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SHADOWING AND ANTISHADOWING IN THE PRODUCTION OF HIGH-p_T HADRONS OFF NUCLEI

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1. Introduction

The long standing investigation of nuclear target effects in the high-p_T hadron production is abundant by dramatic events. Fifteen years ago Cronin's group [1] has discovered interesting effect of antishadowing in the inclusive high-p_T hadron production off nuclei. Parameterizing the atomic-number dependence of the cross section as A^{α}, they found an exponent α to be an increasing function of the transverse momentum p_T, extending unity yet. This observation contradicted expectations from naive parton model predicting the linear A-dependence. The matter is, the interaction of hard pointlike partons should not be screened by nucleus. However, the multiple scattering of partons inside the nucleus makes the A-dependence more strong, and can explain, in principle, the antishadowing phenomenon (see for instance review [2]). There was proposed the "smoking gun" experiment of the high-p_T symmetric-hadron-pair production, where rescattering should be suppressed. As a consequence, linear A-dependence was expected. Indeed some measurements [3,4] confirmed at first this suggestion. It seemed that time as a great triumph of the theory.

However, Sulyaev's group continuing their 70 GeV measurements [5] discovered a puzzling phenomenon: as p_T value was increased the exponent α drops considerably lower than unity, i.e. strong nuclear screening appeared. This unexpected result contradicted theory ones more.

An explanation was suggested by Kopeliovich and Niedermayer [6] who recalled the effects connected with the braking of leading quarks after inelastic collision due to the particle emission, and took into account the nontrivial energy-dependence of the leading hadron formation zone. As the kinematic boundary comes nearer ($x_T \rightarrow 1$), soft nuclear rescatterings become a shadow for hard process.

The recent measurements [7] by E605 Collaboration of the high-p_T hadron-pair production at 800 GeV confirmed the Sulyaev's effect.

These results promted us to make calculations with more refined formulae than in [6], taking into account the transverse motion of quarks in the incident hadron and transverse momenta of hadrons in the produced jets. More correct formula for the formation zone of soft hadrons changes slightly the results at small-p_T. We analyse, except the 70 GeV data [5], the 400 GeV [3,8,9] and new 800 GeV [7] data also. Some ambiguities are connected with the absence of particle identification and bad knowledge of the two-particle correlation parameter at high energies. Up to this unsertainty we obtain a good description of all data. It is amusing that the 400 GeV data [8] considered for a long time [10] as outstanding from the other data totality, also lie down nicely on our predictions.

The paper is organized as follows. In the next section the standard approach to the high-p_T symmetric-particle-pair production on a nucleon target is presented. The effects of nuclear medium are discussed in sect.3. The corresponding formulae for nuclear target are obtained in sect.4. Numerical results of calculations are compared with the experimental data in sect.5. The last section is devoted to the conclusions and propositions of further investigations.

2. Formulae for symmetric-hadron-pair production on nucleon target

It is assumed that high-transverse momentum hadron-hadron process occures as a result of single large-angle scattering ab → cd of partons a and b followed by fragmentation of c and d into observed particles with large-p_T. In this framework the cross section for large-p_T symmetric-hadron-pair production in the process AB → CD + anything (at $\theta_{cm} = 90^\circ$ and $\phi = 180^\circ$) can be represented in the following form [11]:

$$\frac{E_C E_D \, d\sigma}{d^3p_C d^3p_D} = \frac{1}{\pi p_T} \int_{x_T}^{1} \frac{dx}{z} \frac{d\sigma}{d\hat{t}} \frac{G_a^A(x) G_b^B(x) D_C^c(z) D_D^d(z)}{[2\pi(\langle k_T^2\rangle z^2 + \langle q_T^2\rangle)]^{1/2}} \, , \tag{1}$$

where $G_a^A(G_b^B)$ represent the probability for the constituent a(b) of particle A(B) to have fractional longitudinal momentum x ; $D_C^c(D_D^d)$ is the probability that the constituent c(d) fragments into hadron C(D) with fractional momentum z; p_T is transverse momentum of hadron C(D) ; $x_T = 2p_T/\sqrt{s}$; $z = x_T/x$; $\langle k_T^2\rangle \approx (0.4\ \mathrm{GeV}/c)^2$ is the constituent transverse momentum squared in the initial hadrons A and B; $\langle q_T^2\rangle \approx (0.25\ \mathrm{GeV}/c)^2$ is the mean transverse momentum squared of the particle C(D) relative to the direction of motion of the constituent c(d); $d\sigma/d\hat{t}$ is the cross section of subprocess ab → cd.

