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Hadron component of EAS cores detected at Tien-Shan mountain station in comparison with CORSIKA+QGSJET simulations.

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In this paper we study how the knee in primary cosmic ray (PCR) spectrum can reveal itself in the hadron component of EAS cores. The comparison of CORSIKA+QGSJET calculations with available experimental data at mountain level (3340 m a. s. l.) shows that the suggestion about rigidity dependent energy position of the knee and the moderate change of spectrum slope in every nuclear component of PCR does not contradict experimental data.

1. INTRODUCTION

The most intriguing features of the primary cosmic ray (PCR) spectrum obtained in recent years is a rigidity dependent energy of the knee Ek(Z)=E(1)*Z (Z is the charge of a particle) and perhaps the very sharp change of a spectrum exponent at this point (by $d\gamma \sim 2.1$) of every nuclear component of PCR [1,2], that is much more than $d\gamma \sim 0.5$ in the 'all particle' spectrum. The confirmation of this conclusion is very important from the point of view of the cosmic ray origin problem. If a maximal possible energy of accelerated particles in the bulk of supernova remnants is around several PeV, then we can expect such behaviour of elemental spectrum around the knee [3]. The result [1,2] is based on the analysis of muon/electron ratio in extensive air showers (EASs) [1]. So the measured steep spectrum above the knee means a sharp increase in the number of muon rich EASs that is interpreted as an increase of heavy nuclei induced EASs. Therefore it seems reasonable to check this result basing only on a hadron component of EAS. The use of the electron/hadron ratio in EASs in order to distinguish different primary groups at sea level in KASCADE resulted in conclusions different from muon/electron analysis [4]. A hadron component of EAS degrades to sea level very strongly, so it is preferable to investigate hadrons at mountain level, where at least about $\sim 3{-}5\%$ of EAS energy survives as a hadron component. A hadron component of EASs is very sensitive to both primary proton spectrum and to the model cross sections of interactions [5]. The main question we would answer is: how can the sharp knee of primary CR spectrum reveal itself in hadron component and can CORSIKA describe the data?

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2. EXPERIMENTAL DATA AND CALCULATIONS

We used for the analysis the integral spectrum of EAS core hadron energy $F(> E_{cor})$ measured with the help of the big ionization calorimeter (BIC) of 6×6 m^2 area at a mountain altitude 3340 m a. s. l. (the Tien-Shan scientific mountain station) in a wide energy interval 1-600 TeV [6]. At high energies this is the hadron energy summed up over the area 36 m^2 with EAS axes being within the radius 3.5 m, at small energies practically this is a spectrum of single hadrons.

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This is a reason why additionally we used for the analysis the integral spectra of single all hadrons obtained in the experiment 'Pamir' (4400 m a. s. l.) with the help of lead X-ray chambers [8] and carbon chambers [9], recalculated to Tien-Shan level of observation $F(>E_h)$. Large scale X-ray emulsion chambers give a perfect spatial resolution for hadron detection and a wide energy interval up to several hundred TeV. Such single hadrons mainly are the hadrons that reach the observation level without interaction, so their flux is very sensitive to the interaction cross section.

To avoid the uncertainty connected with the transition from global to vertical flux (which is energy dependent) we analyzed the global fluxes.

Both type of analyzed spectra $F(>E_{cor})$, $F(>E_h$ are presented in Fig. 1. Besides, we include in Fig.1 the integral spectrum of hadron component of EASs, obtained at Tien-Shan station [7] with the help of the thin burst calorimeter (10×20 m^2) of the complex 'Hadron' array. The measured hadron energy in this case exceeds the energy E_{cor} by factor 2-2.5. The authors of [6] emphasize the main features of the $F(E_{cor})$ spectrum: a very noticeable change of slope from $\gamma = 1.48 \pm 0.03$ at $E_{cor} < 100$ TeV to $\gamma = 1.9 \pm 0.06$ at $E_{cor} > 100$ TeV within the narrow energy interval 1/2 of the order. The same change of slope was obtained in the experiment 'Hadron' [7]: from $\gamma = 1.54 \pm 0.02$ to $\gamma = 1.86 \pm 0.07$. The spectrum slope of single hadrons is 2.03 ± 0.04 in [8] and 2.01 ± 0.04 up to 70 TeV and 2.07 ± 0.18 above 70 TeV in [9].

Considered spectra continue to be unique though they were obtained a decade ago. The interpolation to 1 TeV leads to the intersections of both spectra, that means E_{cor} comprises one hadron.

