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Tien Shan experimental results on the inelastic proton-air cross section at 0.5 – 5 PeV

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Abstract. The analysis of experimental data from the Tien Shan complex array on extensive air showers originated from 0.5-5 PeV primary cosmic rays is presented. Conclusions are made on the rise of the inelastic proton–air cross section with energy on the base of comparisons with different interaction models. The analysis showed that the rise conforms to (7-9) % per one order of energy from 0.2 TeV (accelerator experiments with fixed targets) to 5 PeV (cosmic rays). These data correspond better to the new QGSJET-II-04 version of the interaction model based on the recent LHC results. This model predicts the slower rise of the cross-section than previous versions of QGSJET-II models.

Keywords extensive air showers, inelastic p–air cross-section at 0.5-5 PeV.

1. Introduction
Many years we attempted to find the law of the rise with energy of the inelastic proton–air cross section $\sigma_{p\text{-}air}$ on the base of the Tien Shan EAS complex array data (starting works [1,2]). The complex array contained detectors of hadrons (the ionization calorimeter), electrons (scintillation and GM counters), muons and Cherenkov light components of extensive air showers (EAS) initiated by primary cosmic rays (PCR). Results of these data analysis were compared with many different former and modern simulation models. Our permanent conclusion is that $\sigma_{p\text{-}air}$ rises slowly as it is predicted by the new QGSJET-II-04 model. In the past our inference conflicted with conclusions of many groups.

2. Experimental results and comparisons with different models
The review of our investigation of $\sigma_{p\text{-}air}$ in EAS at PCR energies $E_0 = 0.5$-5 PeV is presented in this report. EAS were classified according to the total number of electrons $N_e$ ($N_e \sim E_0$) at the Tien Shan level ($43.04\ N; 76.93\ E; P=685\ \text{g cm}^{-2}$).

Firstly Cherenkov light lateral distributions at 50 - 250 m from the axis of EAS at $E_0 = 1$-10 PeV of PCR based on experiments at the Tien Shan and the former Pamir arrays were compared with model calculations [4].

Then experimental EAS “cascade curves” ($N_e$ as a function of depth of the atmosphere $P$ at the constant EAS intensity) were compared with calculations at $E_0 > 2$ PeV as well [5] (figure 1).

Models of simulations with various rise of the inelastic proton–air cross section $\sigma_{p\text{-}air}$ were examined in [4,5]. Conclusions were made from these experiments that $\sigma_{p\text{-}air}$ rise is $\sim (7-8)\ %$ per one order of energy magnitude up to 10 PeV in spite of some uncertainty of PCR mass composition.
The main conclusion was made on the base of analysis of EAS hadron energy spectra at hadron energies \( E_h > 1 \) TeV of EAS in various intervals of electron number \( N_e \). The special procedure of the processing for hadron separation was described in [6].

It was shown on the base of many simulations that the number of hadrons \( N_h (E_h=1 – 5 \) TeV) is practically independent of PCR mass composition at \( E_0 = (0.5 – 5) \) PeV, but it is sensitive to some interaction parameters, especially to \( \sigma_{p\text{-air}} \) and inelasticity coefficient \( K_{\text{inel}} \).

Formerly experimental results on \( N_h (E_h>1 \) TeV, \( N_e) \) were compared with early calculation models [2,7,8,9,10,11] for different \( \sigma_{p\text{-air}} \) values at \( K_{\text{inel}} = \text{var} \). Experimental and model data are presented in figure 2, where number of hadrons \( N_h (E_h> 1 \) TeV) per one shower divided by electron number \( N_e \) is shown. These data are shown as a function of increase of \( \sigma_{p\text{-air}} \) in terms of per cent per one order of \( E_0 \) (lower scale) and of \( \alpha \) (upper scale), where \( \alpha \) characterizes the increase of the cross section by the extrapolation: \( \sigma_{p\text{-air}} = \sigma_0 (1+\alpha \ln E_0) \), where \( \sigma_0 = 260 – 270 \) mb.

