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ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

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HADRON-HADRON AND HADRON-NUCLEUS INTERACTIONS AT SUPERHIGH ENERGIES IN THE CRITICAL POMERON THEORY

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1. Introduction.

The theoretical description of hadronic interactions at superhigh energies seems, at present, highly urgent, owing, first of all, to the appearance of large number of new experimental data [1-4]. Those data can be divided into two groups: hadron-hadron and hadron-nucleus interactions. The former group involves data on pp-scattering on SPS [1,2]; the latter one - data obtained with cosmic ray installations [3,4].

A problem arises as to describe correctly the data of both groups in the framework of selfconsistent theoretical approach.

It is known that all experimentally observed quantities at superhigh energies are described equally well in the Reggeon field theory (RFT) both with critical ($\alpha_p(0) \equiv 1$) [5,6] and supercritical pomeron ($\alpha_p(0) > 1$) (see, e.g. [7,8]). On the other hand, the hadron-nucleus interactions can satisfactorily be described in the multiple scattering theory (MST) [9].

It turned out that in the hadron-nucleus interactions at such energies, a highly essential role belongs to the rate of the slope growth of diffraction cone of the hadron-nucleus interaction. Corrections caused by the inelastic screening and effects conditioned by a concrete setting-up of the experiment, must also be taken into account.

The extraction of pp-scattering from the cosmic ray data, performed by standard methods, leads to unjustedly heightened cross sections of pp-interaction at the energies of $\sim 10^9$ GeV. A correct account of the rate of the slope growth of the pp-interaction diffraction cone obtained in RFT as well as of its influence on the general pattern of interactions with nucleus yield the values of σ_{pp}^{tot} being in good agreement both with the existing experimental data and RFT with critical pomeron. Thus, for example, at $E \approx 10^9$ GeV from the experimental value of $\sigma_{prod}^{p-air} \approx 500$ mb [4] in the standard method they obtained $\sigma_{pp}^{tot} \approx 120$ mb, whereas at the correct account of all the mentioned factors the extracted value of σ_{pp}^{tot} proves to be ≈ 90 mb, this being in sufficiently good agreement with the predictions of RFT with $\alpha_p(0) = 1$.

2. Hadron-Hadron Interactions.

In Ref. [6], they obtained a renormgroup propagator of pomeron which worked equally well both in the region of applicability of perturbation theory and at asymptotically high energies. The imaginary part of the amplitude with exchange of single renormalized critical pomeron had the following form:

$$M(\xi,\kappa^2)=g_1 g_2 \frac{1+\frac{c}{2}}{\Gamma(1+\frac{c}{2})} e^{-c\alpha} (\bar{E}_0 \xi)^{c/2} e^{-(1+c)x} F_1(\xi) F_2(\xi,x), \qquad (1)$$

where

$$\xi = \ln\left(\frac{s}{s_0}\right); \quad \kappa^2 = -t ; \quad \bar{E}_0 = \frac{\tau_0^2 (1-\alpha)}{16\pi \alpha_0' c_0},$$

X is a new scale variable corresponding to the transferred momentum

$$X = \alpha_0' \kappa^2 e^{\frac{c}{2}\alpha} (1+c) (\bar{E}_0)^{\frac{c}{4}} \xi^{1+\frac{c}{4}}, \qquad (2)$$

g_1 and g_2 are vertex functions of the coupling pomeron-particle, c and α are critical indices of theory, τ_0^2 is the bare three-pomeron vertex, α_0' is nonrenormalized slope of pomeron. $F_1(\xi)$ and $F_2(\xi,X)$ are new scale functions determining energy and t -dependence of amplitude. All these quantities were defined theoretically and calculated in Ref. [6].

