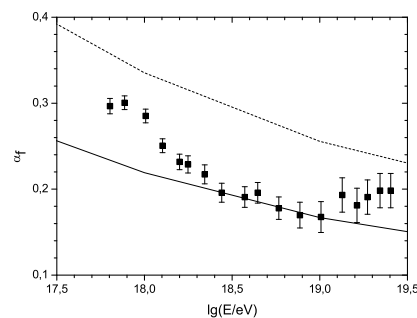


Fig. 3: Dependence of the fraction α_f on the energy E for the YaA . Solid line–protons, dashed line– iron nuclei, solid squares–[26].

3 The composition of the primary cosmic radiation

The ratios α of the signals observed at 600 m from a shower axis in the surface and in the underground detectors of the YaA and results of simulations of these ratios for the primary protons and the iron nuclei have been presented in [25]. The simulations were carried out in terms of the QGSJET II model. A comparison of these ratios shows clearly a rather heavy composition, probably the iron one [25]. But if to take into account the deficit of simulated muons as shown in Fig. 2 and some other factors [21] we may conclude that the correction factor $f \sim 1.3 - 1.4$ should be used.

So, if to increase the calculated ratios α by this factor f we can get results for the ratio α_f shown in figure 3, where

$$\alpha_f = f \times \alpha, \quad (2)$$

It is seen from this figure that at energies $2 \times 10^{18} - 10^{19}$ eV a rather light composition, probably the proton dominated one is observed. At energies above 10^{19} eV statistics is low and the error bars are to high to state a definite conclusion. At energies below 2×10^{18} eV the heavy composition is observed. It should be noted that the energy scale should be adjusted with the help of the more elaborated model of hadron interaction. Such tremendous change from the heavy primary composition in [25] to the light one in [21] shows clearly that all models of hadron interactions should be adjusted to data on the vertical muon energy spectrum if we want to have the more reliable results. Calculations of the ratios α_f in terms of the EPOS 1.99 model are in progress. But it is clear from figure 2 that the huge enhancement of simulated muons by a factor $f = 1.5 - 1.8$ comparing with data [14, 15] would lead to the rather light, probably the proton dominated composition at energies above 10^{18} eV.

4 Conclusion

We have suggested to test models of hadron interactions with the help of the data on the vertical muon energy spectrum and on the energy estimates observed with the calorimetric method which make use of the fluorescence light. The simple method have been suggested to simulate the vertical muon energy spectrum. The simulated vertical muon energy spectra are by a factor ~ 1.5 less than data

[14, 15] in case of the QGSJET II model and by a factor $f = 1.5 - 1.8$ larger than data [14, 15] in case of the E-POS 1.99 model. The iron composition expected in case of the QGSJET II model should be changed to the light one (probably the proton dominated one) if to take into account suggested corrections of this model. So, all models of hadron interactions should be adjusted to data on the vertical muon energy spectrum if we want to get more reliable composition.

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