EPJ Web of Conferences **145**, 19001 (2017) DOI: 10.1051/epjconf/201714519001
ISVHECRI 2016

Inelastic proton-air cross section growth from 0.2 TeV to 10 PeV according to TIEN SHAN experimental cosmic ray data

Comparison with various models

N. Nesterova[a]

P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia

Abstract. Conclusions are made about the increase with energy of the inelastic proton air cross section σ_{p-air} from 0.2 TeV (accelerator experiments with fixed targets) to 10 PeV (cosmic rays). Experimental data from the Tien Shan complex array on various components (mainly hadron, Cherenkov light, and electron) of extensive air showers at 0.5–10 PeV of primary cosmic rays are analyzed. They were compared with many results of different calculated models of cosmic ray interactions in the atmosphere. The analysis showed that the rise conforms to (7–9)% per one order of energy. These data correspond better to the QGSJET-II-04 version of the interaction model based on the recent LHC results. This model predicts better the slower rise of the cross-section than previous versions of QGSJET-II and some other models.

1. Introduction

The purpose of this work is to find the law of the rise of σ_{p-air} – the inelastic protonair cross section - with increasing primary cosmic ray (PCR) energy. It was done using the Tien Shan complex array experimental data at PCR energies, $E_0 = 0.5 - 10\,\text{PeV}$, and their extrapolation from 0.2 TeV (accelerator experiments with fixed targets). Our initial publications are to be found in references [1–5]. Experimental data of various components (mainly hadrons, electrons and Cherenkov light in the atmosphere) of extensive air showers (EAS) initiated by PCRs were compared with many different former and modern models. Comparisons are also shown with some other experimental data up to Very High Energies (VHE).

2. Experimental results and comparisons with different models

The complex Tien Shan array (43.04 N, 76.93 E, $P = 685\ \text{g}\cdot\text{cm}^{-2}$) comprises different EAS detectors: hadrons (the ionization calorimeter), electrons (scintillation and GM counters), muons (underground GM counters) and detectors of atmospheric Cherenkov light [5]. EAS were classified according to the total number of electrons N_e ($N_e \sim E_0$) at the Tien Shan level.

Firstly the Cherenkov light Q (photon$\cdot$m^{-2}) lateral distributions at $R = 50 - 250$ m from the axis of EAS at PCR $E_0 = 1 - 10\,\text{PeV}$ based on experiments at Tien Shan [6] (Fig. 1) and the former “Pamir” [7] arrays were compared with model calculations. After that, experimental EAS “cascade curves” of electrons (N_e as a function of the atmosphere depth P (g$\cdot$cm^{-2}) at $E_0 > 2\,\text{PeV}$ (at a constant EAS intensity) were received for comparing with calculations [8] (Fig. 2). In these models various theoretical rates of increase of the inelastic proton–air cross section σ_{p-air} were used: 0%, 7%, and 10% per one order of E_0 from $\sigma_0(0.2\,\text{TeV}) = 265\,\text{mb}$ (accelerator data). Conclusions were made from these experiments that the σ_{p-air} rise is (7–9)% per one order of energy. Our inference conflicts with earlier conclusions of many other experimental groups and even with some models.

The main conclusions were made on the basis of the analysis of EAS hadron energy spectra at hadron energies $E_h > 1$ TeV of EAS in various intervals of electron number $N_e(E_0)$. The special procedure of the processing for separation of each individual hadron was described in [9].

Many simulations showed that the number of hadrons $N_h(E_h = 1 - 5\,\text{TeV})$ at $E_0 = (0.5\text{–}10)$ PeV is practically independent of PCR mass composition, but is sensitive to some interaction parameters, especially to σ_{p-air} and the inelasticity coefficient, K_{inel}.

Initially [3,4] experimental results on $N_h(E_h > 1\,\text{TeV}, N_e)$ were compared with former calculation models [10–14] for different σ_{p-air} values at the inelasticity coefficient $K_{inel} = var$. Data on $N_h(E_h > 1\,\text{TeV}, N_e)$ indicate that the rise of σ_{inel}^{p-air} is 7–9% and $\sigma_{inel}^{p-air}(1\,\text{PeV}) = (350 \pm 15)\,\text{mb}$.