$$c = 0.555; \qquad \alpha = 0.54; \qquad \bar{E}_0 = 0.123.$$

Substituting these numerical values into (1) and (2) we shall arrive, up to the terms of the order of ξ^{-2} and κ^2, at the following scale functions:

$$F_1(\xi) = 1 + 1{,}32\,\xi^{-1} - 0{,}02649\,\xi^{-1} + 0{,}118\,\xi^{-\frac{3}{2}} + 0{,}432\,\xi^{-2}, \qquad (3)$$

$$F_2(\xi, x) = 1 - \kappa^2\, 3{,}219\, \xi^{1{,}139}, \qquad (4)$$

$$X = 0{,}407\,\kappa^2 \xi^{1{,}139}. \qquad (5)$$

Besides, taking into account that the threshold of single pomeron production is $\xi_0 = 2.5$, we shall finally obtain for the imaginary part of the pole amplitude with single renormalized pomeron exchange the following expression

$$M^{(1)}(\xi,\kappa^2) = i\beta(\xi) e^{-\kappa^2 a(\xi)} F_2(\xi,x), \qquad (6)$$

where

$$\alpha(\xi) = 0{,}407\,\xi^{1{,}139},$$

$$\beta(\xi) = g_1 g_2\, 0{,}4734\, \xi^{c/2} F_1(\xi). \qquad (7)$$

This amplitude corresponds to a diagram of Fig.1. The residues of g_1 and g_2 remain as the only free parameters of theory.

Fig.2 shows the quasi-eikonal amplitude that contributes at low and high energies. At asymptotical energies, the amplitude of Fig.1 survives, which behaves as $\xi^{0.277}$. In the energy region we are interested in, the amplitude of Fig.2 makes a sufficiently great contribution and provides much more higher rate of growth of total cross sections of the order of ξ^2.

Calculate the amplitude in Fig.2. Its eikonal has the form

$$\chi(\xi, b) = 2i \int_0^\infty J_0(\kappa b) M^{(1)}(\xi, \kappa^2)\, \kappa\, d\kappa. \qquad (8)$$

The total amplitude with account of all re-scatterings will be written as

$$M(\xi, \kappa^2) = \int_0^\infty f(b, \xi) J_0(\kappa b)\, b\, db, \qquad (9)$$

where

$$f(b, \xi) = \frac{1}{2ic'} \left\{ e^{c(\xi)\chi(b,\xi)} - 1 + \chi(b,\xi)(c' - c(\xi)) \right\}. \qquad (10)$$

In (10), $c(\xi)$ is the shower amplification coefficient (SAC). As was shown in [10], SAC are functions of energy and transferred momentum. In this work we use the dependence of SAC on ξ obtained in [10] and neglect its dependence on κ^2.

In the case of NN-interaction we are interested in, the residues

$g_1 = g_2 = g$ were obtained in Ref. [10]. Since we do not now consider a detailed behaviour of differential cross sections, we may assume g constant, being equal to 6.71.

The derived in (9) amplitude allows one to obtain predictions for total cross sections and slopes of diffraction cones for pp-scattering. It is rather difficult to calculate differential cross sections, since that needs more precise information on the function $F_2(\xi, x)$, which by itself is a highly complicated problem.

The total cross sections derived by means of amplitude (9) are shown in Fig.3. At low energies they describe the existing experimental data rather well. In the energy range from ISR to SPS the total cross sections grow as ξ^2; at higher energies the rate of the cross section growth becomes slower and at asymptotics turns into $\xi^{0.277}$.

The gaps in the energy range from ISR to SPS and higher fill the experimental points obtained in cosmic ray installations [3,4]. These data are obtained from the investigation of interaction of cosmic protons with the air nuclei. There arises a problem of a possibility of correct extraction of proton-proton interaction cross section from the cosmic data. Fig.3 shows points extracted via the method described in detail in the next section.

Fig.4 presents slopes of pp-scattering diffraction cone at $|t| < 0.02$. At low energies they describe the experiment well; at SPS energies the agreement is sufficiently good either. At asymptotic energies the slope grows as $\xi^{1.139}$.

Fig.5 presents the values $\alpha = \mathrm{Re}\,M / \mathrm{Im}\,M$ as calculated via dispersion relations. Fig.6 shows σ^{el} and σ^{diffr} for pp-interactions as calculated by means of the standard method from SAC (see, e.g. [10]). All the mentioned quantities describe rather well the existing experimental data at all the values of energy.