We parameterize the functions G and D as follows:

$$C \, \frac{x^\alpha (1-x)^\beta}{B(1+\alpha, 1+\beta)} \, . \tag{2}$$

Parameters α and β are equal to:
for valence quarks in proton

$u_V(x)$: $C = 2, \quad \alpha = -1/2, \quad \beta = 3$

$d_V(x)$: $C = 1, \quad \alpha = -1/2, \quad \beta = 4$

for sea quarks $u_S(x) = \bar{u}_S(x) = d_S(x) = \bar{d}_S(x) = 3s_S(x) = 3\bar{s}_S(x)$:

$$C = 0.3, \quad \alpha = -1, \quad \beta = 7$$

and for the quark → meson fragmentation functions $D_\pi^u(x) = D_\pi^d(x) = 3D_K^u(x) = 3D_K^d(x)$:

$$C = 3/4, \quad \alpha = -1, \quad \beta = 2.$$

If the role of constituents a and b is played by the quarks, then [12]

$$\left(\frac{d\sigma}{d\hat{t}}\right)_{qq} = -\frac{\lambda}{\hat{s}\hat{t}^3} \, , \tag{3}$$

where $\lambda = 2300\ \mathrm{mb\ GeV}^6$; $\hat{s}, \hat{t}$ and $\hat{u}$ are the Mandelstam variables for the subprocess.

In the case of baryon production one should add subprocesses with diquarks (pair of valence quarks). The corresponding parameters are fixed [13] by the experimental data and the quark counting rules:

for scalar ud-diquark distribution in nucleon

$$C = 6, \quad \alpha = 1, \quad \beta = 1 \, ,$$

for the diquark → nucleon fragmentation function

$$C = 3/4, \quad \alpha = -1, \quad \beta = 2 \, ,$$

and for the quark-diquark and for the diquark-diquark subprocess cross sections

$$(d\sigma/d\hat{t})_{q(qq)} = (d\sigma/d\hat{t})_{qq} f^2(Q^2)$$

$$(d\sigma/d\hat{t})_{(qq)(qq)} = (d\sigma/d\hat{t})_{qq} f^4(Q^2)$$

$$f(Q^2) = (1+Q^2/M^2)^{-1},$$

where $f(Q^2)$ is the diquark form factor; $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2)$; $M^2 = 12$ $(GeV/c)^2$. The experimental data fix also effective weight of the quark-diquark component of nucleon [13]: $W \approx 0.7$.

3. How does nuclear medium influence the hard process?

In fact, the high-p_T particle production off nucleon bounded in nucleus can differ considerably from the free-nucleon scattering. It is possible to point out a few sourses of the nuclear influence:

i) The energy of incident hadron is spent after inelastic collision to the particle production with constant longitudinal density of the energy losses $dE/dl = -\varkappa_{eff}$. It is true in any reasonable model of multiperipheral type. In the simplified version of the colour-string model [14,15] the factor $\varkappa_{eff}$ is the string tension known from the Regge-trajectory slopes, $\varkappa \approx 1$ GeV/F. In fact, the value of $\varkappa_{eff}$ can exceed this static one due to soft gluon bremsstrahlung [16], for instance. Indeed, the first crude analyses of the nuclear target effects on J/Ψ production [17,18], where braking of hard partons plays the same role, and on the high p_T particle-pair-production [6], provided the value of $\varkappa_{eff} \approx 2 \div 3$ GeV/F, consistent with theoretical estimation [16].

Thus, the real energy of the hard process, we are interested in is less than the initial one by value $\Delta E \approx \varkappa \, \Delta l$, where Δl is the longitudinal distance between the points where the first inelastic collision and the hard scattering have occurred. This energy bias can be essential at any high energy when $x_T \rightarrow 1$.

