NUCLEAR EFFECTS FOR HEAVY-QUARKS AND LEPTON-PAIR PRODUCTION

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Production of particles containing heavy quarks and the Drell-Yan process on nuclei are investigated in the framework of the parton model and reggeon calculus. It is shown that A-dependence of these reactions can be understood in this approach which gives a good description of the light-quark states production on nuclei. An existence of a new large-energy scale for production of heavy states is emphasized. Predictions for future experiments are given.

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Investigation of nuclear effects for production of heavy (c, b, ...)-quarks and the Drell-Yan process is important in order to obtain a consistent space-time picture of strong interactions at high energies. This problem is also essential for heavy ions interactions to clarify an origin of J/ψ-suppression. The data on A-dependence of inclusive cross sections of both heavy states and those made of light (u, d, s)-quarks can serve for critical tests of theoretical models.

Here we will use the approach, based on the parton picture of hadronic interactions at high energies and the reggeon calculus, first introduced for interactions with nuclei by Gribov[1]. This approach is very general and should be valid for any field theory, uncluding QCD.

Production of hadrons, made of light quarks in hadron-hadron (hh), hA and AA-collisions is rather well understood and quantitatively described in some particular realizations of this approach like the Dual parton model[2] or Quark-gluon strings model[3].

Usually A-dependence of inclusive cross section for production of a hadron "a" in hA-collisions $\frac{d\sigma^a_{hA}}{dx}$ is parametrized in the form $\frac{d\sigma^a_{hA}}{dx} \sim A^{\alpha_a(x)}$ and experiments show that for "ordinary" hadrons (π, K, N, Λ, ...) $\alpha_a(x)$ is changing from the values $\alpha_a(x) \approx 1$ for $x \to 0$ to $\alpha_a(x) \approx 0.4 \div 0.5$ as $x \to 1$. This is in agreement to the prediction of the reggeon approach, which leads asymptotically as $s \to \infty$ for small x to A^1-dependence (for the Glauber-type nonenhanced diagrams), while the decrease of $\alpha_a(x)$ as $x \to 1$ is connected to the energy-momentum conservation effects (see for example recent reviews[4,5]).

For heavy-quarks production and the Drell-Yan process a situation is less clear. Experimental data[6,7] show that:

a) for the Drell-Yan process $\alpha(x) \approx 1$ at present energies.

b) For J/ψ and ψ'-production $\alpha(x) < 1$ and decreases with x from values $\alpha \approx 0.9 \div 0.95$ at small x to $\alpha \approx 0.7 \div 0.8$ as $x \to 1$. Analogous behaviour is observed for production of states with open charm. Even for such a heavy state as Υ there are some nuclear effects, leading to $\alpha(x) < 1$[7].

These experimental facts are difficult to explain in theoretical models[8]* . In the parton model, which we will use in the following a fast moving hadron is considered as a system of partons (quarks and gluons) and soft partons of a projectile interact with a target. For hadron-nucleus collisions the shadowing effects are due to interactions of partons of a projectile with different nucleons of nuclei (Fig. 1).

Note that successive rescatterings of the initial hadron on nucleons of a nucleus decrease with energy[1,5] at energies $E > E_0 = m_N \cdot \mu . R_A$, where $R_A = R_0 A^{1/3}$ is a radius of a nucleus and μ is a characteristic hadronic scale $\sim$ 1 GeV. Though a space-time picture of interaction is completely different from the Glauber one, the generalized Glauber-type formula for elastic hA-scattering

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* There is one model[9] which takes into account intrinsic charm component of the initial hadron and is able to describe experimental data. However we emphasize in this paper that this mechanism does not lead to nuclear shadowing for J/ψ at energies $E_L \lesssim 100$ GeV and thus contradicts to the data[6].

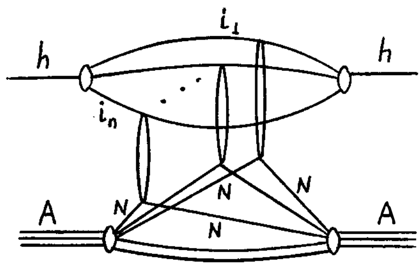

Fig. 1

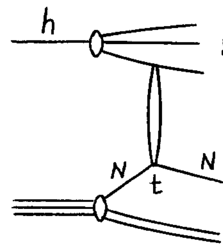

Fig. 2

amplitude is valid[1] in the high energy region. The nonplanar (Mandelstam type) diagrams start to dominate in the energy region $E \gtrsim E_0$, where the diffractive production on nucleons with small momentum transfer $t \sim 1/R_A^2$ (Fig. 2) becomes possible. This corresponds to a condition

$$t_{min} = -\frac{m_N^2\left(S_1 - m_h^2\right)^2}{S^2} = -\frac{\left(S_1 - m_h^2\right)^2}{4E_0^2} \approx \frac{3}{R_A^2} . \qquad (1)$$

For processes, involving "ordinary" hadrons (light quarks and gluons) $E_0 \sim 10$ GeV.

