Space-time evolution of hadronization

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Abstract  Beside its intrinsic interest for the insights it can give into color confinement, knowledge of the space-time evolution of hadronization is very important for correctly interpreting jet-quenching data in heavy ion collisions and extracting the properties of the produced medium. On the experimental side, the cleanest environment to study the space-time evolution of hadronization is semi-inclusive Deeply Inelastic Scattering on nuclear targets. On the theoretical side, 2 frameworks are presently competing to explain the observed attenuation of hadron production: quark energy loss (with hadron formation outside the nucleus) and nuclear absorption (with hadronization starting inside the nucleus). I discuss recent observables and ideas which will help to distinguish these 2 mechanisms and to measure the time scales of the hadronization process.

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1 Introduction

One of the most striking experimental discoveries in the heavy-ion program at the Relativistic Heavy Ion Collider (RHIC) has been the the suppression of large transverse momentum hadron production in nucleus-nucleus (A+A) collisions compared to proton-proton (p+p) collisions [1]. The observable of interest is the ratio of the hadron transverse energy loss due to medium-induced gluon bremsstrahlung, allowing so-called “jet tomography” studies of the QGP (c.cl.), normalized to binary scaled p+p collisions by the inverse thickness function $T_{AB}$ and finally divided by the p+p spectrum:

$$R_{AB} = \frac{1}{T_{AB}(c.c.l.)} \frac{dN_{A+B\rightarrow h+X}}{dp_{T}^{2}dy} \left(\frac{1}{dp_{T}^{2}dy}\right).$$

In the absence of nuclear effects, one would expect $R_{AB} = 1$. By comparing the measured $R_{AuAu} \approx 0.2$ in Au+Au collisions to the mild deformation of $p_T$ spectra observed in deuteron-gold (d+Au) collisions, one concludes that the large suppression of $R_{AuAu}$ is due to the hot and dense medium produced in Au+Au collision, also called “hot nuclear matter”, see Fig. 1. In this case, the medium which induces the attenuation is the target nucleus itself, also called “cold nuclear matter”, see Fig. 1. This measurement is one of the keys to the claimed discovery of the Quark-Gluon Plasma (QGP) at RHIC [2].

The suppression of hadron production in A+A collisions, has been successfully described in terms of parton energy loss due to medium-induced gluon bremsstrahlung, allowing so-called “jet tomography” studies of the QGP [3,4]. However, this success has been recently questioned. Gluon radiation off heavy quarks is expected on theoretical grounds to be suppressed at small angles compared to light quarks, implying a smaller suppression for D and B mesons than for $\pi$ mesons [5]. However, the measured suppression of single non-photonic electrons at RHIC [6], which are the decay product of B and D mesons, is of similar magnitude for pions contrary to theoretical expectations [7]. The common assumption of neglecting elastic parton energy loss in $R_{AA}$ computations has been recently reexamined [8], but the effect seems insufficient to explain the data, at least within conventional schemes for treating the running coupling constant [9]. As further assumption that needs to be tested and will be addressed in this paper, is that the quark which fragments into the observed hadron traverses the whole medium and hadronizes well outside it. If untrue, in-medium interactions and screening of the hadronizing system would need to be accounted for.

Hadron suppression has also been observed in fixed target Deeply Inelastic lepton-nucleus Scattering (nDIS). In this case, the medium which induces the attenuation is the target nucleus itself, also called “cold nuclear matter”, see Fig. 1. Experimental data are usually presented in terms of the “multiplicity ratio” [10, 11, 12, 13, 14]

$$R_{M}(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_{A}^{h}(z_h)}{dz_h} \left/ \frac{1}{N_D^{DIS}} \frac{dN_{D}^{h}(z_h)}{dz_h}\right.,$$

