Possibility of determining the energy dependence of the hadron-nucleus cross section and of the multiplicity within the framework of the scaling-violation model at $x \lesssim 0.1$

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It is shown that a large aggregate of experimental data obtained in cosmic rays does not contradict scaling in the fragmentation region of the incident hadron, violation of scaling in the pionization region with $\langle n_{\rm pion}\rangle \sim E^{0.4-0.5}$, and the associated violation of the growth of the cross section $\sigma(E) = \sigma_0(1 + a_h \ln E)$ up to $E \sim 10^6$ TeV.

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Investigations of the energy dependence of the cross section of inelastic interaction of hadrons in accelerators at energies 20–300 GeV in cosmic rays up to $E \sim 50$ TeV shows that when hadrons interact with nuclei of air this cross section can be represented in the form

$$\sigma_{hA}^{in}(E) = \sigma_{hA}^{0,in}(E_0)[1 + a_h \ln(E/E_0)],$$

where $h - N, \pi^{\pm}$, $E_0 \sim 0.1$ TeV, $\alpha_h = 0.02$–0.05, $\sigma_{NA}^{0,in}(E_0) = 273$ mb. We assume that $\sigma_{NA}^{ih}(E) \approx 1.2\sigma_{\pi A}^{in}(E)$ at $E \sim 1$ TeV and $\alpha_\pi/\alpha_N = \sigma_{NA}^{in}/\sigma_{\pi \pm A}^{in}$.

We associate the growth of the cross section with violation of scaling in the pionization region. We represent the inclusive distribution function $f_e(x,E^*)$ in the form of a sum of scaling ($F_c^{\rm sc}$) and nonscaling ($F_c^{\rm nsc}$) parts (E^* is the energy in the c.m.s.), $F_c(x,E^*) = F_c^{\rm sc}(x) + F_c^{\rm nsc}(x,E^*)$, where

$$F_c^{\rm nsc}(x, E^*)/\sigma_{hA}^{0,in} = \begin{cases} \eta\,\{2\ln E^*/E_0^*\}^{\delta}(x^2 + 4\langle m_\perp^2\rangle/E^{*2})^{-\beta} & \text{if } x < x_0 \\ 0 & \text{if } x > x_0. \end{cases}$$

Here $\beta \lesssim 0.5$, $x_0 \approx 0.1$, $\langle m_0\rangle \approx 0.4$ GeV is the transverse mass of the pion, $\delta = 0$ at $\beta = 0.5$ and $\delta = 1$ at $\beta < 0.5$, c is the channel of the reaction $h + A \to c + X$. Using the inclusive sum rules and assuming that in the central region $F_{\pi^\cdot}(x,E^*) = F_{\pi^0}(x,E^*)$ we find that $\eta = 2\alpha_h/3$ at $\delta = 0$ and is equal to $0.33\,\alpha_h(1 - 2\beta)x_0^{2\beta-1}$ at $\delta = 1$. The multiplicity $\langle n_{\rm pion}\rangle$ of the particles in the pionization region in the forward cone, which is connected with the increase of the cross section, is proportional to $E^{0.5}$ at $\delta = 0$ and $\beta \approx 0.5$ and to $\sim \ln(E/E_0)E^{\beta}$ at $\delta = 1$ and $\beta < 0.5$. The secondary mesons due to the nonscaling processes acquire an energy $\Delta(E^*) = 2\alpha_h \ln(E^*/E_0^*)/(1 + 2\alpha_h \ln[E^*/E_0^*])$. The structure functions for the non-leading particles of the scaling process are chosen in the form $F_c^{\rm sc}(x) = A_{N,\pi}(1 - x)\exp(-B_{N\pi}x)$, where $A_{N\pi} = 1.2$, $B_N = 5.56$ and $B_\pi = 4.76$ for the processes $N(\pi^{\pm}) + A \to \pi^{\pm,0} + X$, respectively. We assumed that in collisions of hadrons with nuclei the structure function for the leading particles remains unchanged. This leads to a decrease of the fraction of the energy of the leading particle by approximately 50% at 10^6 GeV. The charge-exchange process $\pi^{\pm} \rightarrow \pi^0$ will not be considered separately. To describe the interaction of cosmic-ray nuclei we assume a modification of the independent-collision model.[1] The characteristics of single muons, hadrons, and gamma quanta and of their families were calculated in Refs. 2–6 using models in which the cross section increases on account of scaling violation in the pionization region. In all these studies, the behavior of $f(x)$ was significant only in the fragmentation region.

Using the analytic method described in Ref. 5 for the solution of the equations, we calculated the absolute intensities and the energy spectra of the gamma quanta and hadrons in the depth interval $20 \lesssim z \lesssim 750$ g/cm^2 and energy interval $1 \lesssim E \lesssim 10^2$ TeV. The results of the calculations at $\alpha_N = 0.03$ agree with the experimental data[7,8] within the limits of errors. The absorption ranges $\lambda_{\gamma,\text{exp}} = 95 \pm 5$ g/cm^2 and $\lambda_{h,\text{exp}} = 100 \pm 10$ g/cm^2 for particles of energy $\sim$3–10 TeV at $\alpha_N = 0.03$ agree with the calculations. The calculated spectra of the muons at sea levels in the energy interval 1–70 TeV at $\alpha_N = 0.03$ agree with experiment.[9]

The spectra of the γ families over ΣE_γ at $200 \lesssim z \lesssim 700$ g/cm^2 and the energy spectra of the γ quanta in the families with given ΣE_γ at mountain altitudes, calculated at $\alpha_N = 0.03$ agree with experiment.[10] The distribution of the γ families with respect to the particles they contain with energies larger than 2 TeV at a depth $z = 550$ g/cm^2 also agrees with experiment at $\alpha_N = 0.03$. The absorption ranges of the γ families with energy $\Sigma E_\gamma \sim 50$ TeV are $\lambda_{\text{exp}} = 90$–$100$ g/cm^2 at a depth $z \sim 500$ g/cm^2 and $\lambda_{\text{exp}} = 103 \pm 15$ g/cm^2 in the depth interval $225 \lesssim z \lesssim 700$ g/cm^2, while the calculated values λ_{calc} at $\alpha_N = 0.03$ are 96 and 105 g/cm^2 respectively, whereas at $\alpha_N = 0$ their values are 155 and 160 g/cm^2, Monte Carlo calculations[3,11] with allowance for the fluctuations yielded for λ_{calc} at $225 \lesssim z \lesssim 700$ g/cm^2 and $\alpha \approx 0.03$ and $\alpha = 0$ the values 104 and 155 g /cm^2, respectively.

