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HADRON TRANSVERSE MOMENTA IN INCLUSIVE REACTIONS IN THE QUARK-GLUON STRING MODEL

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As is known the quark-gluon string model (QGSM[1-6]), based on the 1/N expansion in QCD[7-9] is quite successfully used to analyse multiple production processes in hadron and hadron-nucleus[4,6,11] interactions. Usually, the characteristics integrated over the transverse momentum P_t are considered in the frame of this model. To derive the dependence of the observed values on P_t it is necessary to know the P_t-dependence of the distribution functions of quarks (diquarks) and their fragmentation into hadrons. The analysis of the processes in the frame of QGSM taking into account the quark and diquark transverse momenta was performed in ref.[12]. But the weak dependence of the average transverse hadron momentum on the number of the quark-antiquark chains and consequently, on the Feynman variables X was derived in ref.[12].

The mechanism of the inclusion of the dependence of the quark (diquark) distribution functions of the transverse momentum P_t is proposed in the frame of QGSM in this paper; it is somewhat different from the method considered in ref.[12]. The hadron and hadron-nucleus processes are analysed in the method suggested.

We shall first consider the hadron-hadron interaction process, for example, $pp \to hX$ in the frame of QGSM taking into account the quark and diquark transverse momenta. The inclusive invariant hadron spectrum based on the cylinder-type graphs, giving the main contribution to the process discussed[2], can be written in the following form[1,2]:

$$E\frac{d\sigma}{d^3p} = \sum_n \sigma_n(s)\,\phi_n^h(x,p_t), \qquad (1)$$

where the following symbols are introduced: σ_n is the cross section of the n-Pomeron shower production or 2n-quark-gluon strings decaying into hadrons; $\phi_n^h(x,p_t)$ is the hadron distribution over X and P_t produced in the decay of 2n quark-gluon strings, $x = 2p_z^*/\sqrt{s}$ is the Feynman variable, P_z^* is the longitudinal momentum of the produced hadron in the c.m.s. p-p;

$$\phi_n^h(x,p_t) = \int_{x_+}^{1} dx_1 \int_{x_-}^{1} dx_2\,\Psi_n(x,x_1,x_2,p_t); \qquad (2)$$

$$\Psi_n(x,x_1,x_2,p_t) = a_h\{F_{qq}^{(n)}(x_+;x_1,p_t)\,F_{q_v}^{(n)}(x_-;x_2,p_t)/F_{\bar{q}_v}^{(n)}(0,p_t) + \qquad (3)$$
$$+ 2(n-1)F_{q_{sea}}^{(n)}(x_+;x_1;p_t)\,F_{\bar{q}_{sea}}^{(n)}(x_-;x_2;p_t)/F_{\bar{q}_{sea}}^{(n)}(0,p_t) +$$
$$+ F_{q_v}^{(n)}(x_+,x_1,p_t)\,F_{qq}^{(n)}(x_-,x_2,p_t)/F_{qq}^{(n)}(0,p_t);$$

$$F_{qq}^{(n)}(x_\pm;x_{1,2};p_t) = \frac{2}{3}F_{ud}^{(n)}(x_\pm;x_{1,2};p_t) + \qquad (4)$$
$$+ \frac{1}{3}F_{uu}^{(n)}(x_\pm;x_{1,2};p_t);$$

$$F_{q_{sea}}^{(n)} = \frac{1}{4+2\delta}[F_u^{(n)} + F_{\bar{u}}^{(n)} + F_d^{(n)} + F_{\bar{d}}^{(n)}] + \frac{\delta}{4+2\delta}[F_{S_{sea}}^{(n)} + F_{S_{sea}}^{(n)}],$$

where:

$$x_\pm = \frac{1}{2}(\sqrt{x_t^2 + x^2} \pm x); \qquad x_t = 2\sqrt{m_h^2 + p_t^2}/\sqrt{s},$$

m_h, p_{th} are the mass and the transverse hadron momentum respectively, $\sqrt{s}$ is the total energy of two initial protons in their c.m.s.;

$$F_r^{(n)}(x_\pm;x_{1,2},p_t) = \int d^2k_t\, f_r^{(n)}(x_{1,2};k_t)\,\tilde{G}_{r\to h}\Big(\frac{x_\pm}{x_{1,2}};p_t - \frac{x_\pm}{x_{1,2}}k_t\Big); \qquad (5)$$
$$F_r^{(n)}(0,p_t) = \int_0^1 dx' \int d^2k_t\, f_r^{(n)}(x',k_t)\,\tilde{G}_{r\to h}(0,p_t) = \tilde{G}_{r\to h}(0,p_t),$$

where the symbol r means the flavour of the quark or the diquark, $f_r^{(n)}(x,k_t)$ is the distribution function of the quark or the diquark after n-Pomeron exchanges over its longitudinal momentum fraction x and the transverse momentum k_t; $\tilde{G}_{r\to h}(z,k_t) = zD_{r\to h}(z,k_t)$; $D_{r\to h}$ is the fragmentation function of the quark (diquark) r into the hadron h.