i.e., the single hadron multiplicity on a target of mass number $A$ normalized to the multiplicity on a deuteron target as a function of the hadron’s fractional energy $z_h = E_{h}/\nu$, where $\nu$ is the virtual photon energy. The ratios in the numerator and denominator cancel to a large extent initial state effects like the modifications of parton distribution functions due to shadowing and EMC effects, exposing the nuclear modifications of the fragmentation process: if we assume factorization formulae to be valid,
we have at leading order \( R_M \approx D_h^A/D_h^D \), i.e., the ratio of the fragmentation functions (FF) in the nucleus A and in deuterium. If no nuclear effects modify the fragmentation process we would expect \( R_M \approx 1 \). In fact, what is experimentally observed is hadron suppression in the \( z_h = 0.2 - 1 \) and \( \nu = 2 - 20 \) GeV range at HERMES [11,12,13], and in the \( \nu = 20 - 200 \) GeV at the EMC experiment [10]. The flavor dependence of the multiplicity ratio has also been measured [12,13], showing suppression for pions, kaons and antiprotons. Protons are enhanced at \( z_h \lesssim 0.4 \) and suppressed above; this is a “proton anomaly” analogous to the “baryon anomaly” observed in p+A and A+A collisions [11,15]. Both the quenching and the enhancement increase with A. Data binned in \( \nu \), and in the photon virtuality \( Q^2 \) are also available from HERMES. Very high-statistics measurements will be available in the near future from the CLAS experiment at Jefferson Labs [14], with some preliminary results already presented [16].

The cleanest environment to address nuclear modifications of hadron production is nuclear DIS: it allows to experimentally control many kinematic variables; the nuclear medium (i.e., the nucleus itself) is well known; the multiplicity in the final state is low, allowing for precise measurements. Moreover, the nucleons act as femtometer-scale detectors of the hadronizing quark, allowing to experimentally study its space-time evolution into the observed hadron. Hadron suppression at HERMES and CLAS is of direct relevance to RHIC physics. In both cases the hadronizing quark has to traverse a length of (hot or cold) nuclear matter of the size of a nuclear radius, see Fig. 1. Moreover, in the HERMES experiment \( \nu \approx 2 - 25 \) GeV and \( z_h \approx 0.2 - 1 \), so that hadrons are observed over an energy range \( E_h \approx z_h \nu = 2 - 20 \) GeV. (measurements at CLAS with \( E_{\text{beam}} = 5, 11 \) GeV will likewise explore the \( E_h = 2 - 10 \) GeV range). For midrapidity hadron production in A+A collisions at RHIC \( E_h \approx p_T \approx 2 - 20 \) GeV, roughly equal to the hadron energy range at HERMES.

Information about parton propagation in cold nuclear matter is needed as an input for the interpretation of data in A+A collisions. In this case one wants to use hadron suppression as a tool to extract the properties of the hot QGP created in the collision. To this purpose we need to develop well calibrated computational tools to relate the magnitude of hadron suppression to properties of the QGP like its density and temperature. Assuming long lived partons, hadron suppression at RHIC would be attributed to parton energy loss, leading to a medium temperature of \( T \approx 400 \) MeV [4], in excess of the critical temperature \( T_c \approx 170 \) MeV for the QGP phase transition. If, on the contrary, hadronization started on the nuclear radius scale or before, in-medium interactions should also be accounted for, leading to a different, presumably lower \( T \). A precise knowledge of parton propagation and hadronization mechanisms obtained from nDIS data is essential for testing and calibrating our theoretical tools, and to determine the properties of the QGP produced at RHIC.

### 2 Formation time estimates

The key quantity we need to investigate is the hadronization time scale. Since hadronization is a non perturbative process, one has to resort to phenomenological models to describe it [17,15,19,20,21,22,23]. However, a few features are expected on general grounds. Due to color confinement, the struck quark must neutralize its color at some stage, say by picking up an antiquark from the vacuum or the surrounding medium. I call this color neutralization; moreover, the prehadron quickly develops its mass and energy. This is a relevant time scale since gluon bremsstrahlung off the struck quark stops after color neutralization, moreover, the prehadron quickly develops a cross section of the order of the hadronic one, leading to its nuclear absorption. Subsequently, the prehadron wave function collapses on the observed hadron, and the corresponding time is called “hadron formation time” \( t_h \). A final caveat: it is difficult to rigorously define the concept of formation time in field theory, so that in the following discussions it is used as a working tool.