We used CORSIKA+QGSJET01 (version 6.2020 [10,11]) and CORSIKA+QGSJET02 (version 6.5001 [10,12]). The last advanced version includes new proton structure functions and takes into account the non-linear interaction effects, which appear to be of extreme importance at high energies [12]. Both models have practically the same cross section in the region 1 - 1000 TeV but different elasticity coefficients 0.33 (QGSJET01)

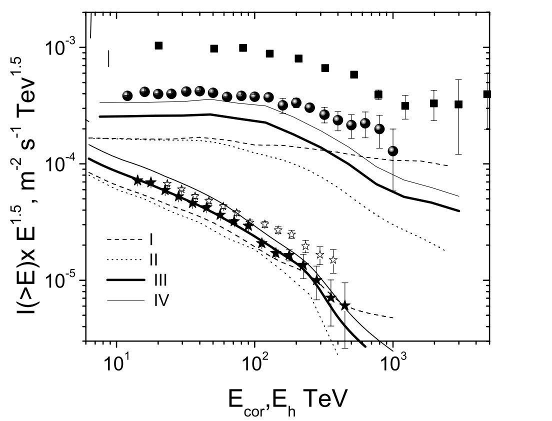

Figure 1. Integral hadron spectra at 3340 m a.s.l., measured in different experiments: EAS core hadron energy spectrum over area 36 m^2 [6] (black balls) and EAS hadron energy measured over 10×20 m^2 in the experiment 'Hadron' (black squares)[7]; the spectrum of single hadrons obtained in the Pamir X-ray emulsion experiment [8](open stars) and [9](black stars), both spectra are recalculated to 3340 m a.s.l. Lines - calculations for different variants of PCR spectra (see the text)

and 0.42 (QGSJET02)[12]. The calculation was performed in a wide energy intervals $10 \div 10^9$ TeV in accordance with a power law $F_0 \sim E^{-1.50}$ in the angular interval $0 \div 45°$, with threshold energy of secondary hadrons 300 MeV. The experimental procedure of EAS axes selection and hadron core energy, E_{cor}, measurement over an area 6×6 m^2 was also simulated.

Firstly we compare QGSJET01 and QGSJET02 models. QGSJET02 predicts by 30% a higher intensity for a single hadron spectrum and by 20% higher the intensity of core hadron energy spectrum for the case $F_0(E) \sim E^{-1.5}$. In a paper at this conference [5] it is shown that the average experimental spectrum of hadrons in one EAS with energy ~ 1 PeV is not described by QGSJET01, which predicts slightly lower (by $20-30\%$) numbers of hadrons. So further we will use only QGSJET02 model.

Secondly we calculated the effective value of a part of energy left in hadron component $K_{ef} =<$

$(E_{cor}/E_0)^{1.70} \quad >^{1/1.7}$ at the level 3340 m a. s. l. at measured energy $E_{cor} \sim 100$ TeV: $K_{ef}(H) = (0.043 \pm 0.02)$; $K_{ef}(He) = 0.024 \pm 0.02$; $K_{ef}(CNO) = 0.017 \pm 0.02$; $K_{ef}(Fe) = 0.0084 \pm 0.02$. Then for the rigidity dependent position of the knee at Ek(1)=3000 TeV we can expect the position of the knee in hadron component: $E_{cor}(knee) \sim 127$ TeV for protons, $E_{cor}(knee) \sim 144$ TeV for He nuclei, $E_{cor}(knee) \sim 306$ TeV for CNO group, $E_{cor}(knee) \sim 600$ TeV for Fe nuclei. It means that the knee in hadron component spreads only to 0.7 of the order, that is much narrower than $lg26 = 1.4$ in energy spectra and close to the conclusion made in [6]

In the third place we calculated $F(> E_{cor})$ and $F(> E_h)$ for different primary spectra $F_0(E)$ using weight factors.

3. PRIMARY CR SPECTRA APPROXIMATION AND RESULTS

As a basic approximation of the primary cosmic ray spectra we used the approximation

$$F_0(E) = I_0(Z)E^{-\gamma(Z))} \times (1+(E/Ek(Z))^S)^{-d\gamma/S} \quad (1)$$

used by J. Horandel in the poligonato model [2], where the 'all particle' spectrum is a sum of different nuclear components with charge Z having the intensity $I_0(Z)$ at 1 TeV, slope $\gamma(Z)$, energy of the knee $Ek(Z) = Z * Ek(1)$, and the slope above the knee $\gamma(Z) + d\gamma$. S characterizes the sharpness of the knee: S=1 for a smooth knee, S=4 for a very sharp knee. We describe here 4 variants of primary spectra used for the analysis.