To derive the p_t-dependence of the functions $F_r^{(n)}$ and therefore the inclusive spectrum (1) it is necessary to know the dependence of the distribution functions f_r^n and the fragmentation functions of quarks $D_{r\to h}(z,k_t)$ on k_t.

In ref.[12] it was supposed that the valence and sea quarks and the diquark in the proton have the internal transverse momenta which add up to zero. The distribution of quarks (diquarks) was represented in the factorized form $f_r(x,k_t) = \tilde{f}_r(x)\,g_r(k_t)$, so it would also be factorized in the n-chain, i.e.,

$$f_r^{(n)}(x,k_t) = f_r^{(n)}(x)\,g_r^{(n)}(k_t).$$

The distribution $g_r^{(n)}(k_t)$ was found as the product of the probabilities to find the quark (diquark) with the transverse momentum k_{it} in every n-chain, i.e. the product of functions $g_r(k_{it})$, the transverse momentum conservation law taken into account, $\sum_{i=1}^{n} k_{it} = 0$, it is integrated over all k_{it} except one. This means that quark (diquark) transverce momentum on the ends of 2n-string would be divided between these strings.

Another method of the division of the internal transverse momentum between the quarks (valence and sea) and the diquark in the proton is proposed in this paper, the method is similar to the consequent energy division between n-Pomeron showers in the p-p interaction [2].

As in ref. [12] we shall represent the quark function in the factorized form. We shall consider the graph of the "cut cylinder" type, fig. 1a, corresponding to the production of one Pomeron shower or the decay of two quark-gluon strings [1-3]. The hadron production can be represented in the following manner: each of two colliding protons is divided into a quark and a diquark with the opposite transverse momenta; after the colour interaction between them and the diquark and the quark respectively of another proton two quark-gluon strings are produced in the chromostatic constant field; then they decay into hadrons. This process of the division of three quarks into a diquark and a quark is repeated n times during production of n-Pomeron showers or 2n quark-antiquark chains and therefore the diquark or the quark at the ends of every string (see fig.1b) acquires the nonzero transverse momentum. The more division stages are the greater

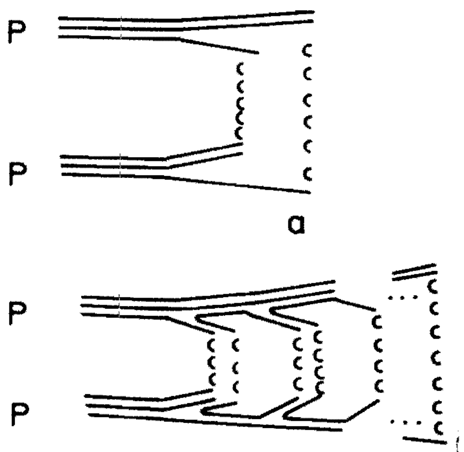

Fig.1. a - The graph of the "cut cylinder" type in the s-channel of the p-p scattering, corresponding to production of two q-$\bar{q}$ chains; b - the graph corresponding to production of n-Pomeron showers or 2n q-$\bar{q}$ chains in the reaction pp → hX.

is the momentum. The calculation procedure of the quark (diquark) distribution after the n divisions can mathematically be represented in the following manner. According to what was mentioned above we have:

$$g_r^{(n)}(k_t) = \int \prod_{i=1}^{n} g_r(k_{it})\, \delta^{(2)}(k_t - \sum_{i=1}^{n} k_{it})\, d^2 k_{it}. \qquad (6)$$

If, for example, $g_r(k_{it})$ is the Gauss distribution normalized to 1, i.e., $g_r(k_{it}) = \frac{\gamma}{\pi} e^{-\gamma k_{it}^2}$ then we have from (6):

$$g_r^{(n)}(k_t) = \frac{\gamma_n}{\pi} e^{-\gamma_n k_{it}^2} \; ; \quad \gamma_n = \frac{\gamma}{n}. \qquad (7)$$

A change in the quark (diquark) transverse momentum k_t at every stage of the above-mentioned process gives, in principle, a change in the longitudinal momentum k_z. At large energies of the initial proton, for example, about 100 GeV, the change in k_z can be neglected if we are not interested in hadrons produced with very small x. Then the x-distribution of quarks (diquarks) can be taken in the form derived in refs. [2].

