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The Knee in the Primary-Cosmic-Ray Spectrum, Observed in the Hadron Component of Extensive-Air-Shower Cores at the Mountain Level

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Abstract—The spectra of the hadron component in extensive-air-shower (EAS) cores detected at the Tien Shan high-altitude scientific station of the Lebedev Institute of Physics, Russian Academy of Sciences, have been analyzed. Simulation was performed using the CORSIKA code within the QGSJET01 and QGSJET02 models under different assumptions about the primary-cosmic-ray (PCR) spectrum in the knee region. It is shown that the QGSJET01 model underestimates the energy of the hadron component of EAS cores at the mountain level. It is also shown that a pronounced knee in the experimental spectrum suggests a sharp ($d\gamma \sim 1.5$) change in the exponent of the proton spectrum slope at an energy of about 5 PeV.

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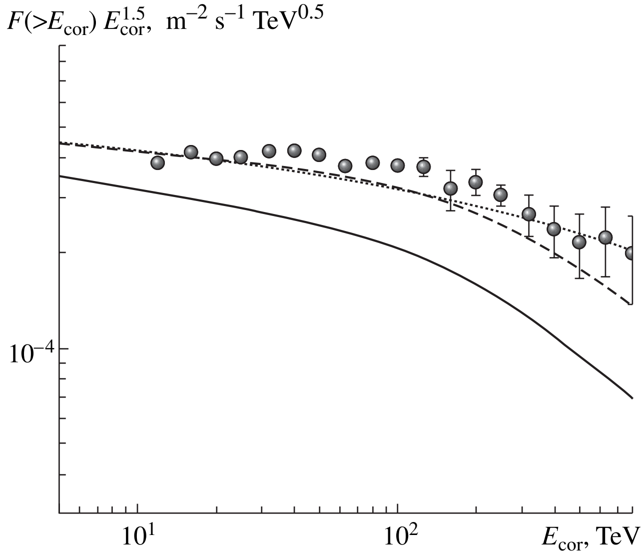
INTRODUCTION

The existing data on the hadron component in the extensive-air-shower (EAS) cores, which was detected in the large ionization calorimeter with an area of 36 m^2 at the Tien Shan high-altitude station at an altitude of 3340 m, still remain unique. First, they were obtained in a wide energy range, including the knee region in the primary-cosmic-ray (PCR) spectrum, where convincing indications of the change in the CR chemical composition are present [1]. Hence, these data make it possible to check different hypotheses about the PCR chemical composition in the knee region. Second, although the fraction of the energy remaining in the hadron component at the mountain level is very small (several percents), this fraction is a characteristic that is extremely sensitive to the interaction model, especially to the interaction cross section and inelasticity coefficients (see [2] and references therein). Therefore, the data on the hadron component at the mountain level can be a good test for adequacy of the modern models used in EAS analysis. Third, due to large thickness of the calorimeter, longitudinal development of hadronic cascades can be used to analyze the particle composition in EAS cores [3].

For comparison, we chose two experimental characteristics of the hadron component in EAS cores obtained at the Tien Shan station: the average spectrum of hadrons with an energy exceeding 1 TeV per shower (obtained by N.M. Nesterova and discussed in [2]) and the E_{cor} spectrum (E_{cor} is the total hadron energy in the EAS core over an area of 6×6 m^2) measured in a very wide range (E_{cor} = 1–600 TeV) without additional selection over N_e [4]. The CR chemical composition and spectrum in the low-energy range (1–10 TeV) has been measured in several direct experiments; therefore, there is an uncertainty in interpolation to energies of 1000 TeV and higher. The purpose of this study is to find out if it is possible to describe the noted spectrum [4] within the CORSIKA + QGSJET model, and if yes, what primary spectra can be used to this end.

