Extensive air showers of cosmic rays and scale invariance in hadronic interactions at ultrahigh energies

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It is shown that the experimental data on the number of high-energy muons in EAS do not agree with the assumption that scale invariance is preserved in hadronic interactions in the energy region 10^{15}–10^{17} eV.

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Intensive experimental investigations with accelerators have led to the conclusion that the scaling hypothesis[1] is valid for the description of pion-nucleon and proton-proton interactions at energies up to 10^{12} eV, with accuracy up to 10%, at any rate if we consider the production of the bulk of the secondary particles.

In this paper we consider the applicability of the quantitative notions concerning scaling in the energy range 10^{15}—10^{17} eV. In a number of earlier papers (see, e.g., [1]) it was concluded that scaling concepts can be extrapolated up to 10^{13} eV on the basis of experimental data on cosmic-ray muons. Recent papers,[3,4] however, lead to contrary conclusions concerning the possibility of extrapolating scaling into the energy region 10^{14}—10^{15} eV. In[3] it is noted that the exponents of the energy spectra of nuclear-active particles and γ quanta at mountain altitudes are different in the energy interval 10^{12}—10^{14} eV, thus contradicting the scaling concept. This difference, however, has not been adequately corroborated by experiment. On the other hand, the experimental data presented in[4] on groups of muons with higher energies (higher than 10^{12} eV), which agree well with the scaling model, can likewise not claim high accuracy by virtue of the uncertainty in the density of the ground, a fact known to impede sufficiently accurate measurements with the setup of[4] even in the case of single muons.

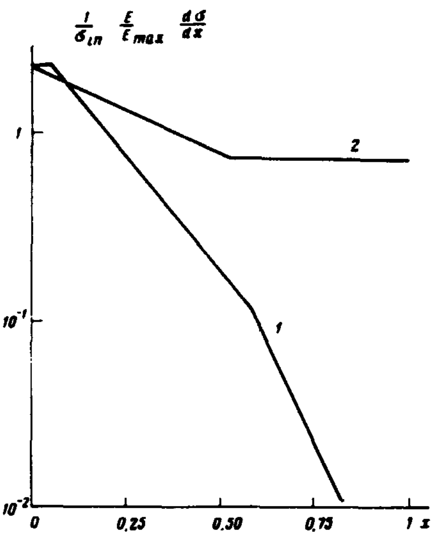

FIG. 1. Inclusive spectra of pions in the c.m.s.: 1—nucleon-nucleon interaction, 2—pion-nucleon interactions.

We regard as much more definite the situation with the experimental data on EAS. There are good experimental studies of the altitude variation of EAS, and yield information on the averaged EAS cascade curve at energies of 10^{15}—10^{17} eV[5], and also the dependence of the number N_μ of high-energy muons (> 10 GeV) on the number N_e of the electrons.[6] A theoretical analysis of these characteristics offers advantages over the comparison with the analysis of single particles and groups of high-energy muons.

Indeed, the result of the analysis is not sensitive to the form and absolute value of the primary energy spectrum, since we are considering the number of particles in showers of specified primary energy. In addition, to obtain the average number of electrons and muons it suffices to know the average characteristics of the elementary act (inclusive spectra), and there is no need to take their fluctuations into account.

We have calculated the number of muons of energy > 10 GeV and the number of electrons in showers coming from primary protons with energies 10^{15}—10^{17} eV. The pion inclusive spectra used in the calculation are shown in Fig. 1. We define

$$\frac{1}{\sigma_{in}}\int_0^1 \frac{E}{E_{max}}\ \frac{d\sigma}{dX}\,dX = \langle K \rangle,$$

where K is the fraction of the energy transferred to all the secondary particles. $\langle K\rangle = 0.5$ for nucleon interactions and unity for pion interactions, since the primary pion, if conserved, is included among the secondary