3. Hadron-Nucleus Interactions.

To determine cross sections of proton-nucleus interaction, the methods of the multiple scattering theory were applied [9] . Here the fact was taken into account that approximations usually used in this theory

$$\int \Gamma(\vec{b}-\vec{s})\rho(\vec{s},z)d^2s \simeq \rho(\vec{b},z)\int \Gamma(\vec{b}-\vec{s})d^2s ,$$

$$\int |\Gamma(\vec{b}-\vec{s})|^2\rho(\vec{s},z)d^2s \simeq \rho(\vec{b},z)\int |\Gamma(\vec{b}-\vec{s})|^2 d^2s ,$$

where $\rho(\vec{b},z)$ is single-particle nuclear density, $\Gamma(\vec{b}-\vec{s})$ is Fourier-transform of scattering amplitude on a single nucleon of nucleus, at the energies under consideration do not hold. (Physically, this implies that the elementary interaction radius becomes comparable with the nucleus radius as the energy grows). Hence for the inelastic cross section of proton-nucleus interaction the following expression was obtained:

$$\sigma^{(0)}_{prod} = \int d^2B\Big[1-\exp_A\Big\{\frac{-\sigma^{tot}_{PN}}{2\pi b}\int \exp\Big\{\frac{-|\vec{B}-\vec{S}|^2}{2b}\Big\}T(\vec{s})d^2s + \qquad (11)$$

$$+\frac{|f_{PN}(0)|^2}{b^2E^2}\int \exp\Big\{\frac{-|\vec{B}-\vec{S}|^2}{b}\Big\}T(\vec{s})d^2s\Big\}\Big],$$

where $\exp_A\{x\}=(1+\frac{x}{A})^A$, A is atomic number of nucleus.

$$T(\vec{s}) = \int \rho(\vec{s},z)dz .$$

If we use the Gaussian parametrization of single-particle nuclear density [11] ,

$$\rho(r) = \frac{A}{(\sqrt{\pi}R^2)^3}e^{\frac{-r^2}{R^2}} ,$$

then expression (11) will turn into

$$\sigma^{(0)}_{prod} = 2\pi\int_0^\infty BdB\Big[1-\exp_A\Big\{\frac{-A\sigma^{tot}_{PN}}{\pi(2b+R^2)}\exp\Big\{\frac{-B^2}{2b+R^2}\Big\}+$$

$$+\frac{A|f_{PN}(0)|^2}{E^2b(b+R^2)}\exp\Big\{\frac{-B^2}{b+R^2}\Big\}\Big\}\Big] . \qquad (12)$$

To describe more correctly the cross sections of proton-nucleus interaction, it is necessary to take into account the correction due to inelastic channels (diffraction dissociation). According to [12] , this correction is given by the following expression

$$\Delta\sigma^{in}_{prod} = -4\pi\int e^{-\sigma^{in}_{PN}T(\vec{B})}d^2B\int\frac{d\sigma}{dM^2dq^2}(q=0)|F(\Delta,\vec{B})|^2\times$$

$$\times\Big(1-\frac{\sigma^{tot}_{PN}}{4\pi(b+b_1)}\Big)^2dM^2 , \qquad (13)$$

where

$$F(\Delta,\vec{B}) = \int e^{i\Delta z}\rho(\vec{B},z)dz ;$$

$\Delta = \frac{M^2-m^2_N}{2E}$ is the minimum longitudinal momentum transfer in the reaction $NN\to MX$; b_1 is slope in the reaction $NN\to MX$. The quantity $\sigma_{prod}=\sigma^{(0)}_{prod}+\Delta\sigma^{in}_{prod}$ represents total cross section of proton-nucleus interaction due to which at least one meson is produced ($\sigma_{prod}=\sigma^{tot}-\sigma^{el}-\sigma^{qel}$). Finally, when comparing the theoretical predictions with the experimental data, one should take into account that in most cosmic ray experiments, particles losing energy lower than some given one are not registered. Owing to that, the cross section measured in such experiments must be somewhat less than the found quantity σ_{prod}

$$\sigma_{exp} = \sigma_{prod} - \Delta\sigma$$

(A detailed analysis of the correction $\Delta\sigma$ is given in Ref. [12]).

