Possible explanation for scaling violation in hadron interactions above 10^3 TeV

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The discrepancy between the experimental data from extensive air showers and the predictions of the scaling model at energies above 10^3 TeV can be explained by the theory of a supercritical pomeron and the additive quark model.

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Recent experiments in colliding $p\bar{p}$ beams[1,2] at an equivalent energy of 155 TeV have confirmed the violation of scaling in hadron interactions at ultrahigh energies which had been predicted from data obtained from cosmic-ray extensive air showers[3,4] and also from x-ray emulsion chambers (the Pamir experiment[5]). The appearance of data at 155 TeV and the planning of experiments for higher energies are attracting considerable interest to what extensive air showers can tell us about the nature of hadron interactions at energies above 10^3 TeV.

The experimental data on hadron-hadron interactions at the ISR energies and at the energy of the $p\bar{p}$ colliding-beam installation can be described well by the theory of a supercritical pomeron,[6,7] i.e., a pomeron for which the value of the trajectory of the Regge pole at $t = 0$ is $\alpha_p(0) = 1 + \Delta$, where $\Delta > 0$. The value of Δ can be chosen in the range 0.07–0.09. The theory of a supercritical pomeron can be used to find both the interaction cross section and the inclusive spectra of the product particles; this information is sufficient to carry out calculations for the nuclear cascade process in an extensive air shower.

According to the theory of a supercritical pomeron, the normalized structure function $\rho(x) = (x(d\sigma/dx))/\sigma_{\text{in}}$ in the central region $(x < 0.1)$ increases with energy, causing a deviation from scaling in accordance with the colliding-beam data. In the fragmentation region $(x > 0.1)$ at primary energies 10–10^5 TeV, scaling holds within 10% for $\rho(x)$.

To compare the predictions of the supercritical pomeron theory with experimental data on extensive air showers, we must first take into account the differences between the hadron-nucleon and hadron-nucleus interactions. The differences lie primarily in the magnitude of the cross section and its dependence on the hadron energy. The results of a Glauber conversion, with allowance for rescattering, from the cross section for the NN interaction predicted by the supercritical pomeron theory to the cross section for the inelastic interaction of nucleons in air at energies 1–10^5 TeV is described within 1% by an expression of the type

$$\sigma_{in} = \sigma_0(1 + \alpha \ln(E/E_t))$$

where E is the hadron energy, $E_t = 0.1$ TeV, α is 0.04–0.05 (for $\Delta = 0.07$–0.09, respectively), and σ_0 is 265 mb. A similar expression describes the pion interaction cross section, but the value of α turns out to be 0.01 larger. At $E \sim E_t$ the ratio of the nucleon and pion interaction cross sections is 1.3.

Furthermore, there is a difference between the normalized structure functions which describe the hadron-nucleon and hadron-nucleus interactions. The difference can be described well by the additive quark model.[8] At a few hundred GeV the structure functions are not greatly different, but the difference becomes more apparent with increasing primary energy. According to the additive quark model the interaction cross section of a constituent quark becomes approximately equal to 1/3 of the *NN* cross section, and an increase in the *NN* cross section leads to an increase in the probability for the absorption of a quark in the nucleus and to a decrease in the number of spectator quarks with increasing energy. As a result of the quark interaction, there is an increase in the number of secondary particles in the pionization region, while there is a decrease in this number in the fragmentation region. The quantity

$$R(x) = \left(x \frac{d\sigma_{in}^{hA}}{dx} \Big/ \sigma_{in}^{hA} \right) \Bigg/ \left(x \frac{d\sigma_{in}^{hN}}{dx} \Big/ \sigma_{in}^{hN} \right)$$

is calculated in accordance with Ref. 9.