The cascade curves for the total number of electrons N_e of an extensive air shower with energy E up to $\sim 10^6$ TeV in the depth (z) intervals 500–1000 g/cm^2 (Ref. 12) and 200–500 g/cm^2 (Ref. 13) agree with the calculation at $\alpha_N = 0.03$ and $\langle n_{\text{pion}} \rangle \sim E^{0.5}$. For the same choice of parameters the experimental data on $\lg J\, [N_e \lg J (N_e > 10^6)]$ (Ref. 13) also agree with the calculations. The experimental dependences of the number of muons with energy above 10 GeV on the number of electrons N_e at sea level[14] and the dependences of the number of hadrons N_H with energy higher than 1–8 TeV on the number of electrons at mountain altitudes[14] agree with the calculations at $\alpha_N = 0.03$–0.05 and $\langle n_{\text{pion}} \rangle \sim E^{0.4-0.5}$. At the same values of the parameters, the ratios E/N_e and Q_{Cer}/N_e (Q_{Cer} is the integral of the Cerenkov light, measured by using Cerenkov light for showers at sea level, agree with the calculated ones up to $E \sim 4 \times 10^6$ TeV.[15]

The foregoing analysis shows that a single component of cosmic rays and families of γ quanta at depths above 200 g/cm^2 are sensitive to the integral characteristics of the structure function in the fragmentation region and the dependence of the cross section on the energy, whereas the form of the cascade curve of extensive air showers, their altitude dependence, the number of hadrons and muons in the shower, and the data on Cerenkov light are in addition also sensitive to the behavior of the structure function in the pionization region. Experimental data up to energies $E \sim 4 \times 10^6$ TeV do not contradict the prediction made by Logunov and co-workers[16] that the multiplicity increases in the pionization region, $\langle n_{\text{pion}} \rangle \sim E^{0.4-0.5}$

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[1]G.B. Khristiansen *et al.*, Kosmicheskoe izluchenie pri sverkhvysokikh énergiyak (Cosmic Radiation at Ultrahigh Energies), Atomizdat, 1975.
[2]A.M. Dunaevskiĭ, Preprint FIAN, No. 150, 1975; A.M. Dunaevski *et al.*, Proc. Fourteenth ICRC **7**, 2562 (1975); Proc. Fifteenth ICRC **7**, 337 (1977); Zeszyty Nauk. Univ. Lodz 199 (1975); J. Wrotnijak *et al.*, Zeszyty Nauk. Univ. Lodz 165 (1977).
[3]V.A. Astafiev *et al.*, Proc. Fifteenth ICRC **7**, 304 (1977); Zeszyty Nauk. Univ. Lodz 289 (1977).
[4]N.L. Grigorov, Yad. Fiz. **25**, 788 (1977) [Sov. J. Nucl. Phys. **25**, 419 (1977)].
[5]I.P. Ivanenko *et al.*, Proc. Fifteenth ICRC **7**, 441 (1977).
[6]K. Kasahara, CRL-Report-62-78-6, Cosmic Ray Laboratory Univ. Tokyo, 1978.
[7]M. Akashi *et al.*, Proc. Fourteenth ICRC **7**, 549 (1975); Proc. Fifteenth ICRC **7**, 430 (1977).
[8]N.L. Grigorov *et al.*, Chastitsy vysokikh énergiĭ v kosmicheskikh luchakh (High-Energy Particles in Cosmic Rays), Nauka, 1973.
[9]K. Kasahara and Y. Takahashi, Prog. Theor. Phys. **55**, 1896 (1976).
[10]Experiment PAMIR-1, Proc. Fifteenth ICRC **7**, 226 (1977); E.A. Kanevskaya, Proc. Fifteenth ICRC **7**, 436 (1977); E. Konishi *et al.*, Prog. Theor. Phys. **56**, 1845 (1976).
[11]V.K. Budilov, Dissertation Fiz. Inst. Akad. Nauk 1977.
[12]Japan-Brazil Emulsion Collab., Can. J. Phys. **46**, 5660 (1968); T.K. Gaisser, Prospects for Strong Interaction Phys. at ISABELLE 107, 108 (1977).
[13]R.A. Antonov and I.P. Ivanenko, Yad. Fiz. **19**, 869 (1974) [Sov. J. Nucl. Phys. **19**, 443 (1974)].
[14]G.B. Khristiansen *et al.*, Zeszyty Nauk. Univ. Lodz, 226 (1977).
[15]Kharakteristiki ShAL kosmicheskikh lucheĭ sverkhvysokikh energiĭ (Charactersitics of Extensive Air Showers of Ultrahigh-Energy Cosmic Rays), Izd. Yakutsk Filiala SO Akad. Nauk SSSR, 1976.
[16]V.V. Ezela, A.A. Logunov *et al.*, Preprint IHEP-72-1, Serpukhov, 1971; M. Cheng and T.T. Wu, Phys. Lett. B **45**, 367 (1973).