Jet Tomography of Hot and Cold Nuclear Matter

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(Received 21 February 2002; published 1 October 2002)

Modification of parton fragmentation functions by multiple scattering and gluon bremsstrahlung in nuclear media is shown to describe very well the recent HERMES data in deeply inelastic scattering, giving the first evidence of the $A^{2/3}$ dependence of the modification. The energy loss is found to be $\langle dE/dL\rangle \approx 0.5$ GeV/fm for a 10-GeV quark in an Au nucleus. Including the effect of expansion, analysis of the π^0 spectra in central Au + Au collisions at $\sqrt{s} = 130$ GeV yields an averaged energy loss equivalent to $\langle dE/dL\rangle \approx 7.3$ GeV/fm in a static medium. Predictions for central Au + Au collisions at $\sqrt{s} = 200$ GeV are also given.

DOI: 10.1103/PhysRevLett.89.162301 PACS numbers: 12.38.Mh, 13.60.–r, 24.85.+p, 25.75.–q

Energetic partons produced via hard processes provide an excellent tool that enables tomographic studies of both hot dense and cold nuclear matter. By measuring the attenuation [1–5] of these partons as they propagate through the medium, one would be able to study the properties such as the geometry [6,7] and the gluon density of the medium. The attenuation will suppress the final leading hadron distribution, giving rise to modified parton fragmentation functions [8]. Such a modified fragmentation function inside a nucleus has been derived recently [9] in a perturbative QCD (pQCD) approach with a systematic expansion of higher-twist corrections to the fragmentation processes. In this Letter, we compare the predicted nuclear modification to the recent HERMES experimental data [10] and extract the effective parton energy loss. We further extend the study to the case of a hot QCD medium including the dynamics of expansion. We then analyze within this framework the π^0 spectra as measured by the PHENIX experiment [11] in central Au + Au collisions at $\sqrt{s} = 130$ GeV, which have shown significant suppression at large transverse momentum. The extracted effective parton energy loss is compared with that in a cold nucleus, and discussions are given about the implications of the PHENIX data on the gluon density in the early stage of central Au + Au collisions at the RHIC energy. We also provide predictions for π^0 spectra in central Au + Au collisions at $\sqrt{s} = 200$ GeV.

In deeply inelastic scatterings (DIS), quark fragmentation functions are factorizable in leading twist from the parton distribution functions and photon-quark ($\gamma^* q$) scattering cross section. In a nucleus target, the quark struck by the virtual photon suffers multiple scattering and induced bremsstrahlung before hadronization. Extending the generalized factorization [12] to the semi-inclusive process, $e(L_1) + A(p) \to e(L_2) + h(\ell_h) + X$, one can define a modified fragmentation function as [9]

$$E_{L_2}\frac{d\sigma^h_{\rm DIS}}{d^3L_2dz_h} = \frac{\alpha^2_{\rm EM}}{2\pi s}\frac{1}{Q^4}L_{\mu\nu} \times \sum_q \int dx f^A_q(x, Q^2)H^{(0)}_{\mu\nu}(x, p, q)\widetilde{D}_{q\to h}(z_h, Q^2), \quad (1)$$

where $f^A_q(x, Q^2)$ is the quark distribution function in the nucleus, $s = (p + L_1)^2$ and $p = [p^+, 0, \vec{0}_\perp]$ is the momentum per nucleon inside the nucleus. The momentum of the virtual photon γ^* is $q = [-Q^2/2q^-, q^-, \vec{0}_\perp]$ and the momentum fraction carried by the hadron is $z_h = \ell_h^-/q^-$. The hard part of the $\gamma^* q$ scattering $H^{(0)}_{\mu\nu}$ is the same as in ep scattering [9] and $L_{\mu\nu} = \frac{1}{2}\,{\rm Tr}(\not{L}_1\gamma_\mu\not{L}_2\gamma_\nu)$.