Figure 1 and 2 show the results calculated for the primary components of extensive air showers by this procedure. The difference between the experimental dependence of the number of muons, N_μ ($E_\mu > 10$ GeV), on the number of electrons N_e at sea level found at Moscow State University[10] and the calculation for a primary proton (curve 3 in Fig. 1) can be eliminated by taking into account the ordinary chemical

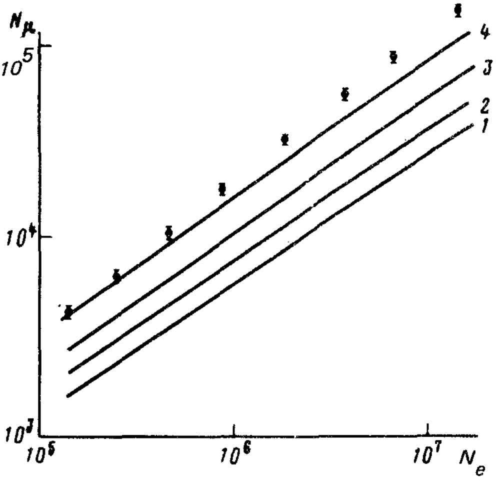

FIG. 1. The number of muons with energies >10 GeV vs the number of electrons in an extensive air shower at sea level. ● —Experimental data[10]; 1—results calculated from the scaling model; 2, 3, 4 —results calculated from the supercritical-pomeron theory; 2—without the additive quark model; 3—with the additive quark model; 4 —with the additive quark model and with a mixed chemical composition of the primary radiation.

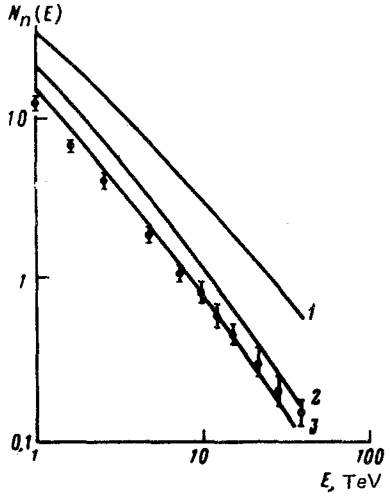

FIG. 2. Hadron energy spectrum at mountain altitudes in showers with $N_e \approx 9 \times 10^5$. ● —Experimental data[11]; 1—results calculated from the scaling model; 2, 3—results calculated from the supercritical-pomeron theory respectively without and with the additive quark model.

composition of the primary radiation[1)] (Ref. 12; see curve 4 in Fig. 1 of the present paper). It is important to note that here we do not need any of the extravagant assumptions regarding the composition which have been characteristic of attempts to reconcile the scaling model with experiment. The nucleus-nucleus interaction is treated by a superposition model whose basis is described in Refs. 14 and 15. The number of high-energy hadrons in an extensive air shower at mountain altitudes changes very slightly with the chemical composition.[4] The experimental hadron spectrum in Fig. 2 is drawn from the data of Ref. 11 obtained with a large ionization calorimeter at the Tien-Shan (Tyan'-Shan') observatory.

Another important characteristic of an extensive air shower is the depth of the shower maximum, $t_{\max}$. The experimental value of $t_{\max}$ at $E_0 \approx 10^3$ TeV is 450 ± 30 g/cm^2 (Ref. 16), while that for $E_0 \approx 10^5$ TeV ranges from 630 to 680 g/cm^2 (Ref. 17). The calculated values of $t_{\max}$ are 560 and 710 g/cm^2 for a purely proton composition and 510–660 g/cm^2 for a mixed composition, for respective primary energies of 10^3 and 10^5 TeV. The calculations are thus consistent with experiment.

The results cannot be reconciled with experiment if we restricted the supercritical pomeron model to the form which ignores the predictions of the additive quark model (Figs. 1 and 2). In order to reach agreement, we need a violation of scaling not only at small values of x (provided by the supercritical-pomeron model) but also in the fragmentation region (provided by the additive quark model). We might also note that the importance of the additive quark model stems entirely from the rapid increase in the inelastic cross section according to the supercritical-pomeron model.

In summary, the predictions of the supercritical-pomeron theory, combined with the additive quark model, are consistent with experimental data on extensive air showers. It would be interesting to test this theory at primary energies up to 10^7 TeV, for which data are still available on the structure of extensive air showers.

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[1)] Agreement between curve 4 in Fig. 1 and experimental data up to $N_e \approx 10^7$ can be achieved by assuming that as N_e varies from 10^5 to 10^7 there is some enrichment of the primary composition with heavy nuclei, as can easily be predicted, for example, in the diffusion model for the origin of the cosmic rays.[13]

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