Note, that considered rescatterings are of planar type, they are possible due to large longitudinal dimension of nuclei. There are also known nonplanar rescatterings of Glauber-Gribov type [19]. But they do not influence the structure function of the quark having high virtuality.

ii) The kinematics of symmetric-hadron-pair production is such that it suppresses the contribution of events with large difference between transverse momenta of the colliding partons. On the other hand, the soft rescattering of a parton inside a nucleus increases its transverse momentum as $\langle k_T^2 \rangle_A \approx \Delta l \, \rho_A \, \sigma \, \langle k_T^2 \rangle_N$, where ρ_A is nuclear density; σ and $\langle k_T^2 \rangle_N$ are the cross section and the mean momentum squared of parton-nucleon scattering. This effect brings forth an additional screening of the symmetric-hadron-pair production.

iii) The hadronization of high-p_T parton needs time, and the high-p_T hadron is emerged somewhere on a distance l_f far from the collision point, known as a formation zone. We estimate the value of l_f in the framework of string model, but the results have more general character.

It is known from the old parton model [2] that l_f grows linearly with momentum, p, of produced particle. It is true in the string model also: $l_f \approx p/\varkappa$. However, as the momentum p is increased more and more, this dependence is broken. It was first proposed in [20,6] that the formation zone l_f disappears, when relative part, z, of the parton momentum carried by a hadron, tends to unity. Indeed, the parton on the end of the string is braked by the string tension and cannot produce a leading hadron with $z \rightarrow 1$ after some time. In this region l_f depends on z as [20,6]:

$$l_f = \frac{k}{\varkappa} (1 - z), \qquad (4)$$

where k is the initial momentum of parton ($k = p/z$).

It is important to emphasize that distance (4) is not in fact connected with formation of a hadron wave function. The latter needs for a large time, which is determined in the lab. frame by the Lorenz time delation factor. One is interested, however, in the moment when the leading parton colour is screened by means of the last string breaking. Produced colourless object turns into a hadron over large distance, only if it has no inelastic interaction up to leaving the nucleus. On the other hand, the rescatterings of a colour string inside a nucleus do not influence considerably the high-x_T part of momentum spectrum [20], as a quark stays after the colour exchange in the triplet state, twisting only in the colour space. If the interactions of a parton during its propagation over distance (4) do not change the measured cross section, one can consider it as noninteracting at all, i.e. distance (4) plays a role of the formation length.

It is seen that if $x_T \rightarrow 1$, i.e. $l_f \rightarrow 0$, parton colour must be screened immediatly after its scattering and the colourless configuration can be absorbed by nucleus. This fact displays as a nuclear screening and is confirmed [20,21] by the experimental data.

Finally, we see that the formatiom zone $l_f(z)$ goes to zero on the ends of interval $z \to 0$ or 1. The corresponding functions $l_f=kz/æ$ and expression (4) are well sewing together at $z=1/2$. Detailed Monte-Karlo calculations[1] in the string model show that the maximum of the function $l_f(z)$ is shifted to the smaller values of arguments, but this fact does not influence the high p_T behaviour, we are interesting in.

iv) It should be taken into account the difference between nucleus and free nucleon structure functions. The influence of widely known EMC-effect [22] reaches maximum magnitude of about 10÷15% for heavy nuclei at Bjorken variable $x \approx 0.6 \div 0.7$, i.e. it is negligibly small in comparison with the observed effect [5]. However,at high values of $x \geqslant 0.9$ the nuclear structure function exceeds considerably the nucleon one and as a result strong nuclear antishadowing should appear. But these values of x_T are far from the kinematic region, where the experimental data exist now.

v) From the Regge-phenomenology of soft inclusive reactions $AB \to AX$ one knows that high-x_F region is dominated by the diffraction dissociation. The reason is clear: both the structure function $G(x)$ and the fragmentation one $D(z)$ go to zero when $x_F= xz \to 1$. Such suppression is absent if all the valence quarks are keeped, i.e. diffraction scattering takes place. Analogous mechanism is possible for the large-p_T reaction and it should dominate at the high-x_T values. We look forward to the linear A-dependence for this contribution because only a point-like configuration can scatter with large-p_T. But nuclear matter is known to be transparent for such configurations [23-25]. We expect also more importance of this mechanism, i.e. scattering with large-p_T of all the valence quarks, for the nucleon production than for the meson one. In the former case, indeed, the single quark scattering contribution is suppressed by small probability of diquark pick up, but the diquark scattering is suppressed by its form factor. Thus one can expect of different nuclear screening of the nucleon and for the meson high-p_T yields in the case of proton beam.