Including the leading twist-4 contributions from double scattering processes, the modified effective quark fragmentation function can be obtained as [9]

$$\widetilde{D}_{q\to h}(z_h, Q^2) \equiv D_{q\to h}(z_h, Q^2) + \Delta D_{q\to h}(z_h, Q^2); \quad (2)$$

$$\Delta D_{q\to h}(z_h, Q^2) = \int_0^{Q^2}\frac{d\ell_T^2}{\ell_T^2}\frac{\alpha_s}{2\pi}\int_{z_h}^1\frac{dz}{z}[\Delta\gamma_{q\to qg}(z, x, x_L, \ell_T^2)D_{q\to h}(z_h/z) + \Delta\gamma_{q\to gq}(z, x, x_L, \ell_T^2)D_{g\to h}(z_h/z)], \quad (3)$$

$$\Delta\gamma_{q\to qg}(z, x, x_L, \ell_T^2) = \left[\frac{1+z^2}{(1-z)_+}T^A_{qg}(x, x_L) + \delta(1-z)\Delta T^A_{qg}(x, \ell_T^2)\right]\frac{C_A 2\pi\alpha_s}{(\ell_T^2 + \langle k_T^2\rangle)N_c f^A_q(x, \mu_I^2)}, \quad (4)$$

where $C_A = 3$, $N_c = 3$, $\Delta\gamma_{q\to gq}(z, x, x_L, \ell_T^2) = \Delta\gamma_{q\to qg}(1-z, x, x_L, \ell_T^2)$ are the modified splitting functions, $x_L = \ell_T^2/2p^+q^-z(1-z)$, and $D_{a\to h}(z_h, Q^2)$ are the normal twist-2 parton fragmentation functions in vacuum. The

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δ-function part in the modified splitting function is from the virtual corrections, with $\Delta T^A_{qg}(x, \ell_T^2)$ defined as

$$\Delta T^A_{qg}(x, \ell_T^2) \equiv \int_0^1 dz \frac{1}{1-z}[2T^A_{qg}(x, x_L)|_{z=1} - (1+z^2)T^A_{qg}(x, x_L)]. \quad (5)$$

Such virtual or absorptive corrections are important to ensure the infrared safety of the modified fragmentation function and the unitarity of the gluon radiation processes. The quark-gluon correlation function

$$T^A_{qg}(x, x_L) = \int \frac{dy^-}{2\pi} dy_1^- dy_2^- e^{i(x+x_L)p^+y^- + ix_Tp^+(y_1^- - y_2^-)}(1 - e^{-ix_Lp^+y_2^-})(1 - e^{-ix_Lp^+(y^- - y_1^-)})\tfrac{1}{2}\langle A|\bar{\psi}_q(0)\gamma^+F_\sigma^+(y_2^-) \times F^{+\sigma}(y_1^-)\psi_q(y^-)|A\rangle\theta(-y_2^-)\theta(y^- - y_1^-) \quad (6)$$

contains essentially four independent twist-4 parton matrix elements in a nucleus [$x_T = \langle k_T^2\rangle/2p^+q^-z(1-z)$]. The dipolelike form factor $(1 - e^{-ix_Lp^+y_2^-})(1 - e^{-ix_Lp^+(y^- - y_1^-)})$ arises from the interference between the final state radiation of the $\gamma^* q$ scattering and the gluon bremsstrahlung induced by the secondary quark-gluon scattering. By generalizing the factorization assumption [12] to these twist-4 parton matrices, we have

$$T^A_{qg}(x, x_L) \approx \widetilde{C}(Q^2)m_NR_Af_q^A(x)(1 - e^{-x_L^2/x_A^2}), \quad (7)$$

with a Gaussian nuclear distribution $\rho(r) \sim \exp(-r^2/2R_A^2)$, $R_A = 1.12A^{1/3}$ fm. Here $x_A = 1/m_NR_A$, and m_N is the nucleon mass. We should emphasize that the parameter $\widetilde{C}(Q^2)$ should, in principle, depend on the renormalization scale Q^2 among other kinetic variables as shown recently in a detailed analysis of the twist-4 nuclear matrix elements [13]. Therefore, it can take different values in different processes.