.g.7 presents now existing experimental points [3,4] attributed to the air nuclei (A = 14.4). The theoretical curve $\sigma^{(0)}_{prod} + \Delta\sigma^{in}_{prod}$ calculate according to (12) and (13) is plotted through these points. Note that the authors of [3] in their handling of the experimental data used e value $\Delta\sigma^{air}$ = 13 mb , whereas according to Ref. 12 at the mentioned energies $\Delta\sigma^{air}$ = 15 ÷ 16 mb.

Fig.8 shows the dependence of σ_{prod} on atomic number of nucleus, calculated according to (11) and (13) with the use of Fermi distribution at A ≥ 20 [13] for the nucleon-nuclear density,

$$\rho(r) = \frac{\rho_0}{1+\exp\{\frac{r-R}{c}\}} .$$

Here the value of energy was chosen E = 10^9 GeV, this corresponding to the energy of initial cosmic protons at the "Fly's Eye" installation [4]. From the curve presented, one can see that with increasing the atomic number the cross section behaves approximately by the law $A^{0.6}$. Some increase in the screening effect (at FNAL energies $\sigma^{PA}_{prod} \sim A^{0.7}$) is due to the growth of both diffraction cone slope and proton-nucleon cross section which at the mentioned energy were assumed equal to 28.9 GeV^{-2} and 82 mb, respectively.

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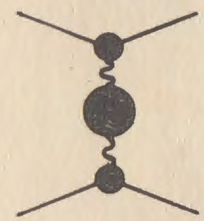