After that we compared the experimental hadrons energy spectra with the modern CORSIKA + QGSJET models for the same $N_e(E_0)$. Values of $N_e(E_0)$ were received in the special calculations. Spectra for different primary nuclei (p, He, O) were examined using the QGSJET-01 model. Energy spectra of hadrons at Tien Shan for PCR $E_0 = 1\,\text{PeV}$, $3\,\text{PeV}$, $10\,\text{PeV}$ are shown in Fig. 3. Calculations show that the number of hadrons per shower, N_h/N_{EAS}, at $E_h = (1\text{-}5)$ TeV is practically independent of the PCR mass composition. So, the number of hadrons in the experiment exceeds the number in this version of the QGSJET-01 model. Experimental data confirms the correctness of our conclusions up to 10 PeV PCR energies.

Then we compared experimental spectra with data of the QGSJET-II-03 model version for primary protons

[a] e-mail: nester@sci.lebedev.ru

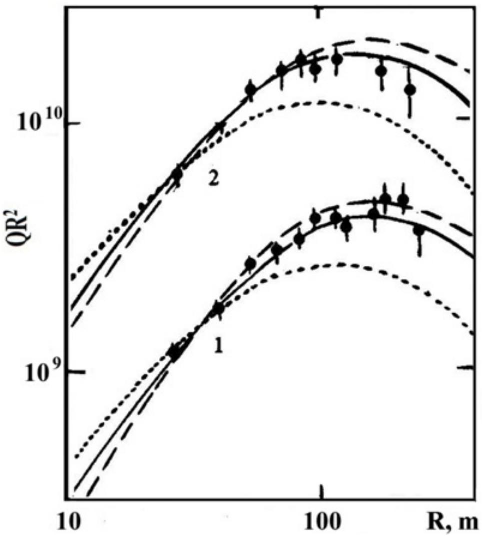

Figure 1. Cherenkov light lateral distributions at Tien Shan. 1. $E_0 = 2\,\mathrm{PeV}$, 2. $E_0 = 9\,\mathrm{PeV}$. Dashed line -0%, solid line -7%, dotted -10% σ_{inel}^{p-air} rise per one order of E_0.

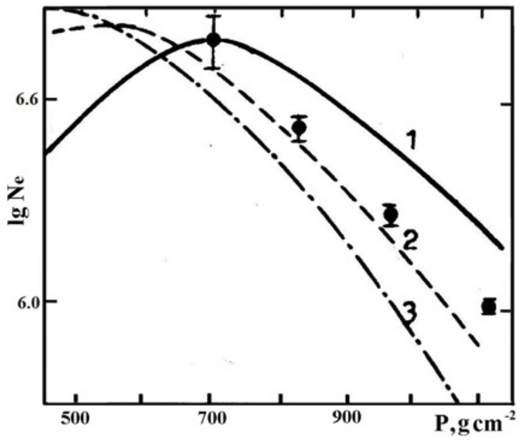

Figure 2. N_e vs. the atmospheric depth P (g·cm^{-2}) at $E_0 > 2\,\mathrm{PeV}$ for a constant intensity of EAS. 1. 0%, 2. 7%, 3. 10% – σ_{inel}^{p-air} rise per order of E_0.

