Gluon Shadowing and Jet Quenching in $A+A$ Collisions at $\sqrt{s}=200A$ GeV

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(Received 20 December 1991)

The sensitivity of moderate $p_T \lesssim 8$ GeV/c singles inclusive spectra in nuclear collisions to gluon shadowing and jet quenching is estimated using the HIJING Monte Carlo model. We show how the systematic study of the nuclear dependence of those spectra in $p+A$ can be used to determine the magnitude of gluon shadowing and how the enhanced suppression in $A+A$ would provide information on the energy loss mechanisms in dense partonic matter.

PACS numbers: 25.75.+r, 12.38.Mh, 13.87.Ce, 24.85.+p

It has been estimated [1,2] that a large fraction of transverse energy deposited in the central region of heavy-ion collisions at BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) energies may arise from multiple minijet production. Minijets are simply moderate $p_T \gtrsim 2$ GeV/c parton scattering processes predicted by perturbative QCD (PQCD). We have recently developed a new Monte Carlo event generator, HIJING [3], merging low-p_T multistring phenomenology [4,5] with high-p_T PQCD [6] to enable more detailed and systematic tests of multiparticle production models for $p+p$, $p+A$, and $A+A$ collisions. An extensive comparison [7] with data on $p+p(\bar{p})$ over a wide energy range, $\sqrt{s}=50$–1800 GeV, revealed that multiple minijet production provides a consistent