\[ \text{Figure 1. } N_e \text{ vs. atmosphere depth } P (\text{g cm}^{-2}) \text{ at a constant EAS intensity. Notations: 1 – 0\%, 2 – 7\%, 3 – 10\% of } \sigma_{p\text{-air}} \text{ rise per order of } E_0. \]

\[ \text{Figure 2. Hadron numbers } N_h (E_h> 1 \text{ TeV}) \text{ per shower } N_{\text{eas}} \text{ and } N_e \text{ vs. rise of proton cross sections } \sigma_{p\text{-air}} \text{: lower scale is } \% \text{ per the order of } E_0 \text{; upper scale is } \alpha \text{ (see the text). Models: black squares show } K_{\text{inel}}=0.55 \text{ (upper) and } K_{\text{inel}} = 0.65 \text{ (lower), empty squares show } K_{\text{inel}} = 0.72. \text{ Two straight lines parallel to horizontal axes show experimental boundaries.} \]
Data on $N_h$ ($E_h>1$ TeV, $N_e$) in figure 2 as well as our data on EAS Cherenkov light and “cascade curves” indicate that rise of $\sigma_{p\text{-}air}$ is 7 – 9% and $\sigma_{p\text{-}air}$ (1 PeV) = (350±15) mb, if the inelasticity coefficient is $K_{\text{inel}} = 0.65±0.05$ and $\sigma_{p\text{-}air/}\sigma_{\pi\text{-}air}=1.30±0.08$.

Thereafter we compared [12] the experimental energy spectra of hadrons with CORSIKA + QGSJET modern models with the same experimental and calculated intervals of $N_e$. Spectra for different primary nuclei (p, He, O) were examined by QGSJET 01. Calculations show that the number of hadrons per shower, $N_h/N_{EAS}$, at $E_h= (1 – 5)$ TeV and at $E_0 \approx 1$ PeV is practically independent of the PCR mass composition. The number of hadrons in the experiment exceeds the number in the model. The difference between spectra of protons and nuclei appears at $E_h>5$ TeV, but the number of hadrons in nuclei is even lesser than for protons, and the difference increases with our experiment.

Then we compared the experimental spectra with data of QGSJET-II model for primary protons [13]. Results of the comparison with initial QGSJET-II indicated that the number of hadrons in the experiment outnumbers the simulated number too. One can explain it as a slower dissipation of the PCR energy in air and a decreasing of $\sigma_{p\text{-}air}$. The decrease of some difference between the experiment and QGSJET-II in comparison with the QGSJET 01 can be explained due to lower values of $K_{\text{inel}}$ and $\pi$–air cross-section $\sigma_{\pi\text{-}air}$ in QGSJET-II. In these initial versions of QGSJET models $\sigma_{p\text{-}air}(1$ PeV)$ \approx 385$ mb and $\sigma_{p\text{-}air}$ rise is about 11% per one order of $E_0$. These values are somewhat more than by our estimates.

The new version of QGSJET-II model (QGSJET-II-04) was presented at 32nd ICRC [14]. Changes of model were based on analysis of recent LHC data on soft multi-particle production. In the new version the rise of $\sigma_{p\text{-}air}$ is about (8 – 9) % per one order of $E_0$ and $\sigma_{p\text{-}air}$ (1 PeV) $\approx 360$ mb. That rise is lower than in previous versions of QGSJET-II and better corresponds to our experimental data. Data of calculations (taken from [14]) and our experimental result as well as other experimental data of last years at $E_0 > 0.1$ PeV are shown in figure 3.

![Figure 3. Proton-air cross section $\sigma_{p\text{-}air}$ vs PCR primary energy $E_0$ by the new version of QGSJET-II-4 (solid line), QGSJET-II-03 (dashed line), SIBYLL (dot-dashed line). Notation: Tien Shan data (circle) and recent experimental data.](image-url)
3. Conclusion

Our analysis based on Tien Shan experimental results on EAS of PCR at 0.5 – 5 PeV always shows a slow rise of the cross section $\sigma_{p\text{-air}}$ with increasing energy. Conclusions are based on comparison of different models with experimental data on EAS hadron spectra as well as EAS Cherenkov light lateral distributions and “cascade curves”, $N_e$ (P). This rise of the inelastic proton–air cross section corresponds to (7-9) % (not more than 10%) per one order of energy magnitude from 0.2 TeV (accelerators with fixed targets) to 5 PeV (EAS).

The main conclusion made on the base of the method of analysis of EAS hadron energy spectra at $E_h >1$ TeV. This value has an advantage that it is almost independent of mass composition of PCR at $E_0=0.5 – 5$ PeV in accordance with QGSJET models and other former model calculations.

If conclusions based on experimental data are right, dissipation of the PCR energy in air is less than it is predicted by such models as CORSIKA+ QGSJET-01, old QGSJET- II (-01, -02, -03), SIBYLL, MC0 [11] and some previous models. In our recent works [12,13] the conclusion was made that it would be desirable to decrease $\sigma_{p\text{-air}}$ in QGSJET-01 and old QGSJET- II models. The new version of QGSJET-II model (QGSJET-II-04) [14] corresponds better to our and other recent data (HiRes, Ulrich et al., Knurenko et al., Aglietta et al.). However these experiments permit yet some small slowdown of the inelastic proton–air cross section rise.

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