#### 2.1 Long formation time: energy loss models

The average hadron formation time \( \langle t_h \rangle \) can be considered as the time for the struck partons to build up its color field and to develop the hadronic wave function [21]. In the hadron rest frame this time is related to the hadron radius, and in the laboratory frame it is boosted to:

\[
\langle t_h \rangle \propto R_h \frac{E_h}{m_h} = R_h \frac{z \nu}{m_h} \tag{3}
\]

For a 10 GeV pion at HERMES, we have \( \langle t_h \rangle \approx 50 \) fm \( \gg R_A \). Note also that the scale for hadron formation is set by \( \kappa_h = m_h/R_h \approx 0.2 \) GeV/fm. This estimate is used in energy loss models [17,15] to assume that hadronization starts outside the medium with a decreased parton energy due to multiple parton scatterings and induced gluon bremsstrahlung. These models are fairly successful in describing \( R_M \) at HERMES, see Fig. 2.

More in detail, the Ref. [17] computes parton rescatterings and gluon radiation in pQCD including Feynman
hadron formation is identified with the q̄q distribution of a fractional energy loss shifting. The FF so obtained can be modeled to a good accuracy by parton-parton correlations in the nucleus. The modified FF depends on 1 parameter, the strength of diagrams up to twist-4. Fragmentation of both the struck quark and the radiated gluon is included. The modification of the FF depends on 1 parameter, the strength of parton-parton correlations in the nucleus.

Left: Multiplicity ratio for $h^\pm$ at HERMES [12] compared to the energy loss model of Ref. [17] and the absorption models of Ref. [21-24]. Center: pure absorption model [21-24] (solid) and energy loss model [21-24] (dashed). Right: Color dipole model from Ref. [22] (dashed: absorption only, solid: absorption and induced energy loss). Data are from Ref. [11,12,13].

The “quenching weight” $P(\Delta z)$ is the probability distribution of a fractional energy loss $\Delta z = \Delta E_q/\nu$ [23,24], and $L_q$ the quark’s in-medium path length. The medium is characterized by the transport coefficient $\hat{q}$, which measures the average momentum transfer per unit path-length from the medium to the parton. When also taking into account a realistic medium geometry and finite medium size corrections to the quenching weight, the model [24] can well describe HERMES data, see Fig. 2.

2.2 Short formation time: nuclear absorption models

A successful non perturbative model of hadronization is the Lund string model [28]. The confined color field stretching from the struck quark to the rest of the nucleus is modeled as a string of tension $\kappa_{str} \approx 1 \text{ GeV}/\text{fm}$. Prehadron formation is identified with the q̄q pair production which breaks the string in smaller pieces [19]. Hadrons are formed when a quark and an antiquark at the endpoint of a string fragment meet. Average formation times can be analytically computed [19,20,21]:

$$\langle t_\sigma \rangle = f(z_h)(1 - z_h)\frac{z_h \nu}{\kappa_{str}} \quad (5)$$

$$\langle t_h \rangle = \langle t_\sigma \rangle + \frac{z_h \nu}{\kappa_{str}} \quad (6)$$

