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HARD HADRON-NUCLEUS PROCESSES AND MULTIQUARK CONFIGURATIONS IN NUCLEI

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I. Introduction.

At last time nontrivial effects of the relativistic nuclear physics: cumulative processes, EMC-effect, anomalous nuclear dependence in large $P_\perp$ processes are of great interest for the general public of physicists. Such an interesting phenomenon as the cumulative particle production shows that multiquark configurations are evidently presented in nucleus /1-3/. In our opinion this is confirmed by NA-4, EMC, SLAC experiments on deep inelastic lepton-nucleus scattering /4-6/. As to the anomalous nuclear dependence in large $P_\perp$ processes observed by Cronin's group in 1974 /7/ and investigated in detail by Sulaev's group at the Serpukhov accelerator /8,9/, the theoretical situation is not satisfactory now /10/.

The interpretation of the observed effects is difficult because of two reasons:

1. Distributions in nuclei and in free nucleons are different due to the Fermi-motion of nucleons and a possible presence of the multiquark fluctons /1-3/;

2. Hard hadron-nucleus interaction can be more complicated in contrast with the deep inelastic lepton-nucleon scattering because of the multiple rescattering effects of quarks of a colliding hadron and the absorption of secondary hadrons /10/.

These circumstances have not been taken into account so far. Therefore, this paper contains the analysis of the relative contributions of multiquark fluctons and rescattering of quark of the colliding hadrons taking the Fermi-motion into account in the formation of anomalies at the large $P_\perp$ meson production, that have been observed in the experiments /8,9/.

This analysis is based on the most realistic hadron and relativistic nucleus models. These models, as we think, are the additive quark model of hadrons /11/ and the quark-parton model of nuclear fluctons, naturally explaining the EMC-effect and the properties of the cumulative production /2,12,13/.

The mechanism of large $P_\perp$ hadron production in hadron-nucleon collisions at high energies should be known in order to analyse the hard hadron-nucleus processes. As is known this mechanism can be the hard elastic scattering of quarks with the subsequent fragmentation of one of them into the observed large $P_\perp$ hadron /14/. In the case of hadron-nucleus interaction the constituent quark of the initial hadron before a hard collision with a quark of a nucleus can have a number of soft collisions (at small momentum transfers), that cannot be neglected if the momentum transverse of the final hadron is not asymptotically large /15/. The quark collisions inside the nucleus succeeding the first hard ones can be neglected because of their small contribution /10/. The physical reason for that is the following: the constituent quark shakes off its gluon and quark-antiquark cloud after the hard collisions, therefore its cross section of the interaction with the nuclear matter decreases fast. The difference between the quark distributions in free nucleons and in nuclei should be taken into account close to the one-nucleon kinematic limits, that is at $x_\perp \to 1$ /2,3,16/. For the process of large $P_\perp$ hadron production in N-N collisions at the angle 90° in the N-N centre of mass the variable x goes to $x_\perp = 2P_\perp / \sqrt{S}$.

Just at large $x_\perp$ the anomalies in the inclusive meson spectra have been found /8,9/. The value of $x_\perp$ in these experiments amounted to $x_\perp = 0.81$ ($\sqrt{S} = 11.5$ (GeV), $P_\perp = 4.65$ (GeV/c).

The paper is organised as follows. In Sec. 2 we consider the model of multiple rescattering processes. The inclusion of multiquark configurations in nuclei will be discussed in Sec.3 . The results calcuation and their discussion are given in Sec.4 Sec.5 is devoted to the main results and the conclusion.

II. Multiple quark collisions.

The role of multiple quark collisions inside the nucleus in spectra of large $P_\perp$ particles produced in h-A interactions at high energies has been investigated in refs. /10,15, 17, 24/. In the general case the quark of the initial hadron can have both soft (at small transfers $/t/ \lesssim 1$ $(GeV/c)^2$) and hard (at large transfers $/t/ \gtrsim 1$ $(GeV/c)^2$) collisions inside the nucleus. It was shown

/15, 19/ that soft multiple rescattering of quarks of the initial inside the nucleus give the main contribution to the spectrum of secondary particles, in particular, mesons at $P \approx 2 \div 3$ (GeV/c), but at larger transverse-momenta hard quark collisions have to be taken into account, that is, the oollisions at large transfer. However, contrary to general opinion the hard rescatterings cannot explain the observed A-dependence of spectra /10, 20, 21/. In this connection, the authors of ref. /18/ have made qualitative and quantitative statements that the main contribution to the formation of the anomalous nuclear dependence is given by the processes in which the large angle scattering occurs because of a several of soft and one hard collisions inside the nucleus. The accurate calculations under these assumptions have not been performed so far. Therefore it is interasting to develop the method proporsed before /15, 17-19/.