In the energy region $E > E_0$ the AGK-cutting rules[10] give a possibility to calculate different inelastic process if contributions of rescatterings to the elastic amplitude are known. Each of iN-elastic amplitudes (Pomerons) in Fig. 1 can be either "cut" and gives a multiparticle final state or "uncut" (absorption) - Fig. 3. This leads to the cancellation of contributions of all rescattering

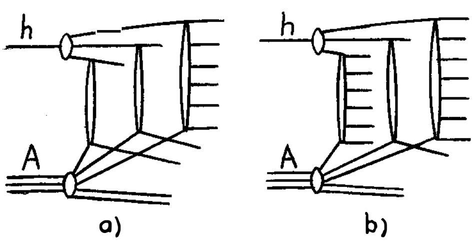

Fig. 3

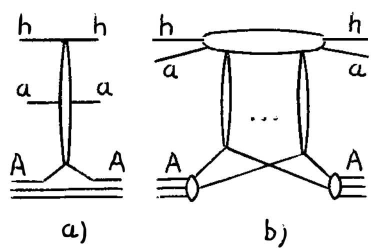

Fig. 4

diagrams to inclusive cross section[10] and $\frac{d\sigma^a_{hA}}{dx} = A\,\frac{d\sigma^a_{hN}}{dx}$, i.e. $\alpha = 1$ (the corresponding diagram for inclusive cross section is shown in Fig. 4a)). This theorem is valid, however, only for particles, which are due to cuttings of Pomerons in the Fig. 1. There is also a contribution to inclusive cross section from partons, which are in the upper blob of the Fig. 1 (Fig. 4b)). These contributions are especially important in the fragmentation region of a projectile and are necessary to account for energy-momentum conservation effects[11,12]. They include the interaction of partons, which are in the same partonic configuration as $Q\bar{Q}$ (or $\ell\bar{\ell}$), and the $Q\bar{Q}$-interaction. The first one leads to a behaviour $\frac{d\sigma^a_{hA}}{dx} \sim A^{2/3}$ (as $A \to \infty$) and it exists for both $Q\bar{Q}$-production* and the Drell-Yan process. For hadrons "a", which are $q\bar{q}$-states these diagrams lead for $\frac{d\sigma^a_{hA}}{dx}$ as $x \to 1$ to the behaviour of the type

$$\frac{d\sigma^a_{hA}}{dx} \sim \int d^2b\, e^{-c\sigma_{Q\bar{Q}} \cdot n_A(b)} \left(1 - e^{-\sigma n_A(b)}\right) \qquad (2)$$

where $n_A(b)$ is a standard nuclear profile function in the impact parameter space, $\sigma_{Q\bar{Q}}$ is the inelastic cross-section of $(Q\bar{Q})$-interaction with a nucleon, σ is the effective cross section for interaction of other partons and C is a constant $\sim$ 1. For light hadrons $\sigma_{Q\bar{Q}} \approx 20\ \mu b$ and $\alpha(x) \to \frac{1}{3}$ as $A \to \infty$ (only edge of a nucleus is important). For realistic values of A calculations[2-5] show that $\alpha(x) \approx 0.4 \div 0.5$ as $x \to 1$. For $c\bar{c}$-systems $\alpha(x) \approx 0.7 \div 0.8$ and for $b\bar{b}$-systems $\alpha(x) \approx 0.9 \div 0.95$ as $x \to 1$.

In the region of small x the contributions of the "nonenhanced"-type diagrams (fast partons with $x_i \sim 1$ in the blob) give asymptotically $\alpha(x) = 1$, but in this region it is also necessary to take into account possible contributions of "enhanced" diagrams (Fig. 5) with interactions between Pomerons. As a result an inclusive cross section can be represented by a sum of terms proportional to A^1 and A^γ (with $\gamma = \frac{2}{3}$ as $A \to \infty$). It is known, however, that the triple-Pomeron coupling is rather small[13], so the deviations from A^1-behaviour should not be very large. This effect can be considered either as due to rescatterings of soft partons of the initial partonic fluctuation, or as a shadowing of soft partons from different nucleons of the target. Note, that they should also be present for the Drell-Yan process, while the absorption-like effects,

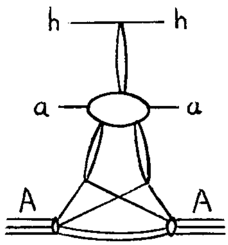

Fig. 5

* Nuclear shadowing due to the "intrinsic charm" component, proposed in ref. 9) corresponds to this mechanism.

discussed above do not exist in this case. So we predict that asymptotically there should be deviations from the A^1-behaviour even in the case of the Drell-Yan process.