1. CALCULATION

We used the CORSIKA + QGSJET01 (version 6.2020, April 3, 2005 [5, 6]) and CORSIKA + QGSJET02 (version 6.5001, March 6, 2006 [5, 7]) codes. The quark–gluon string models QGSJET01 and QGSJET02 deal with the same interaction cross section between protons and nuclei of air atoms: 385 mb at an energy of 1000 TeV, but significantly different elastic constants: 0.33 (QGSJET01) and 0.42 (QGSJET02) [7]. Calculations were performed for primary protons, helium nuclei, and oxygen nuclei on the assumption of a primary spectrum described by a power law ($F_0 \sim E^{-2.7}$) in wide energy range (0.3–10^5 TeV) and the angles of incidence of particles ranging from 0° to 45°. The simulation domain was divided into 3 to 5 intervals with a statistic of 5×10^5 particles in each interval; the threshold hadron energy was 800 MeV. In addition, the procedure of shower core selection in the calorimeter (within the area with a radius of 3.5 m) was simulated and the entire energy arriving at an area of 6×6 m^2 (E_{cor}) was



Integral spectrum of the hadron component of EAS cores $F(>E_{cor})$ from [4] (point with errors) and the results of the calculations within the CORSIKA + QGSJET02 model with two approximations of the primary spectrum: Hoerandel approximation [1] (solid line) and ATIC interpolation (see the text) with $d\gamma = 1.5$ and 0.5 (dashed and dotted lines, respectively).

summed. The spectrum $F(E_{cor})$ was measured for each interval (taking into account the detection technique) and then the obtained spectra were summed with weights corresponding to the primary spectrum under consideration. To analyze the effective fraction of the energy remaining in the hadron component of the EAS core at the observation level (K_{ef}), we used the well-known formulas, which are valid in the case of a weak energy dependence of this quantity [8]:

$$F(E_{cor}) = F_0(E)^* \langle K_{ef}^{1.7} \rangle\,; \quad K_{ef} = (\langle\langle E_{cor}/E)^{1.7}\rangle)^{1/1.7}.$$

It was found that this quantity depends most strongly on the angle of incidence of a particle, differently for different energies. This fact means that the solid angle Ω of the array depends on energy. To avoid uncertainties at the transition from the global to vertical flux, we will compare the global experimental and calculated fluxes. For the global flux in the angular range 0°–45°, the calculated effective energy of the hadron component is $K_{ef} = 0.027 \pm 0.01 E_{cor}^{0.0 \pm 0.01}$ and $K_{ef} = 0.031 \pm 0.01 E_{cor}^{0.03 \pm 0.01}$ for the QGSJET01 and QGSJET02 models, respectively. For primary nuclei, the values of K_{ef} are much smaller than for protons (for example, K_{ef} for helium is smaller by a factor of 1.5). Due to this difference in the models, at energies of several hundreds of TeV, the intensity of the E_{cor} spectrum for QGSJET01 is smaller by a factor of 1.6–1.8 than the intensity predicted by QGSJET02 for the same spectrum of protons. This result is another indication of the strong sensitivity of the characteristic studied to the interaction model.

2. CHOICE OF PRIMARY SPECTRUM APPROXIMATION

The scatter in the experimental data on the behavior of different PCR components in the knee region is very high. As a basic version, we will consider the approximation of PCR spectra proposed by Hoerandel [1]:

$$F_0(E) = \Sigma I_0(z) E^{-\gamma(z)}(1 + (E/E_\kappa(z))^s)^{-\delta\gamma/s}. \quad (1)$$