Since the two interference terms in the dipolelike form factor involve transferring momentum x_Lp^+ between different nucleons inside a nucleus, they should be suppressed for large nuclear size or large momentum fraction x_L. Notice that $\tau_f = 1/x_Lp^+$ is the gluon's formation time. Thus, $x_L/x_A = L_A/\tau_f$, with $L_A = R_Am_N/p^+$ being the nuclear size in the infinite momentum frame. The effective parton correlation and the induced gluon emission vanishes when the formation time is much larger than the nuclear size, $x_L/x_A \ll 1$, because of the Landau-Pomeranchuck-Migdal (LPM) interference effect. Therefore, the LPM interference restricts the radiated gluon to have a minimum transverse momentum $\ell_T^2 \sim Q^2/m_NR_A \sim Q^2/A^{1/3}$. The nuclear corrections to the fragmentation function due to double parton scattering will then be in the order of $\alpha_sA^{1/3}/\ell_T^2 \sim \alpha_sA^{2/3}/Q^2$, which depends quadratically on the nuclear size. For large values of A and Q^2, these corrections are leading; yet the requirement $\ell_T^2 \ll Q^2$ for the logarithmic approximation in deriving the modified fragmentation function is still valid.

With the assumption of the factorized form of the twist-4 nuclear parton matrices, there is only one free parameter $\widetilde{C}(Q^2)$ which represents quark-gluon correlation strength inside nuclei. Once it is fixed, one can predict the z, energy, and nuclear dependence of the medium modification of the fragmentation function. Shown in Figs. 1 and 2 are the calculated nuclear modification factor of the fragmentation functions for ^{14}N and ^{84}Kr targets as compared to the recent HERMES data [10]. There are strong correlations among values of Q^2, ν, and z in the HERMES data which are also taken in account in our calculation. The predicted shape of the z and ν dependence agrees well with the experimental data. A remarkable feature of the prediction is the quadratic $A^{2/3}$ nuclear size dependence, which is verified for the first time by an experiment. This quadratic dependence comes from the combination of the QCD radiation spectrum and the modification of the available phase space in ℓ_T or x_L due to the LPM interferences.

The observed attenuation of the leading hadrons could also be attributed phenomenologically to hadron absorption inside the nucleus. This is, however, achieved only via some *ad hoc* assumption of the hadron formation time [10]. Considering the hadronization process as regeneration of gluon field within a spatial region of a hadron size r_h, the hadron formation time for a light quark will be $t_f^h \approx \nu r_h^2$ [14]. Taking $r_h \approx 1$ fm, t_f^h is about 40 fm for $\nu = 8$ GeV, the lower limit of the HERMES experiment. This is much larger than the size of the heaviest nuclei available. We therefore assume that the nuclear

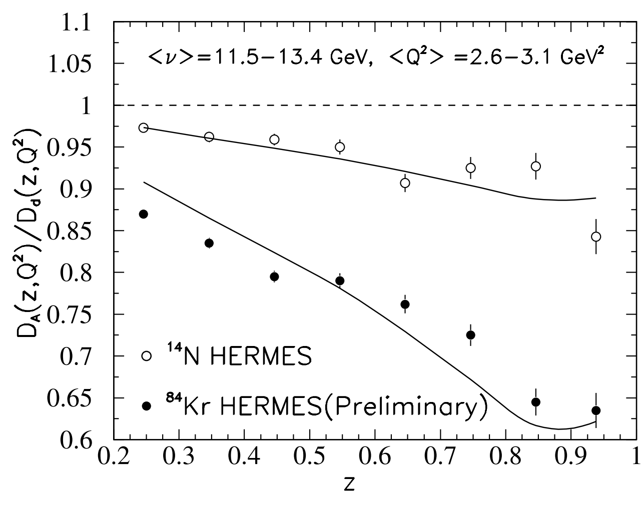

FIG. 1. Predicted nuclear modification of jet fragmentation function is compared to the HERMES data [10] on ratios of hadron distributions between A and D targets in DIS.

attenuation in this energy region is mainly caused by induced gluon radiation and multiple parton scattering.