Functions of quark and diquark fragmentation into hadrons must be known for the calculation of inclusive spectra and other observed values. We shall represent them in the factorized form as in ref. [12]

$$\tilde{G}_{r\to h}(z, k_t, p_t) = G_{r\to h}(z, p_t)\, \tilde{g}_{r\to h}(k_t), \qquad (8)$$

where $\tilde{g}_r(k_t)$ is the function depending on k_t alone, and the function $G_{r\to h}(z, p_t)$ is defined in ref. [12] in the following manner:

$$G_{r\to h}(z, p_t) \sim (1-z)^{-\alpha_R(0) + 2\alpha'_R(0) p_t^2} \equiv$$

$$\equiv (1-z)^{-\alpha_R(0)} \exp(-2\alpha'_R(0) p_t^2 \ln \frac{1}{1-z}), \qquad (9)$$

where $\alpha_R(0) = 0.5$ is the Regge-trajectory at $t = 0$, $\alpha'_R(0) = 1\,(\mathrm{Gev}/c)^{-2}$ is its slope.

It is possible to take the Gauss function as $\tilde{g}_r(k_t)$, as in ref. [12]:

$$\tilde{g}_{r\to h}(k_t) = \frac{\tilde{\gamma}}{\pi} e^{-\tilde{\gamma} k_t^2}. \qquad (10)$$

$F_r^{(n)}(x_\pm ; x_{1,2} ; p_t)$ and the inclusive hadron spectrum (1) can be calculated using (7-10) and taking the quark (diquark) distribution functions over x from ref./2/ .

Note that the quark (diquark) distribution over k_t in the n-chain (see (7)) more strongly depends on n in our case then in ref./12/ where $\gamma_n = \gamma/(2-1/n)$. Consequently there is a stronger x-dependence of the average transverse hadron momentum $\langle p_t \rangle$ in the p-p collision in our case:

$$\langle p_t \rangle = \int E \frac{d\sigma}{d^3p} p_t \, d^2 p_t \Big/ \int E \frac{d\sigma}{d^3p} d^2 p_t . \qquad (11)$$

If energies are high, for example, E_0=100 (GeV), it is easy to see that at $p_t \lesssim 0.5$ (GeV/c) the variable $x_- = \frac{1}{2}\left(\sqrt{x^2 + \frac{4p_t^2}{s}} - x\right)$ is approximately equal to zero in the whole region of x except very small values $x \lesssim 0.01$. Therefore expression (3) can be represented in a simple form:

$$\phi_n^h(x,p_t) = \int_{x_+}^{1} \Psi_n(x; x_1; p_t)\, dx_1$$

$$\Psi_n(x;x_1;p_t) = a_h \{ F_{qq}^{(n)}(x_+;x_1;p_t) + F_{q_v}^{(n)}(x_+;x_1;p_t) + + 2(n-1) F_{q_{sea}}^{(n)}(x_+;x_1;p_t) \}. \qquad (12)$$

Substituting (12) into (1) and using the above-mentioned procedure of the calculation of the inclusive spectrum we obtain the following expression for $\langle p_t \rangle$:

$$\langle p_t \rangle = \sqrt{\frac{\pi}{\bar{\gamma}}} \sum_n \sigma_n \int_{x_+}^{1} \tilde{\phi}_n(x_+,x_1)\, dx_1 \Big/ \sum_n \sigma_n \int_{x_+}^{1} \phi_n(x_+,x_1)\, dx_1 \qquad (13)$$

here the following nonation is introduced:

$$\tilde{\phi}_n(x_+,x_1) = a_n \{ r_n F_{qq}^{(n)}(x_+,x_1) + r_1 F_{q_v}^{(n)}(x_+,x_1) + + F_{q_{sea}}^{(n)}(x_+,x_1) \sum_{k=2}^{n-1} r_k + F_{q_{sea}}^{(n)}(x_+,x_1) \sum_{k=2}^{n} r_{k-1} \}$$

$$r_k = \left[1 + \left(\frac{x_+}{x_1}\right)^2 \frac{\tilde{\gamma}}{\gamma_k}\right]^{1/2} \Big/ \left[1 + \frac{2\alpha_R'}{\tilde{\gamma}}\left(1 + \left(\frac{x_+}{x_1}\right)^2 \frac{\tilde{\gamma}}{\gamma_k} \ln \frac{1}{1-\frac{x_+}{x_1}}\right)\right]^{3/2} ; \qquad (14)$$

$$\phi_n(x_+,x_1) = a_n \{ F_{qq}^{(n)}(x_+,x_1) + F_{q_v}^{(n)}(x_+,x_1) + 2(n-1) F_{q_{sea}}^{(n)}(x_+,x_1) \} g_n ;$$

$$g_n = \left[1 + \frac{2\alpha_R'}{\tilde{\gamma}}\left(1 + \left(\frac{x_+}{x_1}\right)^2 \frac{\tilde{\gamma}}{\gamma_k} \ln \frac{1}{1 - x_+/x_1}\right)\right]^{-1} .$$