The total intensity of the spectrum of all particles is represented as a sum of main groups of nuclei (we will consider only five groups), with different charges z (from protons to iron nuclei) and intensities $I_0(z)$ at an energy of 1 TeV/particle, and different slope exponents $\gamma(z)$, varying from 2.71 for protons to 2.59 for iron (see Table 7 in [1]). The knee in the spectrum in each component occurs at an energy $E_\kappa(z)$ in rigidity ($E_\kappa(z) = E_\kappa(1)z$); the knee energy for protons is $E_\kappa = 4500$ TeV. The exponent of the spectrum slope changes at the knee point by $\delta\gamma = 1.5$; the variable s characterizes the knee sharpness (at $s = 1$ or 2, the knee is smooth or sharp, respectively). In approximation [1], the total intensity of the spectrum of all particles at 10 TeV is $I = 5.1 \times 10^{-5}$ m^{-2} s^{-1} sr^{-1} TeV^{-1} and the chemical composition is as follows: 0.35(p), 0.26(He), 0.12(CNO), 0.13(Ne–S), and 0.35(p), 0.26(He), 0.12(CNO), 0.13(Ne–S), 0.14($z > 17$). The spectra of the main components have the following exponents in this approximation: $\gamma_p = 2.71$, $\gamma_{He} = 2.64$, $\gamma_{CNO} = 2.67$, and $\gamma_{Fe} = 2.59$. Near 10 TeV, this approximation is in good agreement with the new ATIC data [9] obtained during the second flight, both in the total intensity (with an error of 20%) and in the chemical composition. However, the ATIC spectra of protons and helium nuclei are much flatter: $\gamma_p = 2.63$ and $\gamma_{He} = 2.57$. As a result, the ATIC spectrum of all particles is very flat ($\gamma \approx 2.55$) and, being interpolated to the knee region, falls to the upper limit of the EAS data. Approximation of the spectra by formula (1) with changed (in comparison with [1]) exponents of individual nuclear components: $\gamma_p = 2.63$, $\gamma_{He} = 2.57$, $\gamma_{CNO} = 2.65$, and $\gamma_{Fe} = 2.65$ (we referred to it as the ATIC interpolation) will be used as the upper estimate of the primary spectrum.

3. COMPARISON WITH THE EXPERIMENTAL DATA AND DISCUSSION

The figure shows the integral global energy spectrum of the hadron component of EAS cores (6×6 m^2) $F(>E_{cor})$, measured in a wide range of E_{cor} (10–600 TeV) without additional selection over N_e from [4]. The spectrum exhibits a pronounced knee in the range 100–200 TeV. The exponent γ_{exp} of the spectrum slope before and after 100 TeV is -1.48 ± 0.03 and 1.9 ± 0.06, respectively. It was noted in [4] that the region where the slope exponent changes is very narrow: less than half an order. The solid line in the figure indicates the calculated spectrum obtained within the CORSIKA + QGSJET02 model with a primary spectrum in the Hoerandel approximation [1]. Although this approximation also gives a pronounced knee in the theoretical spectrum and the intensity at low energies is in satisfactory agreement with the experimental results, the calculated intensity of hadrons in the knee region is much smaller than the experimental value. Approximation of the primary spectrum in the form of the ATIC interpolation (Section 2), which corresponds to the upper limit of the experimental continuum of the EAS data, much better describes the experimental spectrum of EAS cores (see the figure). We do not report the results of the QGSJET01 calculation here, since this model predicts even lower (by a factor of 1.6–1.8) intensity of the hadron component spectra in the knee region. In [2], we showed that the QGSJET01 code also underestimates the average spectrum of hadrons in a shower, which is already independent of the primary CR spectrum.

We separately investigated the problem of the pronounced sharpness of the knee in the spectrum of the hadron component. In the calculations, we chose a large value $s = 4$, which characterizes the knee sharpness in formula (1), and a large change in the slope exponent for the spectra of nuclear components at the knee point: $d\gamma = 1.5$. In this case, as can be seen in the figure, the knee sharpness in the spectrum of the hadron component of EAS cores is also reproduced well. All considered approximation versions with a smooth knee in each component ($d\gamma = 0.5$, $s = 1$) describe the experimental results much more poorly: such a version is denoted by the dotted line in the figure.

It has been shown in this study that the QGSJET01 model underestimates the energy the hadron component in EAS cores. It is also demonstrated that the pronounced knee in the experimental spectrum of the EAS hadron component suggests a sharp ($d\gamma \approx 1.5$) change in the slope exponent of the proton spectrum at an energy of about 5 PeV.

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