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[1] N.S.Amelin, private communication.

4. Formulae for symmetric-hadron-pair production on nuclear target

Let us separate two contributions to the cross section for the high-p_T symmetric-hadron-pair production on a nucleus. The first one, $\sigma^{(1)}_{inv}$, corresponds to the case when the incident hadron undergone no inelastic collision before hard scattering. Interactions of the partons with high-p_T after the hard collision do not play any role within the formation length l_f, according to the consideration in previous section. In the same time, any interactions after screening of the high-p_T partons colour sould be forbidden due to sharp p_T-dependence of the cross section. Taking all this into account, the contribution $\sigma^{(1)}_{inv}$ can be written as follows:

$$\sigma^{(1)}_{inv}(x_T,s) = \int d^2\mathbf{b} \int_{-\infty}^{\infty} dl\rho(\mathbf{b},l)\exp[-\sigma^{hN}_{in}\, T(\mathbf{b},-\infty,l)] \cdot \qquad (5)$$

$$\int_{x_T}^{1}\frac{dx}{\pi p_T z}\,\frac{d\sigma}{d\hat{t}}(x^2 s)\,\frac{G^h_a(x)G^N_b(x)D^a_C(z)D^b_D(z)}{[2\pi(\langle k^2_T\rangle\; z^2+\;\langle q^2_T\rangle)]^{1/2}}\;\exp[-(\sigma^{CN}_{in}+\sigma^{DN}_{in})T(\mathbf{b},l+l_f,\infty),$$

where $d\sigma/d\hat{t}$ is the cross section of partons a and b scattering. For the qq hard scattering we use the Field-Feynman parameterization [12] $d\sigma/d\hat{t} \propto (\hat{s}\hat{t}^3)^{-1}= 8(x^2x^3_Ts^4)^{-1}$.
The formation length has a form

$$l_f = \begin{cases} \dfrac{x-x_T}{2æ}\,E \quad , & \dfrac{x_T}{x} \geqslant 0.5 \\[2ex] \dfrac{x_T}{2æ}\,E \quad , & \dfrac{x_T}{x} \leqslant 0.5 \end{cases}$$

If l_f is large in comparison with nucleus dimension, the hard scattering takes place mainly on the front surface of a nucleus, i.e. $\sigma^{(1)}_{inv}\propto A^{2/3}$. But if $x_T\to 1$, then $l_f\to 0$ and the hard scattering is contributed mainly from the nuclear edge, i.e. $\sigma^{(1)}_{inv}\to A^{1/3}$.

The second contribution $\sigma^{(2)}_{inv}$, includes all possible inelastic rescatterings inside a nucleus before the hard collision. The braking of partons after the first inelastic collision leads to some shift of the kinematic variables characterising the hard scattering: $E\to\tilde{E}=E-æ\Delta z$,

$x_T \to \tilde{x}_T = 2p_T/\tilde{s}^{1/2}$, $l_f \to \tilde{l}_f$. The corresponding expression has a form

$$\sigma^{(2)}_{inv}(x_T, s) = \int d^2\mathbf{b} \int_{-\infty}^{\infty} dl' \rho(\mathbf{b}, l') \exp[-\sigma^{hN}_{in} T(\mathbf{b}, -\infty, l')] *$$

$$\int_{l'}^{\infty} dl \; \rho(\mathbf{b}, l) \int_{\tilde{x}_T}^{1} \frac{dx}{\pi p_T \tilde{z}} \frac{d\hat{\sigma}}{dt}(x^2\tilde{s}) \frac{G^h_a(x) G^N_b(x) D^a_C(\tilde{z}) D^b_D(\tilde{z})}{[2\pi(\langle k^2_T\rangle_A \tilde{z}^2 + \langle q^2_T\rangle)]^{1/2}} *$$

$$\exp[-(\sigma^{CN}_{in} + \sigma^{DN}_{in}) T(\mathbf{b}, l+\tilde{l}_f, \infty)] \qquad (6)$$

Here all the values marked by waved label should be calculated by using the shifted value of incident energy $\tilde{E}$.

