

# Violation of scaling model on going from accelerator to ultrahigh energies

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(Submitted 15 June 1978)

*Pis'ma Zh. Eksp. Teor. Fiz.* **28**, No. 3, 124–127 (5 August 1978)

We analyze the question of scaling violation in hadron interactions, on the basis of experimental data obtained in cosmic rays, and estimate the energy at which this violation should take place.

PACS numbers: 11.30.—j, 13.85.Mh

As shown in<sup>(1)</sup>, the comparison of the experimental data on extensive air showers (EAS) with calculations based on an extrapolation in accord with the Regge-Mueller scaling model from the region of accelerator energies to the region of ultrahigh energies allows us to postulate the presence of a strong discrepancy, from which it follows that the model of hadron interactions in the region of ultrahigh energies should differ radically from the model obtained from accelerator data. The conclusion that scaling is violated at  $x > 0.05$  was based on an analysis of the experimental and calculated dependences of the number  $N_\mu$  of muons of energy higher than 10 GeV on the number  $N_l$  of the electrons at sea level and the number  $N_H$  of hadrons with energy higher than 1 TeV on the number of electrons at mountain altitudes. Whereas the experimental number of muons exceeds the theoretical one, the calculated number of hadrons turns out to be substantially higher than the experimental one. This allows us to state that the conclusion that scaling is violated does not depend on any assumptions concerning the chemical composition of the primary cosmic radiation (see<sup>(1)</sup>; this question is considered in greater detail in<sup>(2)</sup>).

It is possible at present to point to still another group of experimental cosmic-ray data that attest to scaling violation and make it possible, and this is quite important, to determine more accurately the energy region where this violation should take place. We have in mind the study of the altitude behavior of the  $\gamma$ -quantum families. We have compared the experimental integrated spectra of the  $\gamma$ -quantum families<sup>(3)</sup> with the results of calculations by the scaling model. The shape of the spectrum and the absolute intensity of the primary radiation were taken in accord with<sup>(4)</sup>. Assuming the usual chemical composition of the primary radiation (50% protons, 25%  $\alpha$ -particles, 13% of group  $M$  ( $A=15$ ) and 12% nuclei of group  $H$  ( $A=30$ ), the scaling model agrees with the experimental data at a depth 225 g/cm<sup>2</sup>, while at the depth 700 g/cm<sup>2</sup>

this model contradicts the experimental data. Thus, a single model cannot explain the intensities of the families at both altitudes.

In order not to discuss questions connected with the absolute intensity of the primary-radiation spectrum, it is convenient to change over from the intensities of the families to the absorption range. The absorption range of the families in the scaling model is found to be  $170 \pm 10$  g/cm<sup>2</sup>, as against the experimental  $110 \pm 10$  g/cm<sup>2</sup>, much lower than the calculated value. But if we assume that scaling holds at 225 g/cm<sup>2</sup> and take for the 700 g/cm<sup>2</sup> level, for example, the Cocconi-Koester-Perkins (CKP) model<sup>1)</sup> then the calculated absorption range of the families will be equal to the experimental value. One must not, of course, conclude that at energies of the order of  $10^{15}$  eV a transition takes place from the scaling model to the CKP model. As shown in<sup>2)</sup>, the CKP model also contradicts the data on the hadron component of EAS at mountain altitudes. The results presented attest only to violation of the scaling model, and make it possible to estimate approximately the energies at which this violation takes place. The physical meaning of this assumption is connected with the fact that the energies of the hadrons that contribute to the intensity of these families are substantially different for the depths 225 and 700 g/cm<sup>2</sup>, so that different model may work for different depths. If we consider families with  $\Sigma E_{\gamma} > 30$  TeV, then the average energy of the primary particles contributing to the given families is, according to the scaling model,  $3 \times 10^{14}$  eV at a depth 225 g/cm<sup>2</sup> and  $2 \times 10^{15}$  eV at a depth 700 g/cm<sup>2</sup>. It can thus be assumed that it is precisely in this energy interval that the scaling model is violated.

This violation should affect the fragmentation region, since a study of the distribution of the values of the Feynman variable  $x$  that contribute to the considered families shows that the most significant values of  $x$  pertain to the fragmentation region. Thus, for the families  $\Sigma E_{\gamma} > 30$  TeV the fraction of values of  $x$  less than 0.05 is only 7%. According to calculation, the families are produced with approximately equal probability both on account of  $pp$  and on account of  $\pi p$  interactions.