The factor $z_h \nu$ can be understood as a Lorentz boost factor. The $(1 - z_h)$ factor is due to energy conservation: a high-$z_h$ hadron carries away an energy $z_h \nu$; the string remainder has a small energy $\epsilon = (1 - z_h)\nu$ and cannot stretch farther than $L = \epsilon/\kappa_{str}$. Thus the string breaking must occur on a time scale proportional to $1 - z_h$. The function $f(z_h)$ is only a small deformation of $\langle t_\sigma \rangle$. At HERMES $(t_\sigma) \approx 4 \text{ fm} < R_A$ and $(t_h) \approx 6 - 10 \text{ fm} \gtrsim R_A$. The hadron is typically formed at the periphery or outside the nucleus so that its interaction with the medium is negligible. However, the prehadron is formed well inside and can start interacting with the nucleus. The nuclear absorption model of Ref. [21] can successfully explain $R_M$ measurements at HERMES in terms of prehadron-nucleon inelastic scatterings with the above formation times estimate, see Fig. 2. The prehadron-nucleon inelastic cross-section is $\sigma_\nu = 0.35 \sigma_A(\nu)$ proportional to the experimental hadron-nucleon cross section $\sigma_A$. The proportionality factor is fitted to $\pi^+ \pi^-$ production data on a Kr target [12]. The prehadron survival probability $S_\nu$ is computed in terms of transport equations. Neglecting hadron absorption,

$$S_\nu = \int d^2 b dy \rho_A(b,y) \times \int dx \frac{e^{-\nu z_h}}{\langle t_\sigma \rangle} e^{-\sigma_A z_h} ds A_P(b,s) \quad ,$$

where $(b,y)$ is the $\gamma^*\pi$ interaction point, $\rho_A$ is the nuclear density, and one can recognize exponential probability distributions for prehadron and hadron formation.

In Ref. [22] the formation of a leading hadron $(z_h \gtrsim 0.5)$ is described in a pQCD inspired model. The struck
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3.1 Mass number dependence

In first approximation, one expects \( 1 - R_M^h \propto A^{2/3} \) in energy loss models because the average energy loss \( \Delta E_q \propto \langle L^z_q \rangle \propto A^{2/3} \), due to the Landau-Pomeranchuk-Migdal interference in QCD. On the other hand, in absorption models the survival probability is proportional to the amount of traversed matter, so that \( 1 - R_M^h \propto \langle L_A \rangle \propto A^{1/3} \). Therefore a simple analysis of the \( A \)-dependence of \( R_M^h \) should clearly signal which model is correct.

This argument fails for absorption models. If the prehadron were produced always at the \( \gamma^* \)-quark interaction point (i.e., \( t_s = 0 \)) then \( R_M = c A^{1/3} \) at all orders in \( A^{1/3} \). However, if we allow for a nonzero \( t_s \), its dimension must be neutralized by the nuclear radius \( R_A \), introducing extra powers of \( A^{1/3} \). Quite generally, if the probability distribution for the prehadron formation length is finite at zero formation length, then \( R_M^h \propto A^{2/3} + O(A) \), the same power found in energy loss models.

Then, we can study the breaking of the \( A^{2/3} \) law. To this purpose, it was proposed in [21] to select a set of targets \( \{A_1, A_2, \ldots, A_n\} \), fix the \( z \) bin, and perform a fit of the form \( 1 - R_M^h(z) = c(z) A^\alpha(z) \) with \( c \) and \( \alpha \) free parameters. Results are presented in terms of 2σ confidence contours in the \((c, \alpha)\) plane. As shown in Fig. 3 left, energy loss [27] and absorption models [21][27] are indistinguishable. The same holds true for all \( z \) bins. Experimental data are described by an \( A^\alpha \) power law with \( \alpha = 0.61 \pm 0.14 \), compatible with \( \alpha = 2/3 \) but excluding \( \alpha = 1/3 \). Increasing the number of targets and the span in atomic number does not help in separating the 2 models, either, but clearly shows a non negligible breaking of the \( A^{2/3} \) law at \( A \gtrsim 80 \) [21][27], see Fig. 3 right.