The so-called "sea-gull" effect, i.e. the dependence of the average hadron transverse momentum $\langle p_t \rangle$ on x, in particular, on $\pi^\pm$-mesons produced in p-p- interactions at high energies, calculated by (13) is represented in fig.2. The strong dependence of these functions and, therefore, $\langle p_t \rangle$ on the number of the quark-antiquark chains is shown by expression (14). It gives rise to a stronger dependence of $\langle p_t \rangle$ on x than in ref./12/ (see Fig. 2).

Therefore the considered manner of the transverse momentum division between the quark-gluon string leads to a rather marked sensitivity of the quark (diquark) k_t-distribution functions to their number. It is known that the contribution of the multipomeron chains to the inclusive hadron spectra in the hadron-hadron collisions is only significant in the region of small x but at $x \gtrsim 0.3$ it is negligibly small/1-3/ . But they can't be neglected in the whole region of x in the hadron-nucleus collisions.

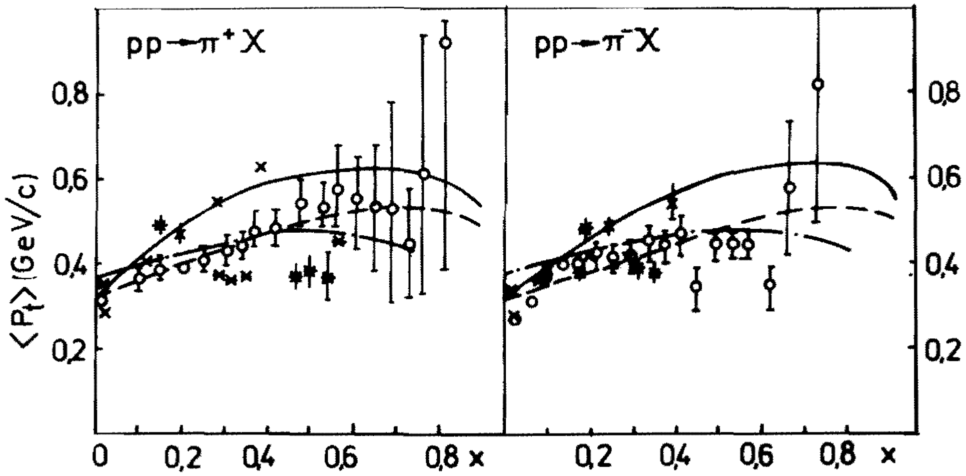

Fig.2. The "sea-gull" effect for the reaction $pp \to \pi^\pm X$, *the curves are the calculations by (13), (14) and from ref./12/ : the full curve corresponds to* $\tilde{\gamma}$ = 40 (GeV/c)$^{-2}$, γ =3 (GeV/c)$^{-2}$, *the dash is for* $\tilde{\gamma}$ = 40 (GeV/c)$^{-2}$, γ = 6 (GeV/c)$^{-2}$; *the dash-and-dot curve from ref./12/; the experimental data:* ⫯ *- for* $\sqrt{s}$ = 45 (GeV) /13/, ✱ *- for* p_0 = 175 (GeV/c)/14/ ; ⫰ *- for the kinetic energy* T_0 = 65 (GeV/c)/15/ .

Therefore it is interesting to consider the proposed method of the inclusion of transverse momenta of quarks in QGMS in the case of h-A interactions. If we choose the dependence of the distribution functions of quarks, diquarks and their fragmentation into hadrons on k_t in the form as in the case of the p-p collision, then the following expression for the inclusive spectrum of particles produced in the p-A interaction can be written:

$$\mathcal{F}_A(x, p_t) \equiv E\frac{d\sigma_A}{d^3p} = \sum_n N_n \phi_n(x, p_t); \tag{15}$$

here the following notation is introduced:

$$\begin{aligned}\phi_n(x,p_t) = \int_{x_+}^{1} dx_1 \{ & f^{(n)}_{qq}(x_1)\, G_{qq}(\tfrac{x_+}{x_1})\, I^{(n)}(\tfrac{x_+}{x_1}; p_t) + \\ & + f^{(n)}_{q_v}(x_1)\, G_{q_v\to h}(\tfrac{x_+}{x_1})\, I^{(1)}(\tfrac{x_+}{x_1}; p_t) + f^{(n)}_{q_{sea}}(x_1)\, G_{q_{sea}\to h}(\tfrac{x_+}{x_1}) \times \\ & \times \sum_{k=1}^{n-1} I^{(k)}(\tfrac{x_+}{x_1}; p_t) + f^{(n)}_{\bar q_{sea}}(x_1)\, G_{\bar q_{sea}\to h}(\tfrac{x_+}{x_1}) \times \\ & \times \sum_{k=2}^{n} I^{(k-1)}(\tfrac{x_+}{x_1}; p_t) \},\end{aligned} \tag{16}$$

where

$$I^{(k)}(z, p_t) = \frac{\gamma_z}{\pi} e^{-\gamma_z p_t^2}$$

$$\gamma_z = \frac{\gamma_n \tilde\gamma}{\gamma_n + z^2 \tilde\gamma} + 2\alpha'_R(0) \ln\frac{1}{1-z},$$

$$N_n = \frac{1}{n!}\int (\sigma T(b))^n e^{-\sigma T(b)} d^2 b$$

are the so-called effective numbers, σ is the inelastic cross section of N-N interaction.

There the contribution of the decay of quark-gluon strings formed between sea quarks, antiquarks of the initial proton and sea antiquarks, quarks of the target nucleus nucleons respectively is neglected. That is justified if we do not consider the region of very small x /1-4/. Moreover we suppose that the hadrons are formed behind the nucleus /4, 11/.

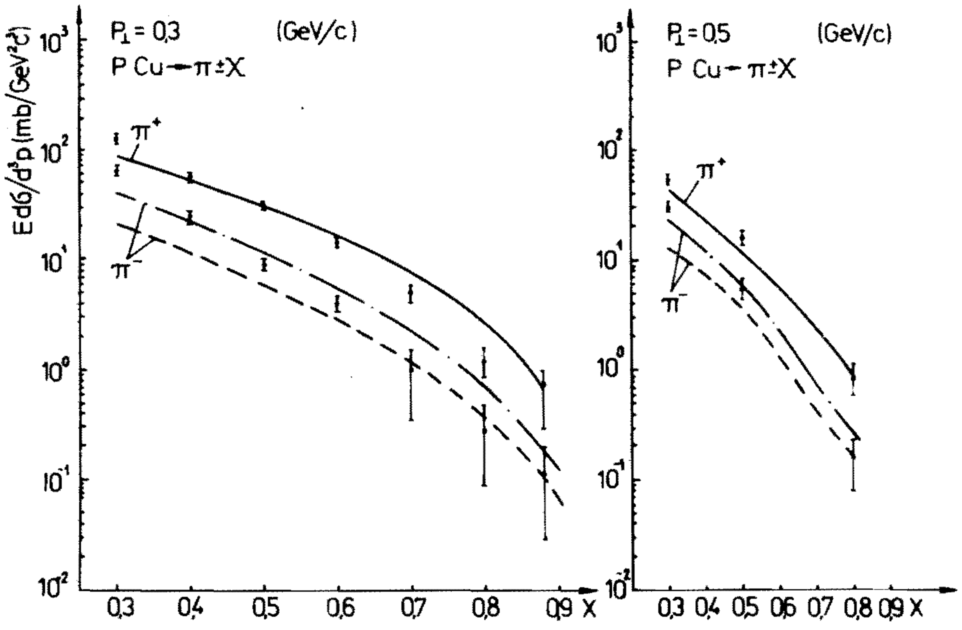

Fig.3. The invariant inclusive spectra of $\pi^\pm$-mesons in the reaction $p^{64}Cu \to \pi^\pm X$ at $E_0 = 100$ (GeV) and $p_t = 0.3$ (GeV/c), $p_t = 0.5$ (GeV/c); the curves show the results obtained in calculations by (15), (18); the full curves are for $B=4\,(GeV/c)^{-1}$ the dash-and-dot curves are for $B = 3\,(GeV/c)^{-1}$ and the dashed curves are for $B = 2\,(GeV/c)^{-1}$.