The dynamics of the production of large P particles in h-A reactions can be considered in the following manner. According to the additive quark model /11/ every constituent quark, valon, of the initial hadron scatters multiply softly on nucleons inside the nucleus, that is at small transfers independently of each other. Then it scatters hardly on the quark of the nuclear nucleon that is elastically at large transfer. After that the quark can be considered as the pointlike parton the cross-section of which is very small. Therefore this quark-parton does not practically interact with nuclear matter until a hadron is formed from this parton mainly without a nucleus /10, 20/. In the case of the production of rather fast hadrons al large P in h-A reactions we take into account multiple soft and one hard quark collisions inside the nucleus.

We shall consider now the inclusive large $P_\perp$ meson spectrum in P-A interactions. According to the above-mentioned and refs. /15, 19 18/ it can be represented in the following form:

$$E\frac{d\sigma}{d^3p} = \sum_{n=1}^{A} P_n F^{(n)}(x, P_\perp) \ ; \qquad (1)$$

Here the following notation is introduced: $F^{(n)}(x, P_\perp)$ is the inclusive hadron spectrum after n - multiple quark collisions inside the nucleus, that depends on the longitudinal momentum

fraction x and transverse-momentum $P_\perp$ of hadron P_n is the probability of n quark collisions inside the nucleus.

We suggest to represent the hadron-spectrum $E\,d\sigma/d^3p$ in pA-collisions in the following form:

$$E\frac{d\sigma}{d^3p} = \sum_n N_n \int G_q^{(n-1)}(x_1, K_\perp)\, G_N(x_2)\, \frac{\hat{s}}{\pi}\, \frac{d\sigma(\hat{s},\hat{t})}{d\hat{t}}\, \frac{1}{z^2}\, * \qquad (2)$$
$$* \, D_q^h(z)\, \delta(\hat{s}+\hat{t}+\hat{u})\, dx_1\, dx_2\, dz\, d^2K_\perp$$

$G_q^{(n-1)} = G_N \otimes f_q^{(n-1)}$ is the convolution of functions G_N and $f_q^{(n-1)}$ determined as follows:

$$G_q^{(n-1)}(x, K_\perp) = \int_0^1 dx_1\, dx_2 \int d^2P_{1\perp}\, d^2P_{2\perp}\, G_N(x_1, P_{1\perp})\, f_q^{(n-1)}(x_2, P_{2\perp})\, *$$
$$* \, \delta(x - x_1 x_2)\, \delta^{(2)}(K_\perp - P_{1\perp} - P_{2\perp}) \equiv G_N \otimes f_q^{(n-1)}$$

$$N_n = \frac{1}{(n-1)!} \int_{-\infty}^{\infty} dz \int d^2b\, (\sigma T_-(b, z))^{n-1} \rho(b, z)\, *$$

$$* \exp(-\sigma T_-(b, z)) \ ;$$

$$T_-(b, z) = \int_{-\infty}^{z} \rho(b, z')\, dz' \ ; \qquad \int \rho(r)\, d^3r = A \ ;$$

$\rho(r)$ is the nuclear density; $f_q^{(n-1)}(x, P_\perp)$ is the probability of the quark to have the longitudinal momentum fraction X and the transverse-momentum $P_\perp$ after n-1 interactions inside the nucleus. It is calculated as the convolution of n-1 differential cross sections of the quark-nucleon interaction

$$f_q(x, P_\perp) = \frac{1}{\sigma} \frac{d\sigma}{dx\, d^2P_\perp},$$

$G_N(x_2)$ is the distribution function of quark in the nucleon (we assume so far that the nucleus consists of A independent nucleons) in the longitudinal momentum fraction x_2, $d\sigma(\hat{s},\hat{t})/d\hat{t}$ is the differential cross section of the elastic quark-quark scattering depending on the total energy square $\hat{S}$ of colliding quarks and on transfer t /14/; $D_q^h(Z)$ is the fragmentation function of the quark into a hadron.