3.2 Formation time scaling

In Ref. [31] I conjecture that \( R_M \) should not depend on \( z_h \) and \( \nu \) separately but should depend on a combination of them:

\[
R_M = R_M[\tau(z_h, \nu)] ,
\]

where the scaling variable \( \tau \) is defined as

\[
\tau = C z_h^{\lambda} (1 - z_h)^\nu .
\]

The scaling exponent \( \lambda \) is introduced as a way of approximating and summarizing the scaling behavior of experimental data and theoretical models. It can be obtained by a best fit analysis of data or theoretical computations. The proportionality constant \( C \) cannot be determined by the fit. A possible scaling of \( R_M \) with \( Q^2 \) is not considered in this analysis because of its model dependence, and because of the mild dependence of HERMES data on \( Q^2 \). As discussed below, the proposed functional form of \( \tau \), Eq. (9), is flexible enough to encompass both absorption models and energy loss models. The 2 classes of models are distinguished by the value of the scaling exponent: a positive \( \lambda \geq 0 \) is characteristic of absorption models, while
a negative $\lambda \lesssim 0$ is characteristic of energy loss models. Thus, the exponent $\lambda$ extracted from experimental data can identify in the experimental data the leading mechanism for hadron suppression in nDIS.

The scaling of $R_M$ is quite natural in the context of hadron absorption models [19,20,21,22,23]. Indeed, prehadron absorption depends on the in-medium prehadron path length, which depends solely on the prehadron formation time $t_s$ as long as $t_s \lesssim R_A$. As argued in Section 3.3, $t_s \propto f(z_h)(1-z_h)z_h\nu$ which is well described by the proposed scaling variable $\tau$ with $\lambda > 0$. E.g., in the Lund model $\lambda \approx 0.7$.

In energy loss models [17,18,24] the scaling is less obvious. For the purpose of discussing the scaling properties of $R_M$, we can consider the model of Ref. [18,27] and neglect finite medium size corrections and finite quark energy corrections. If we further neglect energy loss fluctuations, we can approximate $R_M \approx D_A(z_h)/D(z_h)$ and obtain

$$R_M \approx \frac{1}{1-(\langle \epsilon \rangle/\nu)} \left[ \frac{z_h}{1-(\langle \epsilon \rangle/\nu)} \right] D(z_h)^{-1},$$

where the average energy loss $\langle \epsilon \rangle = \int_0^{(1-z_h)\nu} d\epsilon P(\epsilon) / \int_0^{(1-z_h)\nu} d\epsilon P(\epsilon) = f[(1-z_h)\nu]$ not carried away by the observed hadron. Next, we can approximate the FF using the parametrization of Ref. [22] at $Q^2 = 2$ GeV$^2$ and obtain

$$R_M \approx \left[ \frac{1}{1-(\langle \epsilon \rangle/\nu)} \right]^{\alpha+\beta+1} \left( 1 - f[(1-z_h)\nu] \right)^{1-[(1-z_h)\nu]} \left( 1 - \frac{[(1-z_h)\nu]}{(1-z_h)\nu} \right)^{\beta}.$$  

This shows an approximate scaling with $(1-z_h)\nu$, which implies scaling of $R_M$ with respect to $\tau$ with $\lambda \approx 0$. A similar argument holds for the model of [17]. When performing the scaling analysis of the full models one finds in general $\lambda \lesssim 0$.

The HERMES experiment measures $R_M$ binned in $z_h$ and integrated over $\nu$ and $Q^2$ ("$z_h$ distributions") or binned in $\nu$ and integrated over $z_h$ and $Q^2$ ("$\nu$ distributions"). Eq. (3) is fitted to the combined $z_h$- and $\nu$-distributions, and the scaling exponent $\lambda$ is determined by $\chi^2$ minimization. An example of this procedure is illustrated in Fig. ???. Details can be found in Ref. [31].

