Proton-air cross section and transverse momentum in hadron interactions of primary cosmic rays at 0.3 - 3 PeV

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Abstract. **Tien Shan experimental data on hadron spectra at $0.5 - 30$ TeV and hadron lateral distributions at $0.5 - 5$ TeV in extensive air showers originated by $0.3 - 3$ PeV primary cosmic rays are compared with different model simulations including CORSIKA+(QGSJet 01 and QGSJet II). Conclusions are derived on growth of the proton-air production cross section and transverse momentum of secondary particles. Our results correspond to $(7 - 9)$% rise of the proton-air production cross section per one order of magnitude of energy increasing from the accelerator range to EAS one. Proton-air production cross section at $E_0 = 1$ PeV is equal to 350 ± 15 mb, if inelasticity coefficient is 0.65 ± 0.05. The experiment shows the expansion of hadron lateral distributions at primary energies above 1 PeV that points to the rise of the transverse momentum.**

***Keywords*: PeV EAS interactions.**

I. INTRODUCTION

An experiment was carried out at the Tien Shan cosmic-ray station of the P.N.Lebedev Physical Institute placed at an altitude of 3300 m a.s.l. (690 g·cm^{-2}) near city Almaty ($43.04°N, 76.93°E$). Our inferences on the cross section σ_{prod}^{p-air} and transverse momentum p_t in proton interactions with air nuclei were obtained by many experiments on extensive air showers (EAS) of primary cosmic rays (PCR) at energies $E_0 = 0.3 - 3$ PeV. The inferences were based on the comparison with various previous model simulations [1], [2], [3], [4]. Our conclusions were different from those of many other groups which have found a quickly growth of σ_{prod}^{p-air} with increasing energy. Recently we have compared our data on hadrons in EAS with results of modern model simulations by CORSIKA + QGSJet 01 and QGSJet II [5] and reaffirmed our previous conclusions about the hadron cross section and transverse momentum increasing from the energy range exploited with accelerators with fixed targets ($E_0 \simeq 0.1$ TeV, $\sigma_0 \approx 260$ mb) to the PCR "knee" energy range ($E_0 \approx 3$ PeV).

EAS parameters were estimated for the each event by data of multi-channel scintillation SC and GM counters placed in the centre of the set-up and at various distances from it (up to 200 m) at the Tien Shan array.

Some data on hadron energy characteristics have been obtained by means of the Tien Shan ionization calorimeter [6]. It consisted of 15 rows of copper ionization chambers put on the iron girder and was sandwiched by lead absorber. The total thickness of the absorber (Pb+Cu+Fe) was 875 g·cm^{-2}. The total square of the calorimeter was 36 m^2.

The lateral resolution of chambers was not quite enough to separate every individual hadron in all events. It is possible that an avalanche of several hadrons passed through the same ionization chamber. To exclude this effect, a special processing was carried out in order to select the energy of separate single hadrons from the avalanche in the calorimeter [7].

To test the validity of this processing, we compared hadron spectra obtained in this way with spectra obtained by means of X-ray emulsion films with the high lateral resolution. These X-ray emulsion films had been placed between the calorimeter rows for a certain time. The good agreement was found between these hadron energy spectra [1].

II. HADRON ENERGY SPECTRA

These spectra are very sensitive to interaction parameters, namely, to values of hadron cross-section, σ_{prod}^{h-air}, and inelasticity K_{in} in accordance with many simulation results and detail calculations [8] in the region $E_h = (1 - 10)$ TeV for EAS in the PCR's PeV region.

The advantage of their study at mountain levels in comparison with lower altitudes is that according to calculations, in this case the hadronic energy spectra in the ranges of E_0 and E_h under study depend only slightly on PCR nuclear composition.

We have obtained these spectra at $E_h = 0.5 - 50$ TeV in various intervals of the EAS electron-number size, N_e, from $1.5{\cdot}10^5$ to $1.5{\cdot}10^6$ ($E_0 = 0.3 - 3$ PeV). Dependence of the hadron energy E_h on the ratio N_h ($E_h > 1.0$ TeV)/N_{EAS} (N_h is the hadron number, N_{EAS} is the shower number in N_e interval under consideration) has been obtained for each N_e interval [1].