All these results are valid only at very high energies $E >> E_0$, where the partonic fluctuations with heavy $Q\bar{Q}$-pair or $\ell^+\ell^-$ with large mass M satisfy to the condition (1). It follows from the kinematics of the process that in this case $S_1 \approx x_- S = M^2/x_+$, where $x_\pm = \frac{1}{2}(\sqrt{x^2 + \frac{4M^2}{S}} \pm x)$ and thus

$$E_0 = \frac{M^2}{2x_+} \frac{R_A}{\sqrt{3}} \quad . \tag{3}$$

At lower energies AGK-rules are modified. This modification has been studied in our recent paper[14)]. It was shown that at $E << E_0$, where the diagram of Fig. 1 is close to zero, its different cuttings have some definite values, which differ from those of AGK. For example for double rescatterings the diffractive cutting (Fig. 2) is zero (instead of 1 for $E >> E_0$), the absorption (cutting of one Pomeron - Fig. 3a) 6a)) is reduced (- 2 instead of - 4) and the inelastic interaction with two nucleons - Fig. 3b), 6b) is not modified (+ 2). So the total contribution to the elastic hA-amplitude is zero due to cancellation of last two terms (instead of - 1 for $E >> E_0$). It is easy to see that as a result the rescattering of soft partons of the initial configuration does not lead to the shadowing in the region $E << E_0$. Thus for the Drell-Yan process there should be no deviations from the A^1-behaviour for $E < E_0$ (they are proportional to $e^{\frac{1}{3} R_A^2 t_{min}}$). This result also imply that soft partons of the "intrinsic charm" component[9)] cannot produce shadowing effects for energies $E < E_0$. On the other hand for the $Q\bar{Q}$-states, which have strong interaction with nucleons of the target the diagrams of Fig. 6a) and 6b) do not cancel in inclusive cross section, because of the energy-momentum conservation effects (the x-distributions of the $Q\bar{Q}$-state are different for diagrams of Figs. 6a) and 6b)) and the fact that a projection of the $Q\bar{Q}$ on a given hadronic state (ψ, ψ', χ, Υ, ...) are in general different for diagrams 6a) and 6b). These absorption-like effects are present even for energies $E < E_0$. The energy-momentum conservation effect is especially important as $x \to 1$. This in our opinion explains a

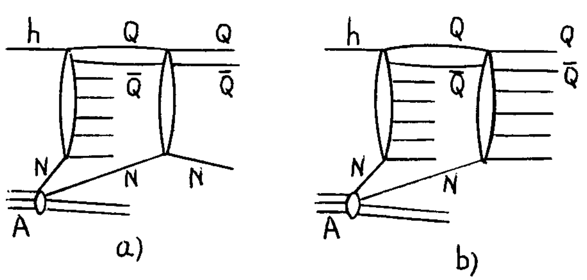

Fig. 6

qualitative difference in A-dependence between the Drell-Yan process and J/ψ or ϒ-production and the decrease of $\alpha_\psi(x)$ as $x \to 1$.

Now we summarize our results and give qualitative predictions for future experiments.

Table 1

Values of E_0 (in GeV) for J/ψ, Drell-Yan (M = 5 GeV) and ϒ for different values of x

	x = 0	x = 0.2	x = 1
J/ψ	10^3	280	70
DY (M = 5 GeV)	$2.5 \cdot 10^3$	700	170
ϒ	10^4	$2.5 \cdot 10^3$	650

There should be an increase of nuclear effects (decrease of $\alpha(x)$) for energies $E > E_0$. Values of E_0 for some particular cases are given in the Table I ($A \sim 100$). It follows from this table that :

a) for J/ψ there should be some decrease of $\alpha(x)$ in the region $x = (0.2 \div 0.4)$ in the energy region $200 \div 800$ GeV. While for $x \approx 0$ it should start at higher energies. At $x \gg 0.5$ $\alpha(x)$ has a very weak energy dependence already for $E \gg 200$ GeV. This agrees with the recent data on J/ψ-production at 800 GeV[7].

b) Deviations from A^1 ($\alpha < 1$) for the Drell-Yan process with $M \approx 5$ GeV should appear for $x_F \gg 0.5$ at energies $E \gg 400$ GeV. The first indication for this effect has been observed at 800 GeV[7]. Let us note that for $\frac{M^2}{x_+ s} > \frac{1}{m_N R_A}$ the shadowing is absent for any energy (this condition corresponds to $x_B > \frac{1}{m R_A}$) for quarks (antiquarks of nuclei).

c) Increase of nuclear effects for $b\bar{b}$-states (like ϒ) occurs in the energy range $E \gg 10^3 \div 10^4$ GeV and can be studied at future accelerators (UNK, RHIC, LHC).

Our results for production of heavy quarks imply that in general A-dependent effects cannot be totally attributed to the A-dependence of structure functions of gluons or quarks in nuclei and correspond to a violation of the factorization theorem.

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