If we choose the functions $g_r(k_t)$ and $\tilde g_{r\to h}(k_t)$ in the form:

$$g_r(k_t) = \frac{B^2_{1r}}{2\pi} e^{-B_{1r}k_t} \quad ; \quad \tilde g_{r\to h}(k_t) = \frac{B^2_{2r}}{2\pi} e^{-B_{2r}k_t} \quad ; \tag{17}$$

normalized to 1, then another expression is obtained instead of (16)

$$\begin{aligned}\phi_n(x,k_t) = \int_{x_+}^{1} dx_1 \int d^2k_t \{ & f^{(n)}_{qq}(x_1)\, G_{qq\to h}(z,p_t)\, \tilde\phi^{(\nu)}_{qq}(k_t) \times \\ & \times \tilde g_{qq\to h}(p_t - zk_t) + f^{(n)}_{q_v}(x_1)\, G_{q_v\to h}(z,p_t)\, \tilde g_{q_v\to h}(p_t - zk_t) + \\ & + f^{(n)}_{\bar q_{sea}}(x_1)\, G_{\bar q_{sea}\to h}(z,p_t) \sum_{k=1}^{n-1} \tilde\phi^{(\mu)}_{\bar q_{sea}}(k_t) \times\end{aligned}$$

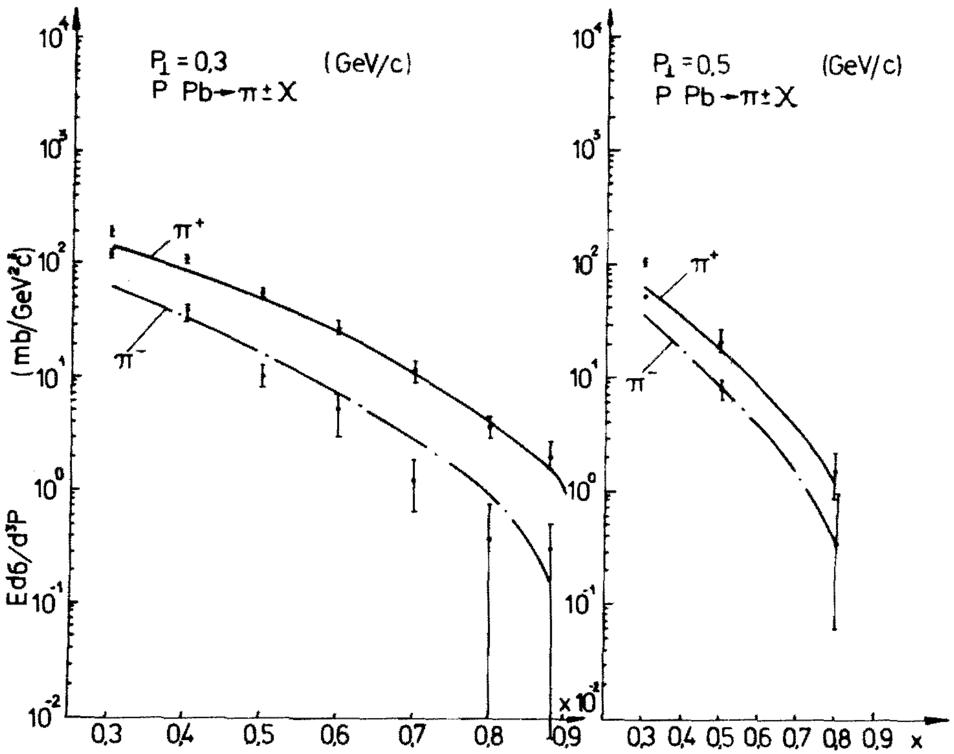

Fig.4. The same as in Fig.3 but for $\pi^{\pm}$*-mesons produced in the reaction* $p + Pb^{207} \to \pi^{\pm} + X$.

$$\times \tilde{g}_{q_{sea}\to h}(p_t - z k_t) + f^{(n)}_{q_{sea}}(x_1)\, G_{q_{sea}\to h}(z, p_t) \sum_{k=2}^{n} \tilde{\phi}^{(\mu)}_{q_{sea}}(k_t) \times$$

$$\times \tilde{g}_{q_{sea}\to h}(p_t - z k_t);\quad \phi_r^{(\nu)}(k_t) = \frac{B_r^2}{2\pi\Gamma(\nu+1)} \left(\frac{B_r k_t}{2}\right)^{\nu} K_\nu(B_r k_t) \qquad (18)$$

it is the same expression for $\phi_r^{(\mu)}(k_t)$, only ν is replaced by μ; $z = x_+/x_1$. Here the following notation is introduced: $\nu = \frac{3}{2}n - 1$; $\mu = \frac{3}{2}k - 1$; K_μ, K_ν are the McDonald functions of the order μ, ν respectively.