The cross section of the total quark-nucleon interaction is chosen in the form $\sigma \approx \frac{1}{3}\sigma_{NN}$ according to the additive assumption /11/, where σ_{NN} is the cross section of the total N-N collision. The momentum spectrum of the quark in the processes qN → qX is chosen the same as in the reaction NN → NX /23/:

$$f_q(x, K_\perp) = (\beta+1)\, x^\beta \frac{B^2}{2\pi} e^{-BK_\perp} \qquad (3)$$

because the quark-nucleon interaction is soft.

Notice that expression (2) in contrast to refs. /15, 19/ was written under the assumption that soft multiple quark collisions take place before a point z, but at z the hard quark collision at large transfer takes place; after that the quark-parton interacts inside the nucleus with a negligible cross section.

The distribution of constituent quarks in the colliding nucleon depending on x and $K_\perp$ is presented in ref. /14/ in a factorised form: $G_N(x, K_\perp) = q_N(x)\, g_N(K_\perp)$. The quark distribution in the nucleon $g_N(K_\perp)$ depending on an internal transverse-momentum can be taken in the form suggested in ref. /14/:

$$g_N(K_\perp) = \frac{B^2}{2\pi} e^{-BK_\perp}.$$

The method of calculation of the quark function $G_q^{(m)}(x, K_\perp)$ after multiple soft quark collisions inside the nucleus is presented in refs. /15, 19/. Omitting the calculational details we give only the final expression for $G_q^{(m)}(x, K_\perp) = q^{(m)}(x)\, g^{(m)}(K_\perp)$:

$$g^{(m)}(K_\perp) = \frac{B^2}{2\pi\,\Gamma(\frac{3m+1}{2}+1)} \left(\frac{BK_\perp}{2}\right)^{\frac{3m+1}{2}} K_{\frac{3m+1}{2}}(BK_\perp),$$

$$q^{(m)}(x) = q_N \otimes W^{(m)},$$

$$W^{(m)}(x) = \frac{(\beta+1)}{(m-1)!}\, x^\beta \left(\ln\frac{1}{x}\right)^{m-1}.$$

Here $K_m(y)$ is the McDonald function of m order, $\Gamma(\alpha)$ is the gamma function, $B = 2/\langle K_q\rangle$, where $\langle K_q\rangle$ is the mean momentum of the quark in the nucleon; it is determined from the deep inelastic l-N scattering data (see refs. in ref. /14/). As $q_N(x)$ we can use in our calculations the distribution of valence quarks since the distributions of constituent and valence quarks are practically equivalent both at small x /24/ and large x /29/. The distributions of valence quarks in the proton are the result of the EMC-data fitting /25/:

$$x\,u(x) = 2\sqrt{x}\,(1 + 1.2x)(1 - x)^{3.3}$$

$$d(x)/u(x) = 0.573\,(1 - x).$$

We should like to notice that these functions describe the EMC-data at $Q^2 = 5 \div 30 (\mathrm{GeV/c})^2$ that corresponds to transverse-momenta $P_\perp \approx 2 \div 5$ (GeV/c).

We use the parametrization of the elastic quark scattering in (1) that is different from the parametrization of the "black box" Feynman-Field model /14/ taking into account the scaling violation:

$$\frac{d\sigma}{d\hat t} \sim \frac{1}{(\hat s + M)^4}, \quad M = 30\ (\mathrm{GeV})^2. \qquad (4)$$

If the parametrization $\frac{d\sigma}{d\hat t} \sim \frac{1}{(\hat s + M_1)(-\hat t + M_2)^3}$ describes the large $P_\perp$ meson inclusive spectra in P-P collisions at FNAL and ISR energies ($19 \le \sqrt{s} \le 62$ (GeV)), then (4) describes the IPhHE data at $\sqrt{s} = 11.5$ (GeV) very well where the scaling violation effects are clearly seen.

In fact, the nucleons inside the nucleus are not frozen, their motion inside the nucleus has to be taken into account in the same way as in ref. /13/. The quark distribution function in the nuclear nucleon is presented in the form of the convolution of the quark function of the free nucleon and the function of Fermi-motion of nucleons inside the nucleus N_F^A /13/:

$$q_N^A(x) = N_F^A \otimes q_N \equiv \int_x^1 N_F^A(x')\, q_N\!\left(\frac{x}{x'}\right)\frac{dx'}{x'}.$$

For simplicity of calculations the function N_F^A can be chosen as in ref. /13/, in the Fermi-step form:

$$N_F^A(x) = \begin{cases} \frac{3}{4\delta^3}[\delta^2 - (x-1)^2] , & |x-1|<\delta \\ 0 , & |x-1| \geq \delta \end{cases}$$

$$\delta = \frac{K_F}{m_N} , \quad K_F = 0.19 \ (GeV/c) .$$

The choice of the Fermi-motion in this form is an approach of course. However, it can be justified by that the inclusion of a rather real function N_F^A changes the quark function $q_N^A(x)$ by about 10% - 15%.

