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HADRONIZATION OF HIGHLY VIRTUAL QUARKS IN NUCLEI

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1. Formation zone of hadron production

Nuclear matter considerably affects the process of hadronization of a high-energy quark created somehow inside a nucleus. It is widely known that the creation of a hadron needs for formation time (see for instance review [1]) which sometimes exceeds a nuclear size. Nuclear attenuation at this early stage of the hadron formation is usually weak. It was suggested by Niedermayer and one of the authors [2,3] that the formation length of leading hadrons decreases when the hadron momentum increases:

$$l_f = \frac{k}{\kappa}(1-z). \qquad (1)$$

Here k is the initial quark momentum, z is its relative part carried by the produced hadron. Parameter κ is a retarding force applied to the quark during hadronization, $\kappa=-dk(t)/dt$, where k(t) is the time-dependent quark momentum. In the orthodoxal version of the string model [4,5] this parameter is fixed at a static value determined by the Regge trajectory slope: $\kappa=(2\pi\alpha'_R)^{-1}\approx 1\mathrm{GeV/Fm}$. However the effective value of the retarding force can considerably exceed the static one due to the gluon bremsstrahlung [6] Though expression (1) was obtained within the string model, it has a more general origin. In fact it trivially follows from the energy-conservation law: the higher is a portion z of the initial momentum k taken by the hadron, the shorter must be the period of the formation during which the leading quark spends its energy to multiparticle production. Note that behaviour (1) of the formation length towards z=1 is confirmed by Monte-Carlo simulation of a string decay [7].

The disappearance of the formation length near the kinematical boundary naturally explains increase on nuclear shadowing of leading hadron production at $x_F \Rightarrow 1$ in soft hadron-nuclear reactions [8], in symmetric hadron-pair production off nuclei at high transverse momenta [2,9], and in inclusive hadron production in deep inelastic scattering in fragmentation region of virtual photon at low energies of virtual photon [10].

In present paper we argue however, that the notion of formation length rather slightly affects the nuclear shadowing in hard processes. In section 2 we consider a space-time pattern of hadronization of high-virtual quark. The results are applied then to the problem of nuclear shadowing of the quark fragmentation function in section 3. Specific examples of deep inelastic scattering and high-p_T hadron production on nuclei are discussed in sections 4,5.

2. Space-time pattern of quark hadronization

The analogy between time orderings in models of hadron production and electromagnetic bremsstrahlung has been noticed long ago [11]. Just the latter possesses a formation length of radiation [12]. Niedermayer [6] demonstrated that electromagnetic radiation by a charge after it was accelerated, produces a constant retarding force acting on the charge during the radiation. On analogy one can expect the same effect of gluon radiation in QCD, which can also simulate the tension of colour string. This fact may be a reason of higher value of string tension extracted from analyses of data on hadron production on nuclei [2,8,9,13] in comparison with the static one.

Let us shortly remind some conclusions of paper [6]. If an electric charge being at rest is instantaneously accelerated up to the rapidity η, then a soft part of its Coulomb field is radiated. The distribution of the radiated energy over rapidity y and transverse momentum k_T has a form,

$$\frac{dE}{d^2k_T dy\cosh y} = \frac{1}{16\pi^3 k_T}(\cosh\eta - 1)\left|\int d^2x_T\ \rho(x_T)\exp(ik_Tx_T)\right|^2 . \qquad (2)$$

Here $\rho(x_T)$ is the distribution function of the charge in the transverse plane.

It follows from (2) that the density of radiated energy is uniformly distributed up to the rapidity η. If the charge is distributed within an area of radius ρ, only soft photon with $k_T<1/\rho$ are emitted. The time needed for the emission of photon depends on its rapidity and transverse momentum:

$$t = \frac{\cosh y}{k_T} . \qquad (3)$$

This is a natural result: the longer is the wave-length of the field the later it is radiated. Expression (3) includes also the time dilation factor.