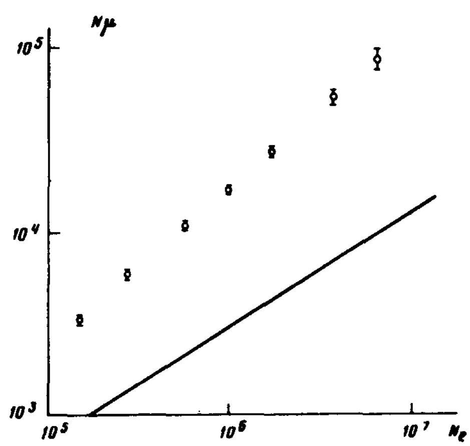

FIG. 2. Dependence of the number of muons with energy higher than 10 GeV on the number of electrons in EAS: ○—experimental data.[6]

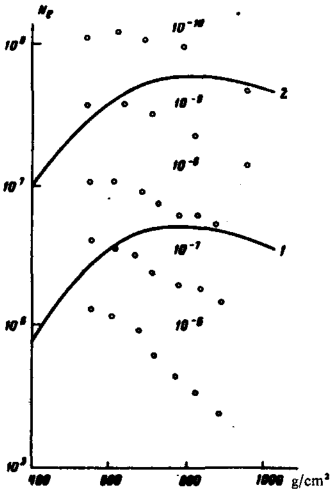

FIG. 3. Altitude variation of EAS: curves 1 and 2—calculation at $E_0 = 10^{16}$ eV and $E_0 = 10^{17}$ eV,[7] ○—experimental data.[5] The groups of experimental data are labeled by the corresponding intensity ($m^{-2}\,sec^{-1}\,sr^{-1}$).

particles. To avoid the need of solving the nuclear-cascade equations for the π^+ and π^- mesons separately, we have averaged the spectra over the types of primary and secondary particles (see[7]). The spectra assumed by us coincide within ~10% with the spectra obtained in[8] from an analysis of modern accelerator data. The π^0-meson spectra were assumed to be similar to the $\pi^\pm$-meson spectra. The inelastic-interaction ranges of the nucleons and pions in air were assumed to be 80 and 120 g/cm², respectively. The results of the calculation at $N_e \sim 10^7$ yield for N_μ a value smaller by a factor of 10 than the experimental one (see Fig. 2). With decreasing N_e this factor decreases slowly to five at $N_e \sim 10^5$, in view of the difference between the theoretical and experimental $N_\mu(N_e)$ dependences. According to experiment $N_\mu \sim N_e^{0.78\pm0.01}$, and according to calculation $N_\mu \sim N_e^{0.61}$.

The increase of the multiplicity of the secondary particle by a factor 1.5 (due to the particles with $X < 0.05$) in nuclear interaction, and the simultaneous assumption (in contradiction to the accelerator data) that $d\sigma/dX$ is the same for pion interaction as for nuclear interaction, increases the ratio N_μ/N_e by only 15%. Taking into account the small statistical error of the experiment, and also the fact that the systematic error does not exceed 15%, we can state that there is a sharp discrepancy between the calculation and the experimental data. The only possibility of bringing the calculation close to the experimental data is to assume that the primary radiation consists of heavy nuclei with $A \sim 100$. Then, within the framework of the superposition model, in order for a shower to be produced by a nucleus A, the value of N_μ increases by a factor $A^{1-0.61} \approx 6$. But the significant difference in the character of the $N_\mu(N_e)$ dependence still remains in this case, and furthermore the assumption $A \sim 100$ greatly contradicts the experimental data on EAS fluctuations. We note also that the shapes of the averaged cascade curves (see Fig. 3) also contradict the extrapolation of scaling to the energy region 10^{15}–10^{17} eV, although the discrepancy here is weaker than in Fig. 2.

Thus, we must state that a sharp contradiction exists between the experimental data on the absolute fraction of the muons and its dependence on the size of the shower, on the one hand, and the scaling-model calculations, on the other. We emphasize that the experimental data contradict scaling with a structure function chosen on the basis of accelerator data. This analysis does not exclude, of course, the possibility that scaling does not hold at either accelerator energies or at energies corresponding to EAS (for example, as a result of a possible dominant role played by $N\bar{N}$ pair production at ultrahigh energies).

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