Far away from the kinematic boundary, where l_f is large and energy loss to the braking can be neglected, all the nucleons contribute to $\sigma^{(2)}_{inv} \propto A$. But if $x_T \to 1$, then the hard scattering is pushed out to the nuclear edge and $\sigma^{(2)}_{inv} \propto A^{1/3}$.

We use the nucleon structure function instead of the nuclear one in equations (5), (6). The screening of the latter at small x is unessential because it has to do with very small x_T values and is integrated over $x \geq x_T$. It was mentioned in the previous section that the EMC effect [22] is small enough to be neglected also. Only in the large x-region $x \gtrsim 0.9$ the nuclear structure function exceeds considerably the nucleon one. This effect can be easily included in (5), (6), but we ignore it now in view of absence of experimental data in this x_T-region.

An essential contribution to the final p_T cross section originates also from the statistical mechanism, i.e. independent occasional production of two high-p_T hadrons with symmetric momenta [6]. There are few evidences of this: 1) the correlation function defined as

$$R(p_T) = \frac{1}{\sigma_{in}} \frac{\sigma(AB \to CX)\sigma(AB \to DX)}{\sigma(AB \to CDX)} \qquad (7)$$

is of the order of unity at small $p_T \leq p^o_T$, but it is increased dramatically with $p_T \geq p^o_T$. such behaviour is clearly demonstrated by the 70 GeV data [26], where $p^o_T \approx 0.7$ GeV/c. Similar growth of $R(p_T)$ at $p_T \geq p^o_T$ is observed at higher energies also [27,28]; ii) the slope of the differential cross section $d^2\sigma/dp^2_{T1}dp^2_{T2}$ is very high and is compatible with the "double inclusive" production at $p_T \leq p^o_T$ but it is broken [29] to a considerably smaller value at $p_T \geq p^o_T$.

A - dependence of the statistic mechanism contribution to the cross section of symmetric-pair production can be easily evaluated as follows. Let us parameterize the A - dependence of inclusive production of a hadron h with high-p_T as $\sigma_o A^{\alpha_1(p_T)}$. Then the exponent $\alpha_{st}(p_T)$ corresponding to the statistic mechanism of high-p_T pair production can be found by using expression (7) regarding the correlation parameter R as energy-independent

$$\alpha_{st}(p_T) = \alpha^C_1(p_T) + \alpha^D_1(p_T) - \alpha_{in} \qquad (8)$$

Here $\alpha_{in} \approx 2/3$ is the exponent corresponding to A-dependence of the cross section of hadron-nucleus inelastic interaction parameterized also as $A^{\alpha_{in}}$.

The exponent $\alpha_1(p_T)$, as was mentioned in the introduction, is a rising function of p_T, consequently the value of $\alpha_{st}(p_T)$ should grow steeply with p_T while the statistic mechanism dominates. At higher p_T the hard parton scattering is turned on, so the exponent $\alpha(p_T)$ falls off due to nuclear absorption.

This nontrivial behaviour of exponent $\alpha_2(p_T)$, which characterizes the A-dependence of high-p_t hadron-pair production, is the result of mixing of two mechanisms with appropriate weights [6]:

$$\alpha_2(p_T) = \frac{\alpha_{st}(p_T)\sigma_{st}(p_T) + \alpha_{hard}(p_T)\sigma_{hard}(p_T)}{\sigma_{st}(p_T) + \sigma_{hard}(p_T)} \qquad (9)$$

Here $\sigma_{st}(p_T)$ and $\sigma_{hard}(p_T)$ are the contributions of the statistic and hard scattering mechanisms; $\alpha_{st}(p_T)$ and $\alpha_{hard}(p_T)$ are the corresponding exponents.

5. Comparison with experimental data

Following the experimentators who represent their results on the A-dependence of high-p_t hadron production as exponent α vs p_t, we also try to express the calculations in the corresponding form. Note that parameterization A^{α} can be crude because value of α depends on A in many cases. In order to bring our calculations closer to experimental situation we determine the value of $\alpha_2(p_T)$ using cross sections on nuclei Cu and Pb.