In calculating the contribution of the multiple quark collisions the quark distribution in the nuclear nucleons including their Fermi-motion has to be taken into account.

III. Multiquark configurations in nuclei

The analysis of the cumulative production in hardon-nucleus reactions /1-3/, data on deep inelastic lepton-nucleus processes and other experiments point out that the distributions of quarks in a nucleus and a free nucleon are rather different. We think that observed effects of relativistic nuclear physics are the result of a permanent formation and decay in a nucleus of multiquark configurations-flutons.

We shall use the fluton model considered in refs. /13/ according to which the momentum distribution of quarks and gluons in the fluton consisting of colourless three quark clusters is the convolution of quark and gluon distributions in the nucleon and of an effective nucleon distribution in the fluton.

According to the model discussed the quark distribution function in the nucleus (averaged over transverse-momentum) is represented in the following form:

$$G_A(x) = \sum_{k=1}^{A} C_k^A \frac{A}{k} \ G_k(x) , \qquad (5)$$

where C_k^A is the probability of the k-nucleon fluton ($\sum_{k=1}^{A} C_k^A = 1$), and $G_k(x)$ is the quark distribution in the fluton consisting of 3k valence quarks ($\int_0^k G_k(x)\, dx = 3k$). The distribution $G_k(x)$ can be represented as the Mellin convolution of the momentum distribution of colourless 3q - clusters and the distribution of the quark in these 3q - clusters:

$$G_k(x) = q_N \otimes N_k , \qquad (6)$$

$G_1(x) = q_N(x)$ is the quark distribution in the nucleon, $N_k(x)$ is the distribution of 3q - clusters. The distribution $N_k(x)$ ($k \geq 2$) follows from the description of the experimental data on disintegration, EMC-effect and the cumulative processes (see ref. /13/). It has the following form (with taking into account the Fermi-motion of 3q-clusters in the fluton and decreasing of the average momentum fraction of valence quarks in the nucleus, etc.)

$$N_k(x) = A_k x^{B_k}(1-x)^{2k-W} , \quad \int N_k(x)\, dx = k , \qquad (7)$$
$$B_k = \frac{\Delta(2k-W+2)-k}{k-\Delta} , \quad W=3 , \quad \Delta = 0.39 ,$$

Δ is the ratio of the momentum fractions of valence quarks in the nucleus and free nucleon. The parameter value $W = 3$ corresponds to the case when the quark of the initial hadron in the hard scattering knocks out only of all quarks of the colourless 3q-cluster of the k-nucleon fluton, thus exciting its colour degrees of freedom of other k-1 colourless 3q-clusters of the fluton remain almost unexcited. We shall not discuss the problems concerning additional quark and gluon sea formed in nuclei /13/, since we are interested in large values x where the sea gives a negligible contribution ($x \gtrsim 0.3$).

IV. Results and discussion

We consider now the large $x_\perp$ meson production processes in the proton-nucleus collisions taking into account both the multiple rescattering processes and the presence in the nucleus of multiquark fluctions of density - flutons.

For this purpose we substitute the quark distribution in the nucleus (5) into the formula of the multiple rescattering (2) instead of the momentum distribution of quarks in free nucleons. First we shall discuss the quntitative results. As is shown in ref. /12/ the quark distribution function in the fluton calculated by expression (6) is considerably larger than the quark function of the nucleon $q_N(x)$ at x close to 1. That means the following: if the minimum integration limit $x_{2\,min}$ is large, the final meson spectrum changes very much if we shall take multiquark states in the nucleus into account. If the internal transverse-momenta $K_\perp$ are neglected in expression (2) the integration limits $X_{1\,min}$, $X_{2\,min}$ will be presented by simple expression /14/:

$$X_{1\,min} = \frac{X_\perp \, ctg \, \vartheta^{NN}_{CM}/2}{2 - X_\perp \, tg \, \vartheta^{NN}_{CM}/2} ,$$

$$\frac{X_{2\,min}}{K} = \frac{X_1 X_\perp \, tg \, \vartheta^{NN}_{CM}/2}{2X_1 - X_\perp \, ctg \, \vartheta^{NN}_{CM}/2} ,$$

where ϑ^{NN}_{CM} is the emission angle of the final meson in the centre of mass of the nucleon-nucleon collision. In the case $\vartheta^{NN}_{CM} = 90°$ we have

$$X_{1\,min} = \frac{X_\perp}{2 - X_\perp} , \qquad \frac{X_{2\,min}}{K} = \frac{X_1 X_\perp}{2X_1 - X_\perp} .$$

