ATTENUATION OF HIGH-ENERGY PARTICLES LEPTOPRODUCED IN NUCLEAR MATTER

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It is shown that the difference in nuclear attenuation of different hadrons produced in deep inelastic scattering of leptons from nuclear targets is sensitive to the composition of the intermediate state in nuclear matter. Measurements of attenuation should not only allow to determine if the high-energy component of this state is a quark or a hadron, but also give information on quark absorption cross-section and on time scale of hadronization.

It has been known for some time (see e.g. Ref. [1] for an early review) that lepto-production of hadrons from nuclei can be used for investigation of strong interactions at very short times. In the present paper we continue the study [2] of the deep-inelastic process

$$1+A \to 1'+h+\text{ANYTHING}, \tag{1}$$

where h is a hadron. In particular we concentrate on analysis of nuclear attenuation of the leptoproduced hadrons [2,5–8]. Our main point is to indicate that comparison of nuclear attenuation of *different* hadrons (as measured from A-dependence of longitudinal momentum distributions [2, 3]) may serve as a sensitive test of the composition of the intermediate state which travels through nuclear matter after the deep inelastic scattering of the incident lepton occured in the nucleus.

As emphasized in Ref. [2] (see also [1]) the analysis of the process (1) is largely simplified in the kinematic region where a) the energy transferred between initial and final lepton is large and b) the leptoproduced hadron carries a large fraction ($z_h > \frac{1}{2}$) of this energy. Such kinematic conditions reduce significantly two potential complications: (*i*) the effects of intranuclear cascade are minimized and (*ii*) a complicated process of gluon generation

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in the nucleus [4] plays only a minor role. Therefore in the present paper we restrict our considerations to this kinematic region.

Assuming that the intermediate state is a single quark, we investigated in Ref. [2] the possibility of measurement of its absorption cross-section in nuclear matter. In the present paper the argument of Ref. [2] is applied to more complicated intermediate states, so that we can discuss some other hypotheses and find experimental methods of determining which one is realized in nature. Following other authors (see e.g. Refs [1, 7, 8]), we shall consider an intermediate state which consists of a high-energy quark which can fragment into observed hadrons, both quark and hadrons possibly interacting with the target. The fragmentation into a given hadron h takes place (on the average) after a characteristic "formation time" τ.

The formation time τ is a crucial parameter in this picture. Its magnitude (as compared to the nuclear diameter) determines the nature of the intermediate state in nuclear matter. For small τ the quark fragments entirely into hadrons inside the nucleus, for large τ fragmentation takes place outside of the nucleus and only quark is present in nuclear matter. The most popular theoretical belief (see e.g. Refs [1,7–9]) is that τ is proportional to the energy of the hadron h (Lorentz factor)

$$\tau = \tau^{(0)}E/m, \tag{2}$$

where $\tau^{(0)}$ is a characteristic formation time of hadron h in its rest frame [10]. If Eq. (2) is valid, the character of the intermediate state in the nucleus depends on the energy transfer between leptons. In our investigation we shall treat τ as a free parameter, possibly to be determined from experiment.

Let us now briefly indicate how one can estimate nuclear attenuation of the lepto-produced hadrons. The argument we present follows closely that of Ref. [2]. It is an application of the standard multiple scattering techniques [11, 12] to our particular problem (see Refs [7, 8] for a somewhat different treatment).

Consider deeply inelastic interaction of a lepton at a point $(\vec{b}, z)$ inside the nucleus (z axis points in the direction of the momentum transferred between leptons). The probability that a particle p created in this collision is absorbed by a nucleon located at a point $(\vec{b}, z')$ is $\sigma P(z'-z)\varrho(\vec{b}, z')$ for $z' > z$ and it vanishes for $z' < z$. Here $\varrho(\vec{b}, z')$ is the nuclear density normalized to unity $\int \varrho(\vec{r})d^3r = 1$, σ is the cross-section for absorption of the particle p by nucleon and $P(z'-z)$ is the probability that the particle p shall indeed be present at the point $(\vec{b}, z')$. If particle p is a hadron h, $P_h(z'-z) = 1-\exp\{-(z'-z)/\tau\}$ where τ is the formation time. If particle p is the quark, $P_q(z'-z) = \exp\{-(z'-z)/\tau\}$. Since we consider only hadrons which carry more than 1/2 of the total available momentum, it is not possible that the quark fragments into two such hadrons. Consequently, the probability that neither quark nor its fragment h are absorbed by a nucleon located anywhere in the nucleus is

$$S(\vec{b}, z) = 1-\sigma_q \int_z^\infty P_q(z'-z)\varrho(\vec{b}, z')dz' - \sigma_h \int_z^\infty P_h(z'-z)\varrho(\vec{b}, z')dz', \tag{3}$$

where σ_q and σ_h are cross-sections for absorption of the quark and of the hadron h.