During the photon emission the charge is retarded with a constant force,

$$\kappa \equiv -dk(t)/dt = \frac{2\alpha}{\pi}\langle k_T^2\rangle , \qquad (4)$$

where the mean value of $\langle k_T^2\rangle$ can be found using distribution (2). It is a result of restoration of a new Coulomb (in the quark rest frame) field of the charge. The time ordering is the same as in (3): the smaller is the rapidity of the photon or the lower is its transverse momentum k_T, the later is this part of the field restored. In another words, acceleration of the charge, the rapidity and the transverse size of its electromagnetic field increase until they will reach a stationary form.

Some of these conclusions can be spread to QCD. It is generally assumed that static field of a colour charge does not propagate to infinity due to specific properties of QCD vacuum. The typical examples are the bag model or the chromoelectric tube model. In these models the colour field is assumed to be confined in a volume of a size $1/\Lambda$, where Λ depending on assumptions changes in range 0.2-0.7 GeV. This fact imposes a low limit upon the gluon transverse momenta of the order of Λ. If a quark is created in a hard reaction with a high virtuality Q^2 and energy ν, it shakes off its field at impact parameters larger than $1/\sqrt{Q^2}$. According to (3) the time of gluon emission of a transverse momentum k_T and a part z of the longitudinal quark momentum, is $t=z\nu/k_T^2$. The transverse momentum averaging weighted with (1) results in,

$$t = z\,\frac{\nu}{\Lambda\sqrt{Q^2}}\,. \tag{5}$$

The total time which takes the bremsstrahlung is ν/Λ^2.

Simultaneously with radiation the quark restores its colour field. In a time interval t after its creation, the quark restores all the field components within a disk of a radius,

$$\rho^2(t) = \frac{1}{Q^2} + \frac{t}{\nu}\,. \tag{6}$$

One can suggest that the quark diminishes its virtuality $Q^2(t) \approx 1/\rho^2(t)$ in accordance with (6).

Note that in QCD apart from QED the gluons emitted by the quark can then cascade. However this fact does not influence on the value of the retarding force acting upon the colour charge. It is given by expression (4), where α should be changed with $4\alpha_s/3$, including the colour factor. If the quark virtuality is Q^2 the colour is distributed within a disk of radius $\rho \approx 1/\sqrt{Q^2}$. Then the value of $\langle k_T^2 \rangle$ can be found using (2): $\langle k^2 \rangle = Q^2/3$. This leads to the retarding force,

$$\kappa = \frac{8}{9\pi}\,\alpha_s(Q^2)Q^2\,. \tag{7}$$

This Q^2-dependence of κ principally differs from that in the chromoelectric flux-tube model. Minimization of the tube energy leads to a decreasing Q^2-dependence of string tension, $\kappa \propto [\alpha_s(Q^2)]^{1/2}$. Thus the simplified version of colour-tube model fails at high Q^2. It can be improved partially accounting for the hard gluon emission [14].

The increase of the energy loss (6) by the quark of high Q^2 leads to a considerable contraction of the formation length (1) in comparison with soft processes. Nevertheless it does not mean a stronger nuclear shadowing: below we argue that a hadron consisted of highly virtual quarks has a tiny absorption cross section at early stage of its production.

3. Attenuation of leading hadrons in nuclei

On the contrary to the spread opinion that the colour transparency manifests itself only in exclusive reactions, we argue that leading hadrons originated from hadronization of highly virtual quarks are created in the point-like configuration. As a consequence they do not attenuate in nuclear matter until quarks will decrease their virtuality to a value of the order of Λ^2.