First we compare our calculations with 70 GeV data [4,5] where the most detailed information exists. The exponent $\alpha_{hard}(p_T)$ is computed by using formulae of chapter 2 and 4, where all the parameters are fixed except the effective string tension $\varkappa_{eff}$. As was mentioned in chapter 3, its magnitude does not coincide with the static value $\varkappa=(2\pi\alpha'_R)^{-1}$ and apparently exceeds it. Earlier we obtained a good description of the data on high-x_F J/Ψ production [17], high-x_F (and small-p_T) hadron production [30] and high-p_T symmetric-pair production [6] using $\varkappa_{eff}$=3(GeV/Fm). Here we try two numbers: $\varkappa_{eff}$=3 and 2 (GeV/Fm). The corresponding results for $\alpha_{hard}(p_T)$ marked by labels A and B respectively are displayed in fig.1 by dotted lines for the case of two-pion production.

In order to calculate $\alpha_{st}(p_T)$ according to (8) we fitted the data on p_T-dependence of inclusive pion production [31] with the parameterization

$$\alpha_1(p_T) = 1+\gamma\exp[-\alpha(p_T-\beta)^2]-\delta/p_T \qquad (10)$$

and found γ=0.1, α=0.123, β=4.15, δ=0.1. The relation between statistic and hard scattering contributions can be determined by fixing value of p_T^0 – the point where these two coincide, and the difference between the slope parameter, characterizing p_T^2-dependence of two contributions. In accordance with the data [31] we fixed the former by p_T^0=0.7 GeV/c and the latter by 6(GeV/c)$^{-2}$. The final results for $\alpha_2(p_T)$ are shown in fig.1 by full curves. They clearly display the nuclear antishadowing at small p_T and strong shadowing at higher p_T in accordance with the data.

The A-dependence of the πK production cross section is computed just in the same manner. The only difference is another set of parameters characterizing p_T-dependence of α_1 in accordance with (10): γ=0.26, α=0.2, β=0.44, δ=0.06. The results for $\alpha_2(p_T)$ are shown in fig.2 by two curves A and B corresponding to $\varkappa$=3 and 2 GeV/Fm. Both agree with the data [5].

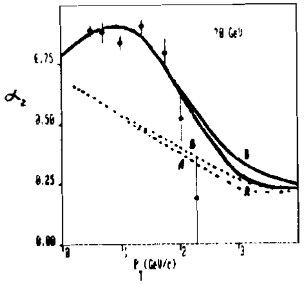


Fig.1. Exponent $\alpha_2(p_T)$ for symmetric-pion-pair production off nuclei at 70 GeV [5]. The marks A and B correspond to $\varkappa_{eff}$=2 and 3 (GeV/Fm) respectively. Dotted curves show the contribution of hard mechanism only. Full curves are obtained taking into account statistic mechanism contribution.

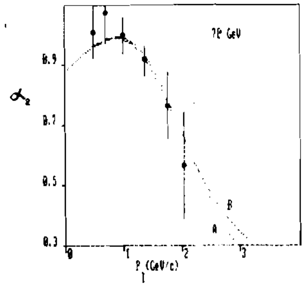


Fig.2. Exponent $\alpha_2(p_T)$ for symmetric-pion-kaon production off nuclei at 70 GeV [5]. The marks A and B correspond to $\varkappa_{eff}$=2 and 3 (GeV/Fm), respectively. Curves are obtained taking into account both statistic and hard mechanism contributions.

The mechanism of high-p_T proton production differs from meson one in two items mainly: i) dominating contribution of diquark scattering; ii) possible contribution of the diffractionlike scattering with high-p_T. Both have been considered above. If one takes into account the former but ignores the latter for a moment, he obtains $\alpha_2(p_T)$ for symmetric pp-pair production shown as curve number 1 in fig.3 ($\varkappa$=3 GeV/c). We have used here more simple parameterization of $\alpha_1(p_T)$ than expression (10): $\alpha_1(p_T)$=a+bp_T, which nicely fits the 70 GeV data [31] on inclusive high-p_T proton production with a=0.83, b=0.117. The curve 1 in fig.3 underestimates the measured [6] cross section at $p_T\geq$1 GeV/c. However the value of $\alpha_2(p_T)$ is highly sensitive to the impurity of statistic mechanisms known with finite precision. In part, if parameter p_T^0 is fixed at p_T^0=.78 GeV/c (instead of 0.7 GeV/c), what is allowed by the data, then new curve number 2 agrees with the data better as is shown in fig.3.