If the correlations between the nucleons in the target are neglected, the probability that no absorption takes place at any of the $A-1$ nucleons in the nucleus is thus given by $S(\vec{b}, z)^{A-1}$, so that we finally obtain the following formula for the nuclear attenuation of the flux of hadrons

$$R_A = \frac{dn_A}{dn_1} = \int d^2b \int_{-\infty}^{\infty} \varrho(\vec{b}, z)\,[S(\vec{b}, z)]^{A-1}, \tag{4}$$

where $S(\vec{b}, z)$ is given by Eq. (3), dn_A is the flux of hadrons leptoproduced from nucleus A and dn_1 is the effective flux of hadrons from nucleon target given by

$$dn_1 = \frac{d\sigma_P}{d\sigma_N + d\sigma_P}\,\frac{Z}{A}\,dn_P + \frac{d\sigma_N}{d\sigma_N + d\sigma_P}\,\frac{A-Z}{A}\,dn_N, \tag{5}$$

where $d\sigma_P$ and $d\sigma_N$ are leptoproduction cross-sections on protons and neutrons, Z is the atomic number of the considered nucleus and dn_P and dn_N are hadron fluxes from proton and neutron targets, normalized to the same number of deep inelastic triggers as dn_A.

At this point it may be worthwhile to explain in more detail the precise physical meaning of the absorption cross-sections σ_q and σ_h introduced in Eq. (3). Suppose that an experiment measures the distribution of hadrons carrying the fraction $z_h > z_0$ of the total momentum transferred between leptons. In such a case we shall consider, say, quark to be absorbed if it looses so much of the longitudinal momentum that its fragmentation into hadrons does not contribute significantly to the region $z_h > z_0$. Thus the absorption cross-section σ_q is different (smaller) than the total inelastic cross-section of the quark on nucleon. This difference depends, in principle, on z_0 (and vanishes for $z_0 \to 1$). However, since the fragmentation spectra of hadrons are steeply falling [13] functions of z_h, even momentum loss of few per cent is enough to classify the quark as absorbed. The same remark applies to the absorption of baryons. Consequently, the difference between $\sigma_q(\sigma_h)$ and the total inelastic-nondiffractive cross-section of quarks (hadrons) is expected to be small. This effect was investigated in Refs [2] and [5] where indeed only small corrections were fund for $z_h > 0.5$. These corrections show up in z_h dependence of the observed attenuation and can be further minimized by restricting measurements to higher values of z_h.

To study the consequences of Eq. (4), let us begin by considering a limiting situation when τ is very large. As suggested by Eq. (2), it is likely that this happens for deep inelastic collisions with very large energy transfer between leptons [14]. In this case we meet the situation considered in Refs [2, 5, 6]: hadrons are created outside of the nucleus, so that only the quark can interact in nuclear matter. As shown in Refs [2] and [6], Eq. (4) simplifies then to

$$R_A = \frac{1}{A\sigma_q}\int d^2b[1-[1-\sigma_q D(\vec{b})]^A] = \frac{\sigma_{qA}}{A\sigma_q}, \tag{6}$$

where $D(\vec{b}) = \int_{-\infty}^{\infty} \varrho(\vec{b}, z)dz$.

In Ref. [2] we studied the dependence of R_A (given by Eq. (6)) on σ_q and we have argued that σ_q can be estimated from measurements of R_A. Here we would like to point out another feature of Eq. (6) which is of phenomenological significance: for a given nucleus, R_A depends only on σ_q and is thus *the same for all leptoproduced hadrons*. It follows