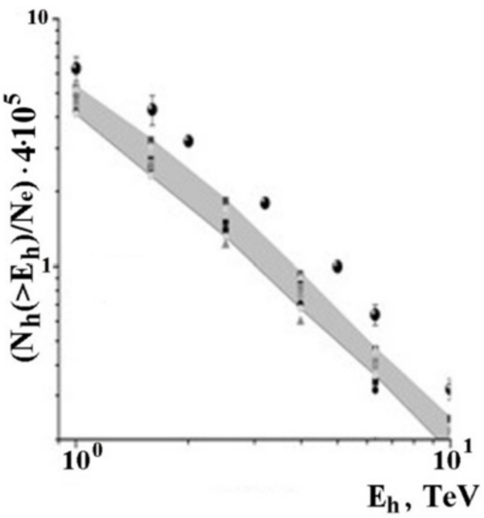

Figure 3. Hadron energy spectra at Tien Shan. The number of hadrons per shower (normalized to $N_e = 4 \cdot 10^5 (E_0 \approx 1\,\mathrm{PeV})$. $E_0 = 1\,\mathrm{PeV}$ (black), 3 PeV(grey), 10 PeV (light grey), from primary nucleus: P (squares), He (circles), O (triangles) – shaded area – QGSJET-I model. Experiment: black circles.

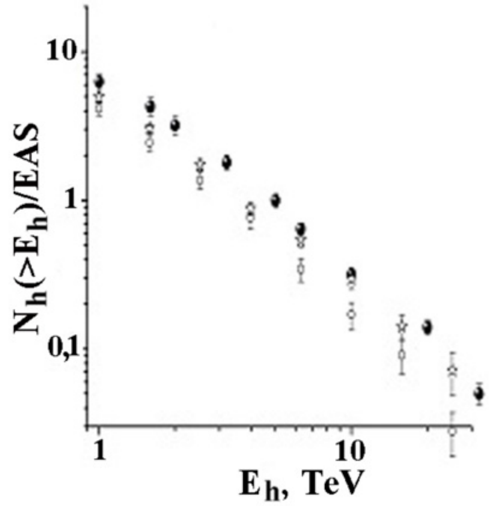

Figure 4. Hadron energy spectra at Tien Shan. The number of hadrons per shower for primary protons $E_0 = 10^{15}\,\mathrm{eV}$ ($N_e = 4 \cdot 10^5$): CORSIKA+QGSJET-I – white squares, CORSIKA+ QGSJET-II white star, Experiment: black circles.

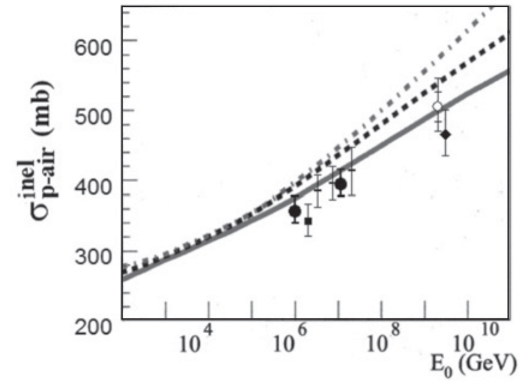

Figure 5. Proton-air cross section σ_{inel}^{p-air} vs PCR primary energy E_0. Versions: QGSJET-II-4 (solid line), QGSJET-II-03 (dashed), SIBYLL (dot-dashed). Notation: Tien Shan data -two black circles, EAS Top- black square, Yakutsk-dashes, Age- white circles, Diamonds-HiRes.

(Fig. 4). Results of the comparison with QGSJET-II-3, indicated that the number of hadrons in the experiment outnumbers the number in this model too. The difference between the experiment and the QGSJET- II-03 model was smaller in comparison with the QGSJET-I. It can explain smaller values of K_{inel} and $\sigma_{inel}^{\pi-air}$ in QGSJET II-03.

It is necessary to decrease σ_{inel}^{p-air} in these versions of QGSJET models. In these initial versions σ_{inel}^{p-air} (1 PeV) ≈ 385 mb and σ_{inel}^{p-air} rise is about 11% per one order of E_0. These values are somewhat more than our estimates.

The new version of the QGSJET-II model (QGSJET-II-04) was presented at the 32nd ICRC [15]. Changes of model were based on an analysis of LHC data on soft multi-particle production. In the new version the rise of σ_{inel}^{p-air} is about (8–9)% per one order of E_0. This rise is slower than in previous versions of QGSJET-II and corresponds better to our experimental data. Data of calculations and our experimental result as well as many other experimental data of recent years at $E_0 > 0.1\,\mathrm{PeV}$ are shown in Fig. 5.