The scaling exponents $\lambda_{\text{best}}$ extracted from HERMES data at $E_{\text{lab}} = 27$ GeV [11,12,13] for different hadron flavors produced on N, Ne and Kr targets are shown in Fig. ???. In all cases $\chi^2/\text{d.o.f.} \lesssim 1.6$, which proves that $R_M$ scales with $\tau$. The central result of this analysis is that pion data exhibit a clear $\lambda_{\text{best}} \approx 0.4 \gtrsim 0$. As discussed, this shows the dominance of the prehadron absorption mechanism as opposed to the energy loss mechanism, or in other words is a signal of in-medium prehadron formation, with formation times $t_s \lesssim R_A$.

### 3.3 $p_T$ broadening

The scaling analysis just described gives only indirect evidence for a short formation time, and cannot measure its absolute scale. An observable which is more directly related to the prehadron formation time is the hadron’s transverse momentum broadening in DIS on a nuclear target compared to a proton or deuteron target [22]. Indeed, when a hadron is observed in the final state, neither the quark nor the prehadron could have had inelastic scatterings. The prehadron-nucleon elastic cross section is very small compared to the quark cross section, so that the hadron’s $p_T$-broadening originates dominantly during parton propagation. As shown in [33,34], the quark’s momentum broadening $\Delta p_T^q$ is proportional to the quark path-length in the nucleus. If the prehadron formation time has
the form (9) as argued in the last section, we obtain:

$$\Delta p_T^2 \propto \langle t_s \rangle \propto z_h^2(1-z_h)^2$$

unless the distance of the quark production point from the surface of the nucleus is smaller than $\langle t_s \rangle$. Then we should expect a decrease of $\Delta p_T^2$ with increasing $z_h$.

This would be a clear and model-independent signal of in-medium prehadron attenuation: indeed, if the quark were traveling through the whole nucleus before prehadron formation, $\Delta p_T^2$ would only depend on the nucleus size and not on $z_h$. A related observable is the $z_h$-dependence of the Cronin effect, which is likewise expected to decrease with increasing $z_h$.

The CLAS collaboration can perform multi-differential $p_T$-broadening measurements in all kinematic variables thanks to a very high beam luminosity. A few preliminary data from CLAS are already available (10). The HERMES collaboration is also studying the $p_T$-broadening at a larger beam energy but with a lower statistics. The scaling analysis proposed in the previous section will be useful to cross-check the results of these measurements.

4 Conclusions and perspectives

Use of hard processes to probe medium processes in A+A collisions requires a detailed understanding of the hadronization process, which can be studied in lepton-nucleus scatterings. The scaling analysis (31) of pion attenuation at HERMES demonstrates for the first time a scaling of the hadron attenuation ratio $R_M$ which is compatible with a short prehadron formation time of the order or smaller than the nuclear radius. Thus, it favors prehadron absorption as dominant mechanism for hadron suppression instead of gluon radiation off a struck quark. This conclusion will be soon checked by hadron $p_T$-broadening data.

Much more can be studied in lepton-nucleus scatterings. (i) In the meson sector, the suppression of $\eta$ mesons at RHIC, which is of similar magnitude than for $\pi$, seems to favor long-lived partons (39). Measuring $\eta$ and heavier meson attenuation at HERMES and CLAS will check the correctness of such interpretation. (ii) Understanding the proton anomaly in nDIS will shed light on baryon transport in nuclear matter and on the baryon anomaly observed in p+p and A+A collisions. Measurements of $\Lambda$ and other baryons at HERMES and CLAS will be needed in this respect. (iii) Neither HERMES nor CLAS are able to study the hadronization of heavy quarks, because of limited luminosity and limited Bjorken’s $x$ coverage, respectively. The proposed Electron-Ion Collider is well suited for such studies, thanks to its low-$x$ coverage and high luminosity. Study of $D$ and $B$ meson suppression will settle the single electron puzzle at RHIC and will put interpretation of LHC data on a firmer ground. Study of “normal” $J/\psi$ suppression will help in distinguishing competing mechanism and in building a precise baseline for measurements of the “anomalous” suppression in A+A collisions.

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