By fitting the overall suppression for one nuclear target, we obtain the only parameter in our calculation, $\tilde{C}(Q^2) = 0.0060$ GeV^2 with $\alpha_s(Q^2) = 0.33$ at $Q^2 \approx 3$ GeV^2. This parameter is also related to nuclear broadening of the transverse momentum of the Drell-Yan dilepton in pA collisions [15], $\langle \Delta q_\perp^2 \rangle \approx \tilde{C}\pi\alpha_s/N_c x_A$. With an experimental value of $\langle \Delta q_\perp^2 \rangle = 0.016 A^{1/3}$ GeV^2 [16] and $\alpha_s(M_{l\bar{l}}^2) = 0.21$ ($\langle M_{l\bar{l}}^2 \rangle \approx 40$ GeV^2), one finds $\tilde{C}(M_{l\bar{l}}^2) = 0.013$ GeV^2, which is about a factor of 2 larger than the value obtained in our fit to the HERMES data. The value of $\tilde{C}$ determined from nuclear broadening in photoproduction of a dijet is even larger [12] at $Q^2 = 4p_T^2 \approx 64$ GeV^2. Such a strong scale dependence of $\tilde{C}(Q^2)$ is in line with one's expectation since it is related to gluon distribution $xg(x, Q^2)$ at small x in nuclei [13].

If one defines theoretically the quark energy loss as that carried by the radiated gluons, then the averaged total fractional energy loss is [cf. Eq. (3)],

$$\langle \Delta z_g \rangle = \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2} \int_0^1 dz \frac{\alpha_s}{2\pi} z \Delta\gamma_{q\to gq}(z, x_B, x_L, \ell_T^2) = \int_0^{Q^2} d\ell_T^2 \int_0^1 dz \frac{1 + (1-z)^2}{\ell_T^2(\ell_T^2 + \langle k_T^2 \rangle)} \frac{C_A \alpha_s^2 T_{qg}^A(x_B, x_L)}{N_c f_q^A(x_B)} \tag{8}$$

$$\approx \tilde{C}(Q^2)\alpha_s^2(Q^2) \frac{C_A}{N_c} \frac{x_B}{Q^2 x_A^2} 6 \ln\left(\frac{1}{2x_B}\right). \tag{9}$$

In the rest frame of the nucleus, $p^+ = m_N$, $q^- = \nu$, and $x_B \equiv Q^2/2p^+q^- = Q^2/2m_N\nu$. One can get the averaged total energy loss as $\Delta E = \nu\langle \Delta z_g \rangle \approx \tilde{C}(Q^2)\alpha_s^2(Q^2) m_N R_A^2 (C_A/N_c) 3 \ln(1/2x_B)$. With the determined value of $\tilde{C}$, $\langle x_B \rangle \approx 0.124$ in the HERMES experiment [10] and the average distance $\langle L_A \rangle = R_A\sqrt{2/\pi}$ for the assumed Gaussian nuclear distribution, one gets the quark energy loss $dE/dL \approx 0.5$ GeV/fm inside an Au nucleus.

To extend our study of modified fragmentation functions to jets in heavy-ion collisions, we assume $\langle k_T^2 \rangle \approx \mu^2$ (the Debye screening mass) and a gluon density profile $\rho(y) = (\tau_0/\tau)\theta(R_A - y)\rho_0$ for a one-dimensional expanding system. Since the initial jet production rate is independent of the final gluon density which can be related to the parton-gluon scattering cross section [2] $[\alpha_s x_T G(x_T) \sim \mu^2 \sigma_g]$, one has then

$$\frac{\alpha_s T_{qg}^A(x_B, x_L)}{f_q^A(x_B)} \sim \mu^2 \int dy \sigma_g \rho(y)[1 - \cos(y/\tau_f)], \tag{10}$$