Note that the parameters B_{1r}, B_{2r} in the functions $g_r(k_t)$, $\tilde{g}_{r\to h}(k_t)$ are in principle different for diquarks and quarks both valence and sea ones. For simplicity however, it was supposed in our calculations that they are equal to each other

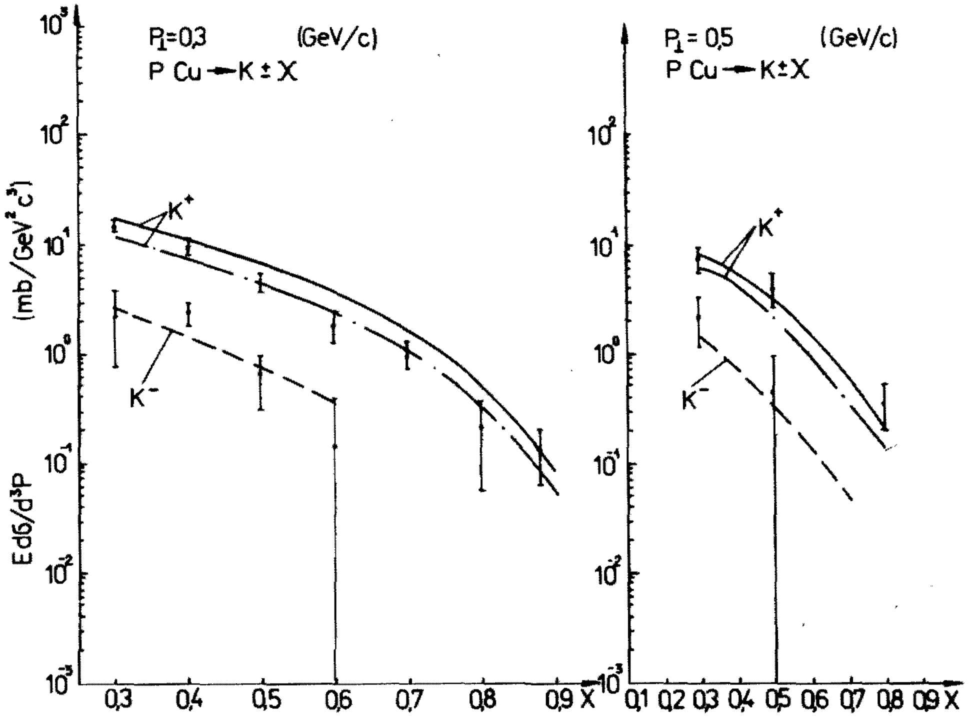

Fig.5. The same as in fig.3, but for $K^{\pm}$*-mesons produced in the reaction* $P + {}^{64}Cu \to K^{\pm} + X$.

and to a parameter B. The form of functions $g_r(k_t)$, $\tilde{g}_{r\to h}(k_t)$ of the type (17) is more realistic than the Gauss form [12]. Therefore we used the form (17) for those functions, and the form (18) for $\phi_n(x, k_t)$.

The results obtained in calculation of the inclusive spectra of hadrons produced in p-A collisions in relation to X at $p_t = 0.3$ (Gev/c) and $p_t = 0.5$ (GeV/c) and experimental data at $P_o = 100$ (GeV/c) [16] are represented in figs.3 ÷ 6; formulae (15), (18) were also used. The figures show good agreement of the calculated curves with the experimental data.

As mentioned above it is supposed that the hadron formation length is more than the size of the nucleus. At high energies, for example, at $E_o = 100$ (GeV) this is justified if we are not interested in very small [17] and very fast hadrons [18]. Note also that we do not take into account the contribution of the diffraction dissociation, i.e., the considered method is valid at $x \lesssim 0.85 \div 0.9$. Our analysis is true