I) In the first variant of calculations (dashed lines in Fig. 1) we used $I_0(Z)$, $\gamma(Z)$ as in table 7 in [2]: γp=2.71, γHe=2.64, γCNO=2.67, γFe=2.59 without knee. This variant predicts slightly steeper integral spectra of single hadrons 2.11 ± 0.02 than we see in mountain experiments. $F(E_{cor}) \sim E_{cor}^{-1.57 \pm 0.02}$ that is also more than 1.48 experimental value. Intensities of both calculated spectra are less than the experimental ones.

II) The second variant - poligonato model [2] with the knee $Ek(Z) = 4500 \times Z$ TeV, $d\gamma = 2.1$ (dotted lines in Fig 1). But every component does not abrupt to the zero above the knee but decreases by 10 times, then every nuclear component has the same slope as before the knee, so the spectrum of every nuclear component looks like a step. It contradicts to both experimental spectra by intensity.

III) In this variant we try to fit the data obtained in ATIC-2 [13] and Sokol direct measurements with the data obtained in the KASCADE experiment for different groups [14]. All particle, proton, helium experimental spectra and fits for them are presented in Fig. 2. The fits correspond to: $\gamma H = 2.67$, γHe=2.53, γN=2.65, $Ek(1) = 3000$ TeV, $d\gamma = 1.2$, S=4 (thick lines in Fig. 1). Above the knee the every component spectrum looks like a step, as in the variant II.

These approximations more or less describe the primary 'all particle' spectrum, proton and helium spectra as shown in Fig. 2. This variant explains the $F(> E_{cor})$ spectrum well by a slope, but intensity is slightly low. It also fits well $F(> E_h)$ spectrum measured by C-chambers [9], but does not describes the spectrum measured by Pb-chambers [8]. Here it is worth to note that the sharpness of the knee was chosen very high S=4, and only in this case can we reproduce the cleary seen knee in hadron component. All considered variants with $d\gamma$=0.5 ans S=1 (smooth knee) describe the data much worse.

IV) This is the III variant of PCR, but with smaller cross sections of interactions. The increase of the interaction pass can be imitated by a decrease of observation level H or by an increase of the average value of $\cos\theta$ of hadrons: $F(Eh) \sim exp{-}H/cos\theta\lambda$. For this aim we slightly changed the sample of simulated events increasing the average $\cos\theta$ by 6%. This variant is presented in Fig.1 as thin line. It describes the spectrum $F(E_{cor})$ slightly better, but $F(E_h)$ is described not so well.

4. CONCLUSION

From the comparison of CORSIKA+QJSJET02 calculations with different sets of experimental data of cosmic ray hadrons at mountain level one can conclude :

1) the rigidity dependent energy position of the knee $Ek(Z) = 3000 \times Z$ TeV and a moderate change of a spectrum exponent in this point (by $d\gamma$ 1.2 $\pm$ 0.03 with S=4) for every nuclear com-

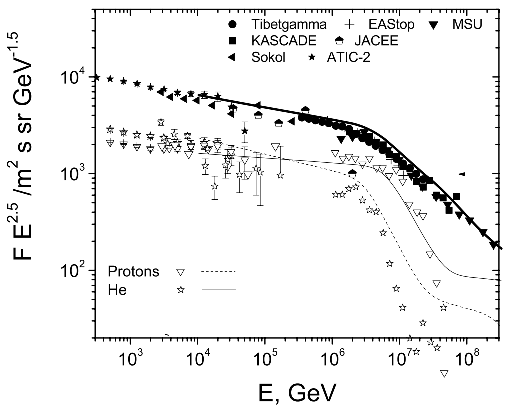

Figure 2. All particle spectrum measured in a number of EAS and direct experiments (full symbols) and the fit III (thick line). Proton spectra, measured in ATIC2 ([13], Sokol, KASCADE [14] (open stars) and the fit IV (thin line). Helium spectra measured in ATIC2, Sokol, KASCADE (open triangles) and the fit IV (dashed line).

ponent of PCR can reproduce the evident knee, detected in hadron component of EAS cores an Tien-Shan station;

2) variant IV of PCR (see text) with decreased (by 6%) cross sections of interactions fits the experimental intensity of spectra better than variant III with original cross sections of QGSJET02 model. Also the spectra of single hadrons obtained in the Pamir experiment [9] do not contradict this hypothesis, but the spectrum obtained in [8] contradicts it;

3) CORSIKA+QJSJET01 underestimates a hadron energy in EAS cores in the knee region.

Other variants of PCR were considered also, but not presented here. One can definitely say that all variants of PCR with steep proton and helium spectra ($\gamma > 2.7$ before the knee) and heavy nuclei in the knee evidently contradict the experiments. The variant of the pure poligonato model [2] with an abrupt of protons and helium nuclei above the knee down to zero is also not consistent with the experiments.

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