Investigations of the absorption range of single  $\gamma$  quanta leads to the same conclusions as the investigation of the absorption range of families. Within the framework of the scaling model, the absorption range of single  $\gamma$  quanta of energy 3–10 TeV is  $150 \pm 10$  g/cm<sup>2</sup>, whereas experiment yields  $110 \pm 10$  g/cm<sup>2</sup>.<sup>15)</sup> The energy of the primary particles responsible for the production of  $\gamma$  quanta of this energy is  $(2-5) \times 10^{15}$  eV at a depth of 225 g/cm<sup>2</sup> and  $(1-2) \times 10^{15}$  eV at a depth of 700 g/cm<sup>2</sup>.

When speaking of the manner of scaling violation, we must examine to see whether the scaling violation can be reduced to the growth of the cross section of inelastic hadron interaction with energy. Calculations<sup>11,21)</sup> show that the cross section growth that follows from accelerator data hardly alters the degree of discrepancy between the calculated and experimental EAS characteristics. We have therefore considered a calculation variant in which we assumed that, starting with an energy  $E_{\text{thr}}$ , the cross section increases in accord with the law

$$\sigma_{in}(E) = \sigma_{in}(E_{\text{thr}}) \ln^2 E / \ln^2 E_{\text{thr}}, \quad (1)$$

which gives the maximum possible cross section growth according to Froissart.

The experimental value of the exponent of the integral spectrum of single hadrons in the energy interval 7–30 TeV amounts to  $1.8 \pm 0.2$  at mountain altitudes<sup>(6)</sup> (see also<sup>(7)</sup>), whereas the scaling model gives an exponent  $3.1 \pm 0.2$  for a cross section increasing like (1). If we turn to the EAS data we find that the energy spectrum of the EAS hadrons at mountain altitudes, calculated by the scaling model using (1), agrees with the experimental data of<sup>(8)</sup> at a hadron energy near 1 TeV, assuming that  $E_{\text{thr}} \approx 1$  TeV. But in this case a discrepancy is observed in the form of the hadron spectrum, such that the experimental results exceed the calculated values by almost five times already at 10 TeV. It can thus be concluded that the necessary change of the hadron-interaction model cannot be reduced to a steeper growth of their inelastic-scattering cross section than the one that follows from the accelerator data.

As shown in<sup>(1)</sup>, the assumption that the  $N\bar{N}$ -pair generation cross section increases cannot reconcile the experiment with the calculation. This assumption leads to a substantial increase of the number of low-energy muons, but alters little the number of muons of energy  $\sim 100$  GeV; yet muons of this energy exhibit the same disparity with experiment as muons of energy  $\sim 10$  GeV. Violation of charge invariance in favor of the  $\pi^\pm$  or  $\pi^0$  mesons can likewise not eliminate these contradictions.<sup>(2)</sup>

The assumption that the inelasticity coefficient of the nucleon increases at energies  $\sim 10^{15}$  eV improves the agreement for the muon component, but has very little effect on the number of high-energy hadrons at mountain altitudes (which decreases by only 20–25%). The steep change of the inclusive secondary-particle spectrum accompanied by a change in the dependence of the secondary-particle multiplicity on the energy of the primary particle does not eliminate the contradiction concerning the hadron component at mountain altitudes, as was demonstrated in<sup>(2)</sup> with the CKP model ( $n_\pi \sim E_0^{1/4}$ ) and with the high-multiplicity model ( $n_\pi \sim E_0^{1/2}$ ) as examples.

The hypothesis advanced in<sup>(1)</sup> that the cross section of direct lepton generation can increase in hadron interactions eliminates the contradiction with the data on the hadron component at mountain altitudes, but this calls for the assumption that an appreciable fraction of the hadron energy (several dozen percent) goes to the leptons already at a hadron energy  $\sim 3$  TeV. This is difficult to reconcile with the data on a single component of cosmic rays.<sup>(2)</sup>

It appears therefore that we must assume simultaneous changes in an entire series of hadron-interaction characteristics, including the growth of the hadron inelastic-interaction cross section, the change of the inclusive spectra of the secondary particles, and the growth of the direct lepton generation cross section.

<sup>(1)</sup>In this model  $n_\pi \sim E_0^{1/4}$ , and the energy spectrum of the secondary pions is  $dn_\pi/dE = (n_\pi/\langle E \rangle) \times \exp(-E/\langle E \rangle)$ , where  $\langle E \rangle = kE_0/n_{\text{el}}$  is the inelasticity coefficient.

<sup>(2)</sup>It should be noted at the same time that at energies  $\sim 10^{17}$  eV and higher it appears that there are no experimental data that contradict the assumption that the hadron cascade dies out gradually.

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