The production of leading hadrons looks like the following: the primary quark picks up a sea antiquark originated from the gluon bremsstrahlung, and then this system does not lose energy, i.e. it does not radiate gluons. The crucial point is that the transverse separation of the quarks should be small, as it is suppressed with high quark virtuality. Indeed the system will not radiate only in the case if all the gluons emitted by one quark are absorbed by another. However if the leading quark during the time t_f of the hadron formation has restored its colour field up to impact parameter $\rho(t_f)$, then it continues emit gluons at impact parameters $r > \rho(t_f)$. In order to be able to absorb these gluons the satellite quark should have an impact parameter close to $\rho(t_f)$. If $\rho(t_f)$ is much smaller than the mean hadron radius, $1/\Lambda$, the hadron has a tiny absorption cross section, until it will restore its average interior field, i.e. get a typical hadron size. Thus the time evolution of the transverse radius of the produced hadron follows the time dependence (6) of the quark radius. This gives a possibility to estimate the nuclear shadowing of the hadron production. The attenuation factor can be represented in the form,

$$S = \exp\Big[- \int dl\,\rho_A(r)\,\sigma[\rho(t)]\Big]\,. \tag{8}$$

Here integration is carried out along the hadron trajectory $l(t)$; $\rho_A(r)$ is the nuclear density function. During propagation through the nucleus the hadron changes its transverse size $\rho(t)$ in accordance with (6). Note that $\rho(t)$

increases like $\sqrt{t}$. The same time-dependence of a mean radius of $q\bar{q}$-system produced in a point-like interaction was used in [15] and derived from the Schroedinger equation in [16]. Absorption cross section $\sigma(\rho)$ at small ρ is proportional to the transverse separation of the $q\bar{q}$-pair. The simplest parameterization is,

$$\sigma(\rho) = \frac{\rho^2}{\langle\rho_h^2\rangle}\,\sigma_{in}^{hN} . \qquad (9)$$

At high energy the produced hadron has no time to increase its size, so it does not attenuate in nuclear matter. The corresponding energy range can be estimated demanding that the absorption cross section remains small even after passing the nucleus:

$$\sigma[\rho(t)]\big|_{t=R_A} \ll \frac{1}{\rho_A R_A} . \qquad (10)$$

Neglecting the term $1/Q^2$ in (6) and using (9) and (10) we find,

$$\nu \gg \frac{\rho_A R_A^2 \sigma_{in}^{hN}}{\langle\rho_h^2\rangle} . \qquad (11)$$

Substituting $\rho_A=0.15$ Fm^{-3}, $R_A=5$ Fm, $\sigma_{in}^{hN}/\langle\rho_h^2\rangle=5$, we get the condition $\nu\gg5$ GeV. At this energies the nuclear shadowing should disappear, what is a direct consequence of the colour transparency.

Note that condition (11) guaranties a lack of nuclear shadowing in any case, otherway the formation length of the hadron should be taken into account. At large z the formation length can be found from (1). Moreover this expression can be considered as an upper limit on l_f at any z. However, while the quark radiates gluons and loses the energy, it can interact with nuclear matter by means of gluon exchanges. Both in QED [3,6] and in the string model [3,17] such reinteraction results in stopping of the previous process of radiation, and then the scenario starts from the very beginning: the recoloured quark having a virtuality and an energy which it has got to this moment, begins radiate gluons. This does not affect the total formation length of the hadron of fixed z, but makes some shift of effective variable in the quark fragmentation function [17]. This does not suppress the cross section only if $l_f \gg R_A$, otherway the rescatterings during formation time cause an additional attenuation. Relevant formulae can be found in ref. [17].

4. Deep-inelastic scattering on nuclei

Most clear conditions seem to exist in deep inelastic scattering. In this case the upper limit on formation length is

$$l_f \le \frac{9\pi}{16 x m_N \alpha_s}(1-z), \qquad (12)$$

where x is the Bjorken variable. We see that l_f can be quite long. For instance, if the $x=0.1$, $\alpha_s=0.2$, z is small, then $l_f \le 17$ Fm. This value exceeds a size of any nucleus, and is sufficient to make a nucleus transparent. To emphasize the effects of colour transparency one needs for some specific predictions. First he should go to a kinematical region, where the formation length is small,i.e. both x and z are large. In this case the following predictions can be made.

- Strong z-dependence (12) of formation length would cause a dramatic increase of nuclear shadowing towards z=1, as was indeed observed in soft inclusive hadronic reactions [8]. However the effects of colour transparency at high Q^2 maintain the full transparency of a nucleus independent on z.
- Decreasing of ν towards the preasymptotic energy-region (11) at fixed Q^2 and z should cause an increase of nuclear shadowing. This effect was indeed observed by the EMC collaboration [18-21]. These data were described quantitatively in [10] taking into account specific behaviour (1) of formation length. However the used string tension $\kappa=0.8$ GeV/Fm was much smaller than value (7) predicted for high Q^2. As the result the formation length was considerably overestimated, and this fact allowed to fit the data in spite of neglecting the colour transparency.

- There are a few possibilities to distinguish between the present pattern of quark hadronization and the string model. The first one is the above mentioned z-dependence of nuclear shadowing at high energies. On the contrary to the expectation of the string model we insist on independence on z, if the energy ν satisfies condition (11). Experimental data [21] indeed demonstrate the independence on z up to z=0.8.

Next is Q^2-independence of the nuclear shadowing at fixed ν and z expected in the orthodoxal string model. On the contrary, we predict a strong dependence on Q^2 at that values of ν and z where l_f is comparable with the nuclear radius. However one should take care of the so called EMC-effect, the distinction of the nuclear structure function from the free-nucleon one.

5. Hadron production with high transverse momenta

This process is usually considered as a result of scattering of one of the projectile partons with high transverse momentum, q_T, and subsequent hadronization. All the above consideration is relevant if the quark virtuality, q_T^2, is high. However in the case of nuclear target, there is a possibility to get a high p_T by means of a few semihard rescatterings. To avoid that one should study a symmetric hadron-pair production. On the contrary to predictions of naive parton model experimental measurements performed at 70 GeV [22] and 800 GeV [23] have claimed to observe a strong nuclear shadowing at high transverse momenta. This effect was interpreted in [2,9] as the result of energy losses of projectile partons after a soft interaction on the face surface of the nucleus, and the decrease of the formation length (1) at large z. Now we realize that the latter reason becomes irrelevant if both the quark energy and p_T^2 are high enough to make the nucleus transparent due to the colour screening effects. The energy 70 GeV is not sufficient, because a projectile valence quark carries only about 20% of incident proton momentum, and this amount is shared then in equal parts between scattered and recoil quarks. In this case the effects of formation length are essential. At the same time the energy 800 GeV seems to be high enough to satisfy condition (11). Nevertheless one should recalculate the cross sections including the colour transparency effect and Q^2-dependence (7) of the effective retarding force.

6. Conclusions

Starting from the analogy between QCD and QED we developed a space-time pattern of hadronization of a highly virtual quark. A steep increase of energy losses as function of Q^2 leads to a considerable contraction of the hadron formation length, and as a consequence to an increase of nuclear shadowing. On the other hand we argued that a colourless $q\bar{q}$ system, incorporating the high-virtual quark has a small transverse size of the order of $1/Q^2$ at the moment of its creation. This fact and nuclear colour transparency diminish the nuclear shadowing. A few predictions able to distinguish between this approach and the naive string model are proposed for deep inelastic scattering and high-p_T hadron production on nuclei.

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Адронизация высоко-виртуальных кварков в ядрах

Показано, что тормозное излучение глюонов высоко-виртуальным кварком вызывает сильную зависимость торможения от Q^2, в противоположность предсказаниям ортодоксальной модели цветных струн. В результате длина формирования адронов значительно сокращается. Лидирующие адроны, рожденные при адронизации высоко-виртуального кварка при высокой энергии, не поглощаются ядром благодаря цветовой прозрачности. Даны предсказания для процессов глубоко-неупругого рассеяния лептонов и образования адронов с большими поперечными импульсами на ядрах.

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Hadronization of Highly Virtual Quarks
in Nuclei

We argue that bremsstrahlung by highly virtual quark causes a strong Q^2-dependence of retarding force on the contrary to orthodoxal colour-string model. As the result the length of hadron formation is considerably contracted. Leading hadrons originated from hadronization of a high-energy and highly virtual quark do not attenuate in nuclear matter due to effect of colour transparency. Predictions for deep inelastic scattering and particle production with high transverse momenta on nuclei are made.

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

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