In our earlier paper [1] Tien Shan experimental data on the number of hadrons at $E_h > 1$ TeV had been compared with simulations [1], [9], [10], [11], [12]. These simulations were based on different extrapolations of parameters of hadron interactions from accelerator to

EAS energies. It was concluded that our experiment contradicts to simulations assuming constant ($\sigma_{prod}^{p-air} = 260$ mb) or rapidly increasing cross section $\sigma_{prod}^{p-air}(E_h)$. So, a slow rise of σ_{prod}^{p-air} (E) is preferable.

In this work we compare our data with results of model simulations by CORSIKA + QGSJet 01 and QGSJet II for different N_e intervals. Experimental and simulated energy spectra of hadrons in EAS with $N_e = 4 \cdot 10^5$ are presented in Figs.1 and 2. Spectra found by QGSJET 01 are shown in Fig.1 for different primary nuclei (p, He and O). Spectra found by both QGSJet 01 and QGSJet II are shown in Fig.2 for primary protons only.

One can see that number of hadrons in the experimental spectrum denoted by black circles exceeds the simulated one even for primary protons.

Decreasing of some difference between the experiment and the QGSJet II model in the comparison with the QGSJet 01 is the result of assumptions on some decreasing of K_{in} and $\sigma_{prod}^{\pi-air}$.

According to the QGSJet II-based simulation, the number of hadrons for a complex composition of PCR must be lower than for the primary protons only, so the difference between experimental and simulated data should be greater.

This demonstrates that the EAS dissipation of PCR energy in air is less than it is predicted by CORSIKA + QGSJet and some other modern models (MC0 [12], e.g.). For the agreement with our experiment, a some decrease of σ_{prod}^{p-air} is necessary as compared with CORSIKA + QGSJet models.

As is seen in Fig.1 the number of hadrons per the shower $N_h(> E_h)/N_{EAS}$ at $E_h \approx 1$ TeV is rather weakly dependent on mass number of PCR nuclei.

The comparison shows that the better agreement is achieved under saaumption that the proton production cross section in interaction with air nuclei, $\sigma_{prod}^{\pi-air}$, corresponds to $(7-9)$% increase per one order of energy magnitude from 0.1 TeV (accelerators with fixed targets) to 3 PeV (EAS).

For proton interactions $\sigma_{prod}^{p-air}(1PeV) = 350 \pm 15$ mb at $K_{in_p} = 0.65 \pm .005$ and $\sigma_{prod}^{p-air}/\sigma_{prod}^{\pi-air} = 1.30 \pm 0.08$.

Our conclusion is the following. σ_{prod}^{p-air} increases not more than by 10% per one order of energy magnitude.

This result reaffirms our previous conclusion [1], [3], [7] and agrees with measurements of EAS-TOP group (G.C. Trichero *et al*) [13] and with an extrapolation to HiRes data (K. Belov *et al*) [14] from $10^{14.5}$ to $10^{18.5}$ eV.

III. Hadron lateral distributions

The analysis of width of hadron lateral distributions (HLD) can give information on behavior of the transverse momentum P_t in interactions as a function of PCR energy E_0.

HLD had been obtained at hadron energies $E_h = 0.5 - 5$ TeV in narrow intervals of shower sizes, $N_e = (1.5-10) \cdot 10^5$ ($E_0 \simeq 0.3-3$ PeV), at distances $1-8$ m from the shower axis, where the main fraction of hadrons with such energies is localized.

In earlier studies [15] we used the quantity $Y = E_h \cdot R$ (here R is the distance between hadron and EAS axis) to estimate hadron lateral characteristics as a function of N_e. The correction to the method registration by our calorimeter was always taken into consideration (including [15]) .

We compared later the experimental HLD results with simulations [2], [4] assuming only a slight P_t increase in interactions of hadrons with air nuclei. Processes of jet generation were disregarded. The comparison was derived in a wider N_e range, namely, at $N_e = (0.05 - 15) \cdot 10^5$ ($E_0 = 0.05 - 3$ PeV). Only a slight growth of experimental width of HLD at $E_0 < 1$ PeV in agreement with simulations has been shown. However, the experimental HLD width increased more quickly at $N_e > 5 \cdot 10^5$ ($E_0 > 1$ PeV) that conflicted with these simulations.

In this study we compare the experimental HLD with that found by CORSIKA+QGSJet 01 simulations for EAS generated by different primary nuclei, namely, protons, helium and oxygen nuclei. The dependence of the number of hadrons, N_h, with $E_h > 0.5$ TeV at distances $R = 1 - 8$ m. from the shower axis for $N_e = 4 \cdot 10^5$ is shown in Fig 3. N_h is normalized to the summary number of hadrons at these distances.