Therefore, it is shown that $X_{2\,min}/K$ goes to 1 also at $x_\perp \to 1$. Since the kinematic boundaries of quark distributions in the free nucleon and in the flucton are different, the inclusion of quark fluctons in (1) has to give a considerable increase in the spectrum at $x_\perp$ close to 1.

Consider now the simplest example - the scattering on the deuteron $Pd \to hX$.

The invariant differential cross section of the process Pd has the following form $\left(f \equiv \frac{E d\sigma}{d^3p} \right)$:

$$f_{pd} = (1 - C^d_{6q}) \{ f_{pp} + f_{pn} + P_2 f^{(2)} \} + + C^d_{6q} f_{p6q} , \qquad (8)$$

C^d_{6q} is the probability to find a 6q - state in the deuteron, $P_2 = \frac{1}{4\pi} \sigma \langle r^{-2} \rangle$ is the probability of the double rescattering, $f^{(2)}$ is the hadron spectrum after the rescattering calculated by (2).

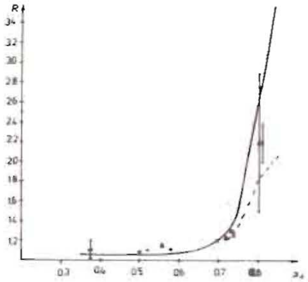

Fig. 1

The $x_\perp$-dependence of $R = \frac{f_d(\pi^+) + f_d(\pi^-)}{2[f_p(\pi^+) + f_p(\pi^-)]}$, where $f_d(\pi)$, $f_p(\pi)$ are the invariant π - meson spectra produced in P-d and P-P interactions respectively; the dashed curve is the results of calculation the double quark rescattering and Fermi-motion are taken into account. The solid curve is drawn taking the double quark collisions and Fermi-motion, and 6q-states in deuteron into consideration; ⌶ ⌶ ▫ are the experimental data at initial proton energy E = 70(GeV) from ref. /8/ and /9/ respectively.

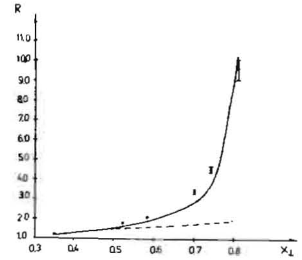

Fig. 2

The $x_\perp$-dependence of $R = \frac{f_{C^{12}}(\pi^+) + f_{C^{12}}(\pi^-)}{12[f_p(\pi^+) + f_p(\pi^-)]}$, where $f_{C^{12}}(\pi)$ are π -meson spectra in the reaction $P\,C^{12} \to \pi X$; the solid curve is drawn taking both the multiple rescatterings and other multiquark configurations in nuclei into account; the dashed curve is the contribution of multiple quark collisions and Fermi-motion of nucleons in nucleus only. ⌶ are experimental data at E_0 = 70 (GeV) from ref. /9/.

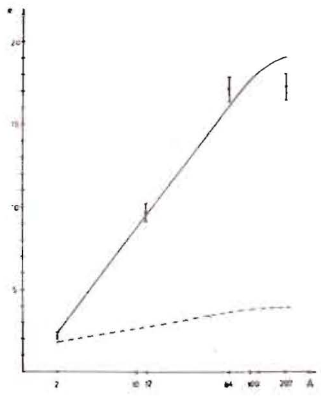

Fig. 3. A-dependence of the ratio R at $x_\perp$ = 0.81, the solid and dahsed curves denote the same as in fig. 2; ⌶ are experimental data /9/.

The ratio of cross sections

$$R(x_\perp) = \frac{f_{pd\to hX}}{2f_{pp\to hX}}$$

$$\left(\vartheta^{NN}_{CM} = 90^\circ,\ C^{d}_{6q} = \quad \%,\ h = \frac{\pi^+ + \pi^-}{2}\right)$$

in comparison with the experimental data /9/ is presented in fig. 1. It is shown that the mechanism of double rescattering is dominating at $x_\perp \leqslant 0.7$. At larger $x_\perp$ the main contribution comes from the hard scattering processes. But the experimental error can reach a very large value (dashed curve in fig. 1) at $x_\perp = 0.81$ according to /9/ thus we cannot inder that the contribution of the 6q-state to the inclusive process $Pd \to hX$ is large at attainable experimental accuracy at $x_\perp = 0.81$.