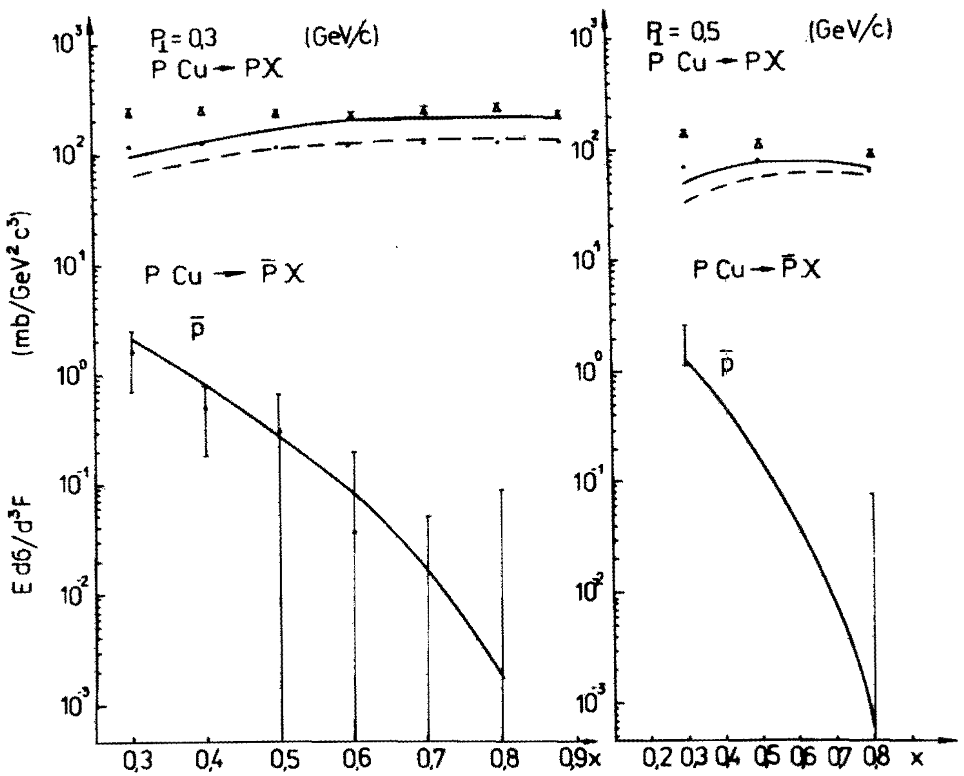

Fig.6. The inclusive spectra of protons (a) and antiprotons (b) produced in the inelastic $p-^{64}Cu$ *interaction, full and dash-and-dot curves correspond to* $B = 4\ (GeV/c)^{-1}$ *and* $B =$ $= 3\ (GeV/c)^{-1}$ *in (18).*

at not very large p_t, $p_t \leq 1$ (GeV/c), and not very small x. The mechanism suggested in ref.[19] is stated to be the main one at small x of hadrons.The division of gluons, which the quarks of the colliding hadrons exchange, is taken into account in ref.[19] . This mechanism leads to an increase in the average hadron transverse momentum if the charged particle multiplicity increases. Our mechanism dominates basically in the fragmentation region of colliding hadrons, but its contribution is negligible in the central region.

Thus we arrive at the following conclusions. One of the possible mechanisms of the inclusion of the quark (diquark) transverse momenta of hadrons is considered in the frame of QGSM. This mechanism leads to a stronger dependence of the average transverse momentum of particles in the hadron interactions on x and on the number of Pomeron showers n of 2n quark-antiquark chains than the mechanism of the type[12] that is experimentally confirmed[13-15] . This mechanism has to show up more clearly in h-A collisions, where the contribution of multipomeron chains is significant[4] even in the fragmentation region of initial hadrons. Note that it is possible to use a similar method of the inclusion of the transverse quark momentum in QGSM for the analysis of fragmentation processes on nuclei into hadrons in the cumulative region, if we assume that the nucleus consists not only of nucleons but also of quark clusters[20,21] . This is however another problem, its investigation, we think, will be of interest in future.

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Поперечные импульсы адронов в инклюзивных реакциях в модели кварк-глюонных струн

В рамках модели кварк-глюонных струн предлагается механизм учета зависимости функций распределения кварков, дикварков и их фрагментации в адроны от поперечного импульса $K_\perp$. Предполагается последовательное деление $K_\perp$ между 2n-кварк-антикварковыми цепочками или n-померонными ливнями. Анализируются адронные и адрон-ядерные процессы: вычисляются зависимость среднего поперечного импульса π-мезона в p-p соударении от x, инклюзивные спектры адронов в p-A взаимодействии при фиксированных и разных поперечных импульсах адронов. В таком подходе получается сильная зависимость наблюдаемых величин от n, это особенно важно при анализе адрон-ядерных столкновений.

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Hadron Transverse Momenta in Inclusive Reactions in the Quark-Gluon String Model

The mechanism of the inclusion of a dependence of distribution functions of quarks, diquarks and their fragmentation into hadrons on a transverse momentum K_t is proposed in the frame of the quark-gluon string model. The consequent division of K_t between 2n-quark-antiquark chains or n-Pomeron showers is supposed. Hadron and hadron-nuclear processes are analyzed: the dependence of the average π-meson transverse momentum in the p-p collision on x, hadron inclusive spectra in p-A interactions at fixed and different hadron transverse momenta are calculated. A strong dependence of the observed values on the number n is derived in this method, it is of special importance for the analysis of hadron-nucleus collisions.

The investigation has been performed at the Labotatory of Nuclear Problems, JINR.

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