One can see in Fig. 3 that the experimental distribution is wider then the simulated ones. This indicates a growth of P_t in the range $E_0 > 1$ PeV. The use of the modern QGSJet models leads to a better agreement of simulation results with our experimental data due to a more careful consideration of the interaction parameters, in particular, jet generation. However, QGSJet models, as a whole, cannot describe the experimental data.

IV. Conclusion

1. Comparison of Tien Shan experimental data on energy spectra of $(0.5 - 30)$ TeV hadrons in EAS from PCR at primary energies $E_0 = 0.3 - 3$ PeV with results of CORSIKA+QGSJet 01 and CORSIKA+QGSJET II model simulations shows that the experimental number of hadrons exceeds the simulated values. The CORSIKA+QGSJet II simulation results show a slight increase in the number of hadrons and somewhat better agreement with the experiment, apparently, due to the decrease in K_{in} and $\sigma_{prod}^{\pi-air}$ in comparison with the QGSJet 01. Our experiment conflicts with results of both previous simulations [1], [2], [3], [4] and CORSIKA+(QGSJet 01, QGSJet II) new models carried out under assumptions that cross section either increases sufficiently quickly to PeV interval or remain constant ($\sigma_0 = 260$ mb). Thus, a slow growth of $\sigma_{prod}^{p-air}(E)$ is preferable.

According to our data on hadron energy spectra, the proton cross sections in interactions with air nuclei increases no more then 10% per one order of energy

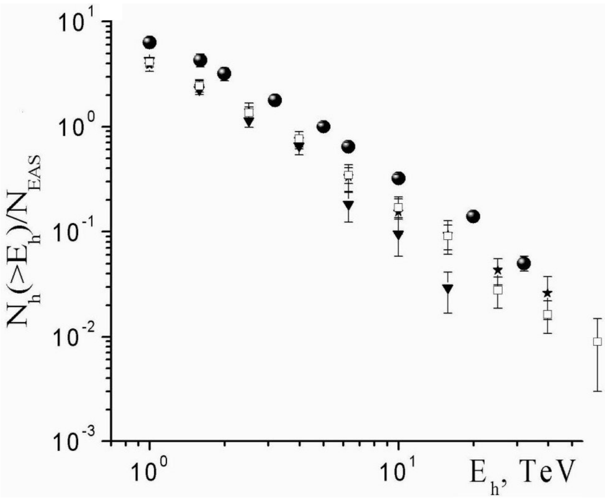

Fig. 1. The integral hadron energy spectrum per shower at $N_e = 4 \cdot 10^5 (E_0 \approx 1$ PeV). Notation: experimental data (black circles); QGSJET 01-simulated data: p (open squares), He (asterisks), O (triangles).

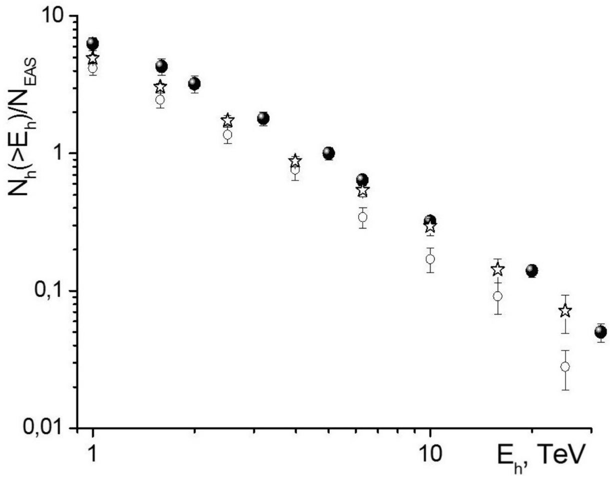

Fig. 2. The hadron integral energy spectrum at Tien Shan: the number of hadrons per shower for $N_e = 4 \cdot 10^5 (E_0 \approx 1$ PeV). Notation: experimental data (black circles); simulated data for primary protons: QGSJET 01 (open circles), QGSJET II (asterisks).

magnitude in the range from 0.1 TeV (accelerators with fixed targets) to 3 PeV (EAS).