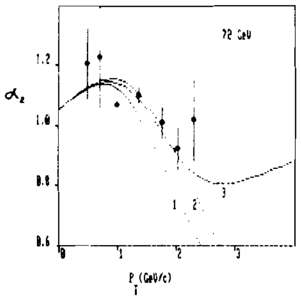
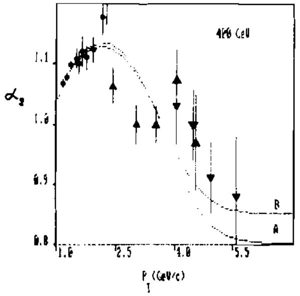


Fig.3. Exponent $\alpha_2(p_T)$ for symmetric-proton-pair production off nuclei at 70 GeV [5], calculated with $æ_{eff}$=3 GeV/Fm. Curves 1 and 2 correspond to the values p_T^0=0.7 and 0.78 (GeV/c), respectively. Curve 3 results from the 10% - addition of diffraction-like mechanism contribution, characterized by linear A-dependence.

The behaviour of $\alpha_2(p_T)$ at higher p_T strongly depends on presence of diffractive-like mechanism characterized by linear A-dependence. If one adds for instance only 10% of such contribution (independently of p_T), then the behaviour of $\alpha_2(p_T)$ changes drastically as is shown in fig 3 (curve 3).

The next set of data we intend to discuss are the results of measurements [8,3,9] of $\alpha_2(p_T)$ at energy 400 GeV which are presented in fig.4. There exists a widely spread opinion (see for instance ref.[10]) that the data [8] shown by full circles in fig.4, lie too high in contradiction with the totality of other data and theory (even the authors of [8] have come to a similar conclusion). However we see that behaviour of $\alpha_2(p_T)$ in fig.4 is typical one: the antishadowing at low-p_T is changed by shadowing at higher values of p_T. Moreover, one can easily describe these data by our formulae. The fit with expression (10) of the 400 GeV data [1] on p_T-dependence of inclusive charged particle production gives the following parameters: γ=0.163, α=0.174, β=4.41, δ=0.1. Note that number 2/3 for the value of α_{in} in (8) is very approximate. We adjusted α_{in}= 0.776 in order to get better description of the data shown in fig.4 in the low-p_T region.

Fig.4. Exponent $\alpha_2(p_T)$ of symmetric-hadron-pair production off nuclei at 400 GeV (o - [8], $\bar{\nabla}$ - [9], Δ - [3]). The marks A and B correspond to $æ_{eff}$=2 and 3 (GeV/Fm), respectively. Curves are obtained taking into account both statistic and hard mechanism contributions.



Comparison of data on the correlation parameter $R(p_T)$ (defined in (8)) at different energies: 70 GeV [26], 400 GeV [27] and 800 GeV [28], demonstrates that value of the parameter p_T^0 (the point where $R(p_T)$ starts its steep growth, i.e. the hard scattering is turned on) rises with the incident energy. Indeed, at 70 GeV $p_T^0\approx$0.7 GeV/c, at 400 and 800 GeV/c linear extrapolation to small values of $R(p_T)$ leads to crude estimates $p_T^0\approx$1.5 and 2.1 GeV/c, respectively. We have chosen p_T^0=1.64 in the limits of experimental uncertainty. These small adjustments result in a good description of experimental data on $\alpha_2(p_T)$ shown in fig.4 by curves A and B.

Collaboration E-605 [7] announced the possible observation of shadowing in the high-p_T symmetric hadron-pair production off nuclei at 800 GeV. We see from the previous consideration that this phenomenon is not a novel one. We computed $\alpha_2(p_T)$ putting p_T^0=2.1 GeV/c. The results shown in fig.5 agree with the data [7].

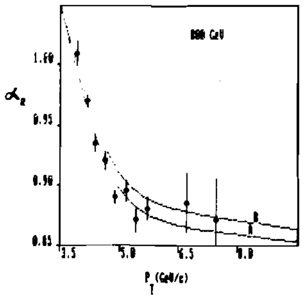


Fig.5 Exponent $\alpha_2(p_T)$ of symmetric-hadron-pair production off nuclei at 800 GeV [28]. The marks A and B correspond to $æ_{eff}$=2 and 3 (GeV/Fm), respectively. Curves are obtained taking into account both statistic and hard mechanism contributions.