Really, the calculated results (see fig. 2) for $P^{12}C \to hX$ show that the contribution of the flucton mechanism is sufficient at $x_\perp \approx 0.7$ and it is dominant at $x_\perp \gtrsim 0.8$.

We shall consider the medium and heavy nuclei where the anomalies are large /9/.

Since the power ansatz for A-dependence is not true in the inclusive one-particle spectra of large $P_\perp$ hadrons, i.e., the cross section cannot be represented in the form /9/:

$$\frac{Ed\sigma}{d^3p}(pA \to hX) = A^{\alpha(P_\perp)}\frac{Ed\sigma}{d^3p}(pN \to hX)$$

we shall consider the ratio

$$R = \frac{Ed\sigma}{d^3p}(pA \to hX) \Big/ A\,\frac{Ed\sigma}{d^3p}(pN \to hX)$$

in the dependence on A at the fixed value $x_\perp$.

The calculated results at only one value of $x_\perp$ (the value $x_\perp = 0.81$ is most improved in the experiment /9/ now) are presented in fig. 3 because of the difficulty of the numerical calculations. One can easily show that the main nuclear effect that gives an anomalously large meson emission at $x_\perp > 0.7 \div 0.8$ is the existence of multiquark flucton in nucleus. The inclusion of multiple rescattering processes and Fermi-motion of nucleons describes only 20% of the effect observed at $x_\perp = 0.81$. In this case the value of the coherence radius of nucleons in the flucton as the parameter of the flucton model was equal to 0.97 (fm.) for all nuclei (except

deuteron). This corresponds to the probability of flucton formation in ^{12}C approximatly of 18.5% and in ^{64}Cu, ^{207}Pb of 25% and 30% respectively. These probabilities calculated in the framework of the gas description of EMC and cumulative effects /13/, preliminary NA-4 data and anomalies found by Sulaev's group /9/, which confirms the basic assumptions of the flucton model /2, 13/.

Our results point out that the results of refs. /26/ are uncorrect, where the anomal A-dependence of large $P_\perp$ processes /7/ has been explained with the help of multiquark states at comparatively small $x_\perp$ $(0.2 < x_\perp < 0.6)$.

Our results agree with ref. /16/ qualitatively, where the particle production on nuclei at $0.8 < x_\perp < 1.2$ ($\vartheta^{NN}_{CM} = 90^\circ$) is predicted. It has been noticed /8/ a rapid decrease of cross sections with respect to $x_\perp$ for large $P_\perp$ cumulative processes ($\vartheta^{NN}_{CM} \approx 90^\circ$, $x^{max}_\perp \approx 2$) in contrast with the cumulative production of small $P_\perp$ hadrons ($\vartheta^{NN}_{CM} \approx 180^\circ$, $x^{max} \approx A$).

V. Conclusion

The analysis of the inclusive large $x_\perp$ meson production in the hard hadron processes on nuclei has allowed one to understand the relative contribution of multiple rescattering processes and the existence of multiquark fluctons in the nucleus in dependence on $x_\perp$ the multiple rescattering processes are dominating at $x_\perp < 0.7 \div 0.8$ whereas at larger $x_\perp$ the mechanism of hard scattering on fluctons is dominating. The model of multiple rescattering in which the multiple soft collisions suggested in this paper are taken into account before the hard collision allows one to describe the multiple rescattering processes inside the nucleus correctly.

The flucton model succesfully used earlier for the description of the cumulative production and EMC-effect with such parameters is applied for the description of anomalous phenomena in the large $p_\perp$ processes in nuclei.

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Жесткие адрон-ядерные процессы
и многокварковые конфигурации в ядрах

Исследуется инклюзивное образование адронов с большими поперечными импульсами $P_\perp$ в P-A реакциях. Показано, что отличие распределений кварков в свободном нуклоне и в ядре может привести к аномально большому выходу адронов, в частности, мезонов, с $x_\perp = 2P_\perp/\sqrt{S} \geq 0,7$-$0,8$, что подтверждается экспериментально. При меньших $x_\perp$ основной вклад в рассматриваемые спектры дают многократные кварковые столкновения внутри ядра.

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