In accordance with our estimates, the cross section is $\sigma^{p-air}_{prod}(1 \text{ PeV}) = 350 \pm 15$ mb on conditions that the inelasticity coefficient value is within the range 0.65 ± 0.05 and $\sigma^{p-air}_{prod}/\sigma^{\pi-air}_{prod} = 1.30 \pm 0.08$.

2. Comparison of Tien Shan experimental data on hadron lateral distribution (HLD) ($E_h > 0.5$ TeV) with results of CORSIKA+QGSJET 01 simulations shows that the experimental HLD is somewhat wider then the calculated one. This is in agreement with our previous conclusions [2] on a more rapid increase of the transverse momentum in hadron interactions with air nuclei for PCR in PeV energy region.

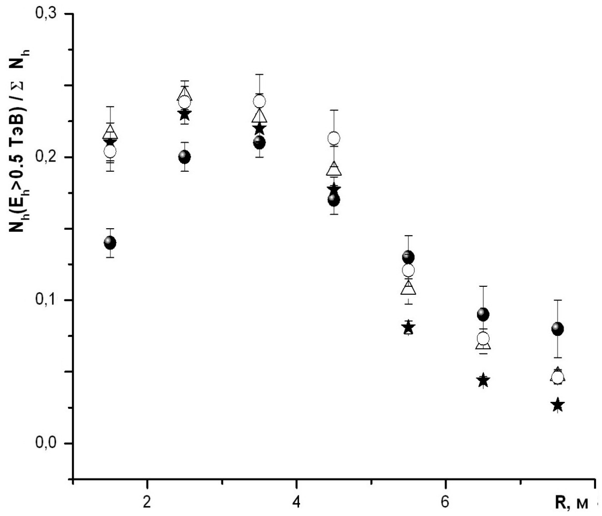

Fig. 3. Hadron lateral distributions: dependence of relative number of hadrons with $E_h > 0.5$ TeV in EAS with $N_e = 4 \cdot 10^5$ at distance R from the EAS core): experimental data (closed circles); QGSJET 01 simulation data for different primary nuclei: protons (asterisks), He (triangles), and O (open circles).

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REFERENCES

[1] T.V. Danilova,A.G. Dubovy, A.D. Elykin *et al.*. Proc. 20th ICRC, Moscow**6**(1987) 47.
[2] A.G. Dubovy, N.M Nesterova, A.P. Chubenko *et al*. Nucl. Phys. (SU, in Russian).**54**, no. (7), (1991) 178.
[3] A.G. Dubovy, N.M Nesterova, A.P. Chubenko *et al.*. Proc.18th ICRC, Bangalore. **6** (1983) 163.
[4] A.M. Dunaevsky, Yu.A. Emelyanov. Proc.17th ICRC, Paris. (1981) He 5.
[5] S. Ostapchenko. hep- ph/0412302; hep-ph/0501093. (2005).
[6] D.S. Adamov, Arabkin, K.V., Barkalov K.V. *et al.*. Proc. 20th ICRC, Moscow. **6** (1987) 144.
[7] A.G. Dubovy, N.M Nesterova, V.P.Pavlyuchenko *et al.*. Bulletin of Russian Academy of Sciences, Ser. Phys. **71**, no 4 (2007)551.
[8] V.A. Litvinov and V.V.Uchaikin. Izvestiya Vuzov MV i SSO SSSR, ser. Fizika. Tomsk. (1985) 160.
[9] N.N. Kalmykov, G.B. Khristiansen, M.V. Motova. Proc. 19th ICRC, La Jolla. **7** (1987) 44.
[10] R.A. Antonov *et al.*. Voprosy atomnoi nauki i tekhniki **29** (1986) 39 (in Russian).
[11] J. Kempa. Nuovo Cimento. **31** (1986) N 4, 568.
[12] Fedorova G.F. and Mukhamedshin R.A. Bull. Soc. Sci. Lettr. Lodz. SER. Rech Ref.XVI. (1994) 137.
[13] G.C. Trichero *et al.* Proc. 15th ISVHECRI (2008) (to be published in Nucl. Phys.Proc.Suppl. B.)
[14] K. Belov *et al*. Proc. 29th ICRC, Pune. **7** (2005) 343.
[15] V.A. Romakhin and N.M. Nesterova. Cosmic Rays and Nuclear Interaction at High Energies. Trudy FIAN, **109** (1979) 77 (in Russian).