6. Conclusion

High-energy hadron-nucleus interaction is a traditional tool for the investigation of the space-time pattern of strong interactions. By rescattering an unformed hadronic states within a short time interval (about 1 Fm) after the interaction, on another target (bounded nucleon) one obtains though indirect but unique information concerning the properties of unformed states.

The high-p_T symmetric-hadron-pair production off nuclei is one of the mostly studied reactions because theoretical interpretation is simplified considerably in this case by suppression of the multiple scattering contribution. Nevertheless this contribution, as is shown above, is not eliminated at all, but dominates the hadron pair production in the intermediate region of $p_T \leq 1$ GeV/c, where considerable nuclear antishadowing can exist. We avoided computing of multiple rescattering inside a nucleus (most uncertain theoretically) by means of using the available experimental information, and concentrated ourself on the problem of hard scattering.

Two main phenomena influence the hard parton-parton scattering inside a nucleus: i) the braking of color charges after the inelastic interaction on face nuclear surface due to the particle emission. This soft process shadows nevertheless subsequent hard interaction if the latter is measured near the kinematical boundary. ii) Soft interactions of fast coloured parton don't influence its braking, consequently one should not forbid soft rescatterings up to the moment when parton picks up another parton and forms a colourless object of small mass, which subsequently will turn into a hadron. The inelastic interactions of this object should be forbidden if one wants to have a hadron with high-x_T. These conditions are realized in formulae as a formation length l_f. The higher is x_T, the shorter is l_f.

These phenomena are tightly connected with the magnitude of parameter which we called effective colour string tension $\ae_{eff}$, because it is just this value in the naive string model. $\ae_{eff}$ is a free parameter in our model, it does not coincide with (and apparently exceed) the static value $\ae \approx 1$ GeV/Fm, fixed by the slope of Regge trajectories, because the inelastic collision, i.e. the colour exchange, is always accompanied a gluon bremsstrahlung. Previous investigations of soft [30] and hard [6,17,18] high-energy nuclear reactions (see, e.g. review [32]) found $\ae_{eff}$ in the range of $2 \div 3$ GeV/Fm.

Present analysis of available data on high-p_T symmetric-hadron-pair production off nuclei in the framework of this elaborated model demonstrates a nice agreement. The braking of coloured objects during the hadronization is displayed as nuclear shadowing in high-p_T region, where the multiple rescatterings are irrelevant.

It is desirable to have new experimental data on this subject at high energies including particle identification. It is important in part to investigate proton-pair production at higher p_T, in order to emphasize the diffraction-like mechanism. Experiments with meson and hyperon beams are of great interest too.

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Ким В.Т., Копелиович Б.З. E2-89-727
Экранирование и антиэкранирование процессов
с большими p_T на ядрах

В противоположность предсказаниям наивной партонной модели рождение симметричных адронных пар с большим поперечным импульсом экранируется ядром. Это с очевидностью следует из экспериментальных данных, полученных при энергиях 70, 400 и 800 ГэВ. Главной причиной экранирования является торможение партонов, обусловленное испусканием частиц после неупругого соударения. В области малых p_T доминирует статистический механизм, т.е. случайное рождение пары адронов в симметричной конфигурации. Этот вклад приводит к ядерному антиэкранированию при малых значениях p_T. Существующие экспериментальные данные хорошо описываются при значении эффективного коэффициента натяжения цветной трубки около 2÷3 ГэВ/Фм.

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Kim V.T., Kopeliovich B.Z. E2-89-727
Shadowing and Antishadowing in the Production
of High-p_T Hadrons off Nuclei

On the contrary to naive parton model prediction, the symmetric-hadron-pair production is shadowed by nuclear matter at high transverse momenta. It has been clearly demonstrated by measurements at 70, 400 and 800 GeV incident energy. The main reason of shadowing is the braking of partons due to emission of particles after soft inelastic collision. The higher is x_T, the more is the influence of braking. The low-p_T region is dominated by statistic mechanism, i.e. occasional creation of hadron-pair in symmetric configuration. This contribution causes the nuclear antishadowing at low-p_T. The existing experimental data are nicely described if the effective colour-string tension is about 2 ÷ 3 GeV/Fm.

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

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