3. Conclusion

Our analysis based on Tien Shan experimental results on EAS produced by PCRs at 0.5–10 PeV shows a slow rise of the inelastic protonair cross section σ_{inel}^{p-air} with increasing PCR energy [1–4]. Conclusions are based on a comparison of different models with experimental data on hadron energy spectra as well as EAS Cherenkov light lateral distributions in the atmosphere and electron cascade curves: $N_e(P)$. This rise of σ_{inel}^{p-air} corresponds to (7–9)% (not more than 10%) per one order of energy magnitude from 0.2 TeV (accelerators with fixed targets) to 10 PeV (EAS).

This corresponds to σ_{inel}^{p-air} (1 PeV) $\approx$ 350 mb and σ_{inel}^{p-air}(10 PeV) $\approx$ 380 mb.

The main conclusions were made on the basis of the method of analysis of EAS hadron energy spectra at $E_h > 1$ TeV. This value has the advantage that it is almost independent of mass composition of PCR at $E_0 = 0.5 -$ 10 PeV in agreement with QGSJET models and other former models. If conclusions based on experimental data are correct, the dissipation of the PCR energy in air is less than predicted by models such as CORSIKA+ QGSJET-I, old QGSJET-II (−01, −02, −03), SIBYLL and some previous models. In our recent work [3,4] the conclusion was made that it would be desirable to decrease σ_{inel}^{p-air} in QGSJET-I and old QGSJET-II models. The new version of QGSJET-II model (QGSJET-II-04) [15] corresponds better to our data and for some other data (HiRes, PAO, Ulrich et al. [16], Yakutsk, Knurenko et al. [17], EAS-TOP, Aglietta et al. [18]).

The author thanks colleagues in the development and operation of the Tien Shan array and help in the process of the work and L.G. Sveshnikova for the calculation.

References

[1] Chubenko A.P., Dubovoy A.G., Nesterova N.M. et al., Proc.18th ICRC (1983) **6**, p. 163
[2] Danilova T.V, Dubovy A.G., Krutikova N.P. et al. Proc.20th ICRC, Moscow (1987) **6**, p. 47
[3] Chubenko A.P., Dubovy A.G., Mukhamedshin R.A. et al., LG, 2009, Proc. 31st ICRC (Lodz) isrc0222
[4] Nesterova N.M., Sveshnikova L.G., 2009, Bull. RAS **73**, 612
[5] D.S. Adamov., V.V. Arabkin, K.V. Barkalov et al., Proc. 20-th ICRC, (1987) HE.6, 144
[6] Afanasiev B.N., Nesterova N.M. and Khein L.A., BLPH (1987) **3**, 42
[7] A.E. Chudakov, N.M. Nesterova. Nuovo Chimento N.2 Supplimento. (1955) **8**, Ser. X, p. 606
[8] Barkalov K.N., Dubovy A.G., Dyatlov P.A., BLPH (1987) **12**, 25
[9] N. Nesterova, Journal of Physics. Conference (2013) **409**, 012066
[10] Kalmykov N., Khristiansen G.B. and Motova M., Proc. 19th ICRC (La Jolla) (1985), **7**, 44
[11] Dunaevsky A.M. and Emelyanov Y.A., Proc. 17th ICRC (Paris) (1981), HE 5
[12] Ivanenko I.P., Kanevsky B.L. and Roganova T.P., Sov. J. Nucl. Fiz. (1979) **29**(3), p. 694
[13] Kempa J., Nuovo Cimento (1976) **31**(4), p. 568
[14] Fedorova G.F., Mukhamedshin R.A., Bull. Soc. Sci. Letter (Lodz) (1994) SER. Rech. Def., XVI, 137
[15] Ostapchenko S. Proc. 32nd ICRC (Beijing) (2011), HE 1.3, 681
[16] Pierre Auger Observatory Collaboration. Phys. Lett. B (2010) **685**, 239–246
[17] P. Knurenko, A.V. Sabourov. EPJ Web of Conferences (2013) **53**, 07006
[18] M. Aglietta et al., Phys. Rev. D (2009) **79**, 032004