Fig. 1

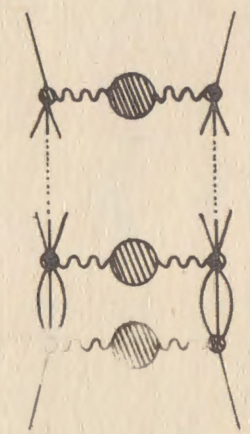

Fig. 2

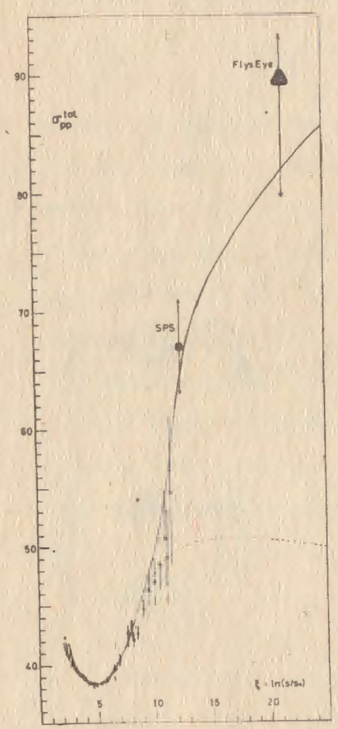

Fig. 3

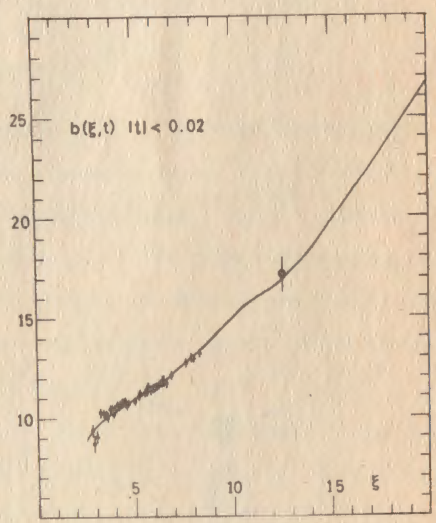

Fig. 4

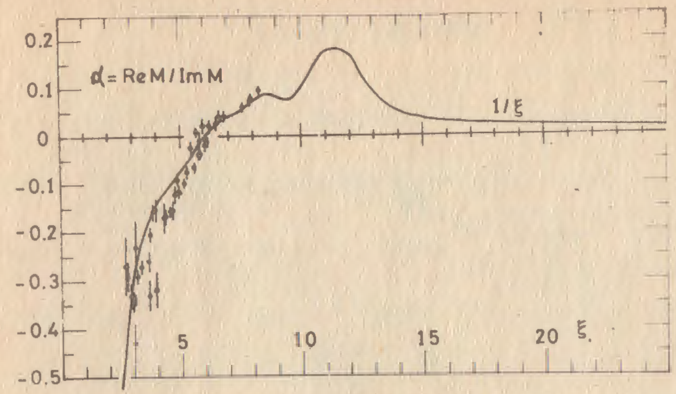

Fig. 5

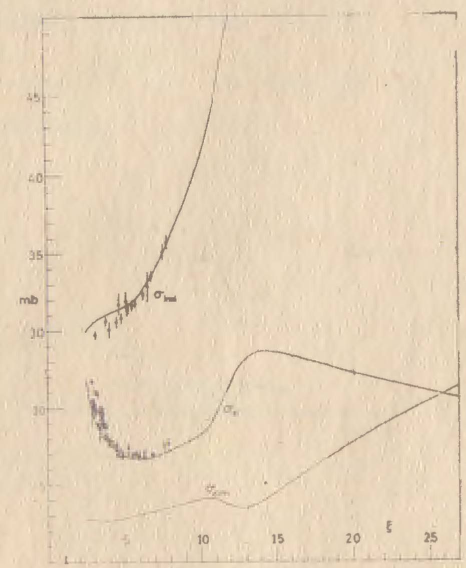

Fig. 6

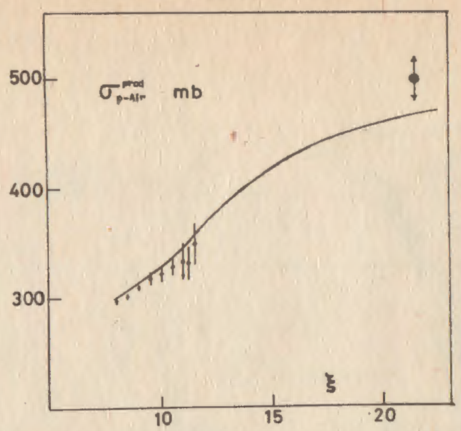

Fig. 7

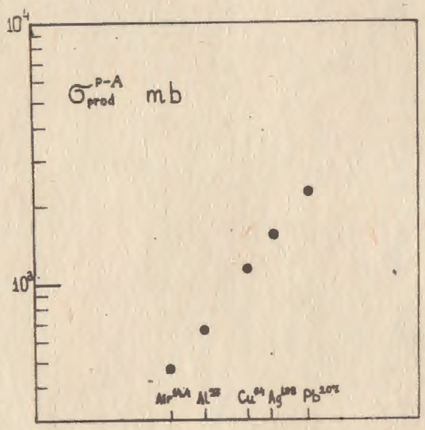

Fig. 8

FIGURE CAPTIONS

Fig.1. Amplitude with single renormalized pomeron exchange.

Fig.2. Quasi-eikonal amplitude with renormalized pomerons.

Fig.3. pp-scattering total cross sections.

Fig.4. Slope of pp-scattering diffraction cone at $|t| < 0.02$.

Fig.5. The ratio $\alpha = Re\, M / Im\, M$ for pp-scattering.

Fig.6. Elastic cross section σ^{el} and diffraction dissociation cross section for pp-scattering.

Fig.7. The production cross section $\sigma^{p\text{-}air}_{prod}$ on the air nuclei.

Fig.8. The value of $\sigma^{p\text{-}A}_{prod}$ for different nuclei at the energy $E = 10^9$ GeV.

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