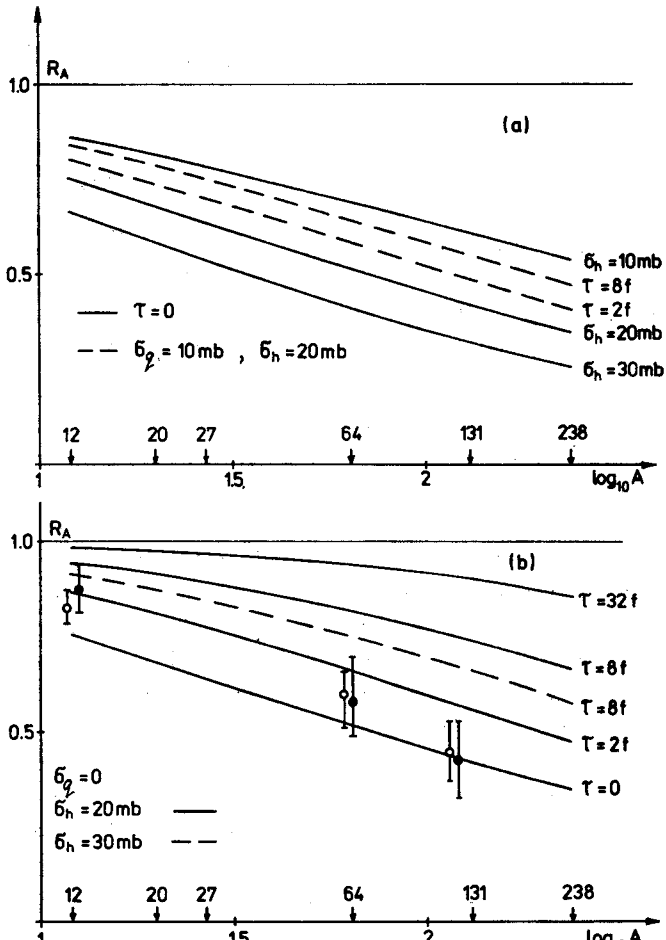

Fig. 1. Nuclear attenuation plotted versus nuclear number. (a) Attenuation of ϕ-mesons, pions and nucleons for $\tau = 0$ (full lines) and for pions with $\tau \neq 0$ and $\sigma_q = 10$ mb (dashed lines). (b) Attenuation of pions for $\sigma_q = 0$ and different values of τ. Data points taken from Ref. [15] show attenuation of negative particles at $z_h = 0.5$ (open circles) and $z_h = 0.8$ (closed circles). Dashed line shows attenuation of protons for $\tau = 8$f. Nuclear density was taken in the form $\varrho = \varrho_0 \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$ with $R = 1.14\, A^{1/3}$ and $a = 0.545$ [16]

that measurement of nuclear attenuation of different hadrons may serve as a test of the nature of the intermediate state in the nuclear matter. Indeed, were hadrons present in the nucleus, the attenuation would depend on hadronic absorption cross-sections on nucleons. Since these are different for different hadrons, one would expect also differences in attenuation. This is well illustrated if we consider another limiting case $\tau = 0$, corresponding to very fast fragmentation of the quark into hadrons, so that only hadrons interact in the nuclear matter. The attenuation is now again given by Eq. (6) but with σ_h substituted in place of σ_q. It is thus obviously *different for different hadrons*. In Fig. 1a, R_A from Eq. (6) is plotted versus A for $\sigma_h = 10, 20$ and 30 mb, corresponding roughly to the absorption cross-section of ϕ-mesons, pions and nucleons. A clear difference is seen in attenuation of different particles. We conclude that the proposed test has indeed a chance to work.

Let us now turn to the general case described by Eq. (4), when τ is comparable to typical nuclear dimensions.

Consider first the possibility $\sigma_q = 0$, the standard assumption of most models (see e.g. Refs [1, 7, 8]). Under this condition the only unknown parameter is the hadronic formation time τ. One can thus attempts to determine τ from the data. In Fig. 1b, R_A from Eq. (4) is plotted for different values of τ. One sees that the attenuation is quite sensitive to τ. The data of Ref. [15] are also plotted in the Fig. 1b. They seem to indicate $\tau \simeq 1$ f, in agreement with the estimate from Ref. [8] obtained by a somewhat different analysis. No dependence of attenuation on hadron momentum is seen, but the errors are too large to draw any conclusions about the validity of Eq. (2). Finally, let us note that also in this case there are differences between attenuation of different hadrons, as illustrated by two curves for $\tau = 8$f.

Some authors suggested that the leptoproduced quark has a non-vanishing cross--section $\sigma_q \simeq 20$ mb [5] or $\sigma_q \simeq 10$ mb [6]. We have investigated this possibility. For small $\tau(\tau < 5\text{f})$ we found again clear differences in attenuation of different hadrons. This is illustrated in Fig. 1a where, assuming $\sigma_q = 10$ mb, the attenuation of mesons ($\sigma_h = 20$ mb) is plotted for $\tau = 2$f. For the same τ and σ_q, the attenuation of baryons practically coincides with the curve labelled $\sigma_h = 20$ mb and is thus substantially different from that of mesons. For large τ, attenuation is dominated by the quark cross-section σ_q and thus the sensitivity to hadronic parameters is reduced, as can also be seen from Fig. 1a.

To summarize, we have shown that the nuclear attenuation of the leptoproduced hadrons depends sensitively on the nature of the intermediate state interacting in nuclear matter. Measurements of attenuation for *different hadrons* as function of their laboratory energy should allow to point out the components which are responsible for attenuation. Thus it appears possible to determine if the high-energy component of the intermediate state is a quark or a hadron. Such measurements will also give information on quark absorption cross-section σ_q and on the time scale of hadronization.

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