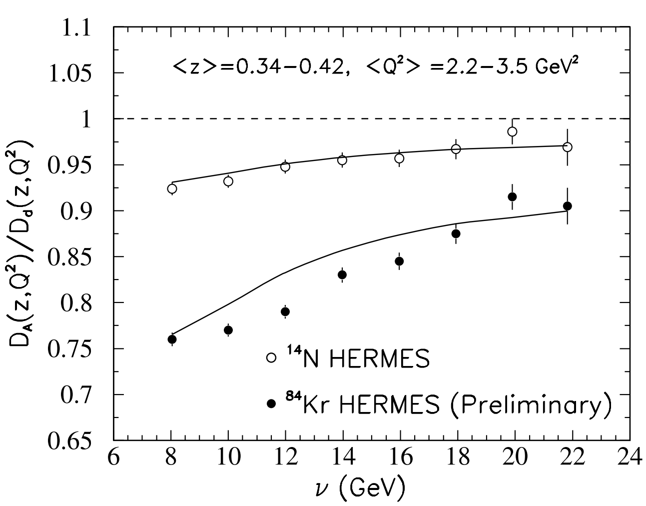

FIG. 2. Energy dependence of the nuclear modification compared with the HERMES data [10].

where $\tau_f = 2Ez(1-z)/\ell_T^2$ is the gluon formation time. One can recover the form of energy loss in a thin plasma obtained in the opacity expansion approach [2,7],

$$\langle \Delta z_g \rangle = \frac{C_A \alpha_s}{\pi} \int_0^1 dz \int_0^{Q^2/\mu^2} du \frac{1 + (1-z)^2}{u(1+u)} \times \int_{\tau_0}^{R_A} d\tau \sigma_g \rho(\tau) \left[1 - \cos\left(\frac{(\tau - \tau_0)\, u\, \mu^2}{2Ez(1-z)}\right)\right]. \tag{11}$$

Keeping only the dominant contribution and assuming $\sigma_g \approx C_a 2\pi\alpha_s^2/\mu^2$ ($C_a = 1$ for qg and $9/4$ for gg scattering), one obtains the averaged energy loss,

$$\left\langle \frac{dE}{dL} \right\rangle \approx \frac{\pi C_a C_A \alpha_s^3}{R_A} \int_{\tau_0}^{R_A} d\tau \rho(\tau)(\tau - \tau_0) \ln\frac{2E}{\tau\mu^2}. \tag{12}$$

Neglecting the logarithmic dependence on τ, the averaged energy loss in a one-dimensional expanding system can be expressed as

$$\left\langle \frac{dE}{dL} \right\rangle_{1D} \approx \frac{dE_0}{dL} \frac{2\tau_0}{R_A}, \tag{13}$$

where $dE_0/dL \propto \rho_0 R_A$ is the energy loss in a static medium with the same gluon density ρ_0 as in a 1D expanding system at time τ_0. Because of the expansion, the averaged energy loss $\langle dE/dL \rangle_{1D}$ is suppressed as compared to the static case and does not depend linearly on the system size. This could be one of the reasons why the effect of parton energy loss is found to be negligible in AA collisions at $\sqrt{s} = 17.3$ GeV [17].

An effective model of modified fragmentation functions was proposed in Ref. [8]:

$$\tilde{D}_{a\to h}(z) \approx \frac{1}{1 - \Delta z} D_{a\to h}\left(\frac{z}{1 - \Delta z}\right), \tag{14}$$

with Δz to account for the fractional parton energy loss. This effective model is found to reproduce the pQCD result from Eq. (3) very well, but only when Δz is set to be $\Delta z \approx 0.6\langle z_g \rangle$. Therefore the actual averaged parton

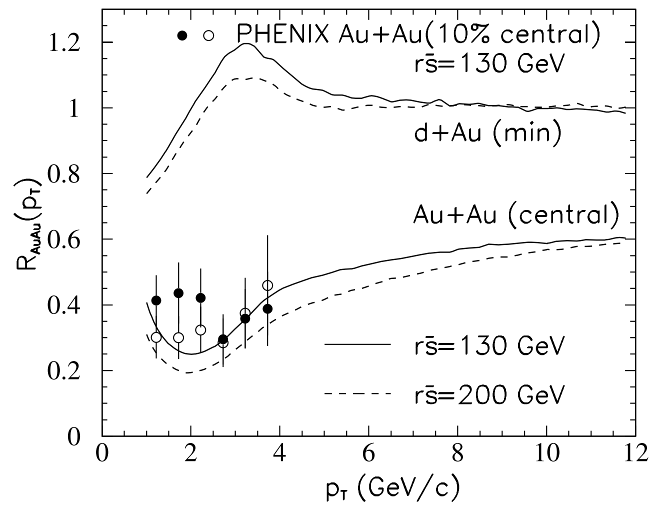

FIG. 3. Calculated nuclear modification factor of π^0 p_T spectra for d + Au and central Au + Au collisions at $\sqrt{s} = 130$ (solid line) and 200 GeV (dashed line) as compared to PHENIX data [11] (solid circles are measured spectra normalized by PHENIX parametrization of the pp spectra while open circles are normalized by our calculated pp spectra).

energy loss should be $\Delta E/E = 1.6\Delta z$ with Δz extracted from the effective model. The factor 1.6 is mainly caused by unitarity correction effect in the pQCD calculation. A similar effect is also found in the opacity expansion approach [18].

The PHENIX experiment has reported [11] a strong suppression of high p_T hadrons in central Au + Au collisions at $\sqrt{s} = 130$ GeV. To extract the parton energy loss, we compare the data with the calculated hadron p_T spectra in heavy-ion collisions using the above effective model for medium modified jet fragmentation functions [19]. Shown in Fig. 3 are the nuclear modification factor $R_{AA}(p_T)$ as the ratio of hadron spectra in AA (pA) and pp collisions normalized by the number of binary collisions [20]. Parton shadowing and nuclear broadening of the intrinsic k_T are also taken into account in the calculation which describes pA data for energies up to $\sqrt{s} = 40$ GeV [19]. The nuclear k_T-broadening gives the so-called Cronin enhancement at large p_T in pA collisions, where there is no parton energy loss induced by a hot medium. Fitting the PHENIX data yields $\langle dE/dL\rangle_{1D} \approx 0.34 \ln E/\ln 5$ GeV/fm, including the factor of 1.6 from the unitarity correction effect. We consider only π^0 data here, since at large p_T the charged hadrons are dominated by baryons, which could be influenced mainly by nonperturbative dynamics [7].

Taking into account the expansion, the averaged parton energy loss extracted from the PHENIX data would be equivalent to $(dE/dL)_0 = 0.34(R_A/2\tau_0)\ln E/\ln 5$ in a static system with the same gluon density as the initial value of the expanding system at τ_0. With $R_A \sim 6$ fm and $\tau_0 \sim 0.2$ fm, this would give $(dE/dL)_0 \approx 7.3$ GeV/fm for a 10-GeV parton, which is about 15 times that in a cold Au nucleus as extracted from the HERMES data. Since the parton energy loss is directly proportional to gluon density of the medium, we can predict the π^0 spectra at $\sqrt{s} = 200$ GeV as given by the dashed lines in Fig. 3, assuming that the initial parton density in central Au + Au collisions at $\sqrt{s} = 200$ GeV is about 10% higher than at 130 GeV.

In summary, the nuclear modification of parton fragmentation function predicted in a pQCD study describes well the HERMES experimental data. The extracted energy loss is $dE/dL \approx 0.5$ GeV/fm for a quark with $E = 10$ GeV in a Au nucleus. Analysis of the PHENIX data of π^0 spectra suppression in central Au + Au collisions yields an averaged parton energy loss in an expanding system that would be equivalent to $(dE/dL)_0 \approx 7.3$ GeV/fm in a static medium.

This work was supported by DOE under Contract No. DE-AC03-76SF00098 and by NSFC under Projects No. 19928511 and No. 10135030. We thank N. Bianchi and P. DiNezza for discussions about the HERMES data.

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