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ARE HIGH-ENERGY QUARKS ABSORBED IN NUCLEAR MATTER?

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Literally speaking a high-energy colour quark cannot be absorbed with a sizeable probability in a nuclear matter, because the main contribution to the inelastic cross section is connected with small momentum transfer. Nevertheless interaction of the quark with nuclear medium can influence the probability of production of the final state we are interesting in. In a figurative sense the decreasing of that probability can be interpreted as an absorption of quark.

The problem is closely connected with a concept of formation zone in particle production. Unlike the old parton model with short range rapidity correlations, in the QCD motivated approach a hadron can interact at any moment, but it appears only some time after the beginning of the quark hadronization. Let a quark of high momentum **k** be produced inside a nucleus (for example in a lepton deep inelastic scattering). Then it propagates accompanied by a satellite diquark or antiquark, compensating its colour. A string stretched between them is successively broken with quark pairs tunneling from vacuum. This is just the mechanism of quark hadronization [1]. In the lab. frame light fragments of the string are chipped off the leading heavy string in accordance with the chronology typical for the multiperipheral models: the higher is a particle momentum, the later it is created. The leading particle, carrying a considerable part x_F of the initial quark momentum, is produced last. Nevertheless, its formation zone decreases with the particle momentum and tends to zero towards $x_F=1$. This is a trivial consequence of the momentum conservation low: the leading quark is continually slowed down with a constant force

$$dp/dt=-æ \ , \qquad (1)$$

where æ is a string tension [1]. The quark energy is spent on particle creation till the formation of the leading hadron. The longer is the time of action of braking force the lower can be maximum momentum of the leading hadron. For example, production of a binary final state corresponding to $x_F=1$, needs no formation time at all. The formation zone for the leading particle is connected with its momentum by a simple relation

$$l_f=(1-x_F)k/æ. \qquad (2)$$

This expression had been obtained first in ref.[2] and then it was widely used and corroborated by analyses [3-5] of experimental data. It is frequently called a constituent formation length [4]. Note that relation (2) is not a prerogative of a string model, but obviously bears a general character: any incoherent system will radiate and loss its energy until it turns into stationary state. Note that so called yo-yo formation length [4] is in fact a distance needed for formation of the wave function of the produced hadron. It is of course much longer than formation zone (2) needed for production of colourless quark system, attenuating then in a nuclear matter with a hadronic cross section.

The central point of this consideration is a question: what would happen after the quark interacted with a nuclear matter before the leading hadron was produced? It is natural to assume that the string, which has a length in the lab. frame of the order or shorter than a target nucleon, interacts at high energy like an ordinary hadron, i.e. forms after the interaction two triplet strings (this corresponds to the cylindric Pomeron in the dual topological model). Indeed calculation of Born diagram in perturbative QCD [6] shows that interaction doesn't depend on a longitudinal dimension of a hadron but is determined only by its transverse size only. Thus, after the interaction of the string with a bound nucleon, its slow end would throw over to the rest diquark (or quark if an antiquark is in the lead) and the scenario would perform from the very beginning, but with the lower input momentum of quark:

$$k'=k-æ(z'-z), \qquad (3)$$

where z and z' are the points where the quark was initially produced and then interacted. So as soon as the string had interacted, two new strings would appear, as if a quark of momentum k' was produced just in this point.

It's interesting that expression (2) for the formation zone is valid in any way, both in the vacuum and in the nuclear medium, even if the string interacted at the intermediate stage many times. Indeed the leading quark is slowed down according to (1) independently on the string life: is it breaking or not, does it rescatters in the nucleus or not. In the point z' where the quark has interacted the last time, its momentum k' was given by (3). So the production of the hadron of momentum $x_F k$, corresponds to a new Feynman variable:

$$x'_F = x_F\,\frac{k}{k-\text{æ}(z'-z)}\,. \tag{4}$$

New formation length l'_f (beginning from the point z') is given by expression (2) with substitutions $k \Rightarrow k'$ and $x_F \Rightarrow x'_F$. Now it is a trivial exercise to check that $z'-z+l'_f=l_f$, i.e. the total formation length didn't change.

Though the nuclear medium doesn't influence the formation length, it can change a probability of production of a particle of momentum $x_F k$. In the vacuum a fragmentation function $D(x_F)$ is known to die out towards $x_F=1$ as a power of $1-x_F$:

$$D(x_F) \propto (1-x_F)^{\alpha}, \tag{5}$$

where for example $\alpha \approx 2$ for $q \Rightarrow \pi$, $\alpha \approx 3$ for $u \Rightarrow p$, $\alpha \approx 4$ for $d \Rightarrow p$ [7]. The interaction with a nuclear matter as was mentioned, results in the effective shift of the Feynman variable, $x_F \Rightarrow x'_F > x_F$, and consequently suppresses the fragmentation function: $D(x'_F) < D(x_F)$. Under the influence of the nuclear matter the effective fragmentation function take the form

$$D_{eff}(x_F z, \mathbf{b}) = D(x_F)\exp\{-\sigma_s \int_z^{z+l_f} dz'\rho(\mathbf{b},z')\} +$$

$$\sigma_s \int_z^{z+l_f} dz'\rho(\mathbf{b},z')D(x'_F)\exp\{-\sigma_s \int_{z'}^{z+l_f} dz_1\rho(\mathbf{b},z_1)\}\,. \tag{6}$$

Here **b** is an impact parameter, $\rho(\mathbf{b},z)$ is a nuclear density; σ_s is a cross sections of inelastic interaction of the string with a nucleon. The first term in (6) takes into account the possibility of no interaction of the string on the interval $z<z'<z+l_f$. The second term corresponds to the possibility of being of the last string interaction at the point z', any number of interactions before it and no subsequent interaction on the interval $z'-z+l_f$. The value of x_F' in (6) is given by expression (4). Note that formula (6) takes into account also the possibility of preliminary production of a hadron (more exactly speaking a light colourless state) with higher value of x_F'', which then interacts and produces the final hadron of wishful momentum $x_F k$.

Note that in the special case of constant function $D(x)$ the integration in (6) is carried out explicitly resulting in $D_{eff}(x_F)=D(x_F)$, i.e. the nuclear medium in this case doesn't influence the quark fragmentation. If $\alpha>0$ then $D_{eff}(x_F)/D(x_F)<1$ and this fact can be naively interpreted as a manifestation of the quark attenuation. From this point of view the effective quark absorption cross section σ^q_{eff} can be defined as

$$D_{eff}(x_F)/D(x_F) = \exp[-\sigma^q_{eff}\int_z^{z+l_f} dz_1\rho(\mathbf{b},z_1)]. \qquad (7)$$

Sometimes σ^q_{eff} is introduced as an unknown parameter [4,5]. However we have just found out that it can be determined within the same theoretical approach. Moreover, the value of σ^q_{eff} turns out to be strongly dependent on the process under consideration. To illustrate this let us consider for example $\rho(z'')=\rho_o\theta(R-z+z')$, where R is a distance of the order of nuclear radius. Let's fix $\rho_o=0.15$ Fm^{-3}, $R=5$ Fm. The string interaction cross section σ_s, as was noted above, is of the order of the hadronic one, because it is determined by the string transversal dimension, so we put $\sigma_s=20$ mb. The results of calculations of σ^q_{eff} with formulae (6) and (7) are shown in fig.1. They depend only on the formation length l_f and the exponent α. The value of σ^q_{eff} is of about 10–15 mb for $l_f<R$ (it is amusing that this value is close to the constituent quark cross section) and dies out steeply for large l_f. The latter could be foreseen as the finite energy corrections induced by nucleus, should become negligible at high energies. Just for this reason the quark attenuation was

neglected in Refs.[2,3], but now we see that this approximation can be too crude in some cases. It worth noting that quark attenuation indeed changes remarkably depending on the process in question. For instance, the agreement with the data on reaction $\pi A \Rightarrow p(\bar{p})X$ at 30 GeV was achieved in Ref.[4] at σ^q_{eff}=7.7(9.9)mb, but it was found preferable to put the same parameter to zero in the case of pion production in deep inelastic muon scattering [5]. This agrees with our conclusion because in the former case the formation zone is shorter and the fragmentation function is steeper than in the latter case.

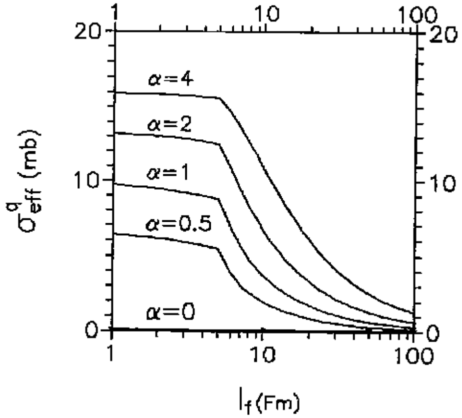

Fig.1 *Effective cross section of quark absorption in nuclear matter depending on the formation length l_f and the exponent α defined in (5).*

The numerical example in fig. 1 illustrates the unfeasibility of the phenomenological approach treating the effective cross section of quark absorption as an universal parameter. Value of this parameter strongly correlates with incident energy, momentum of produced hadron and atomic number of target nucleus. The only correct way to take into consideration quark interaction is the employment of expression (6). This nuclear affected fragmentation function should be used in calculations of momentum spectra of hadrons produced in deep inelastic lepton scattering, high-p_T hadron scattering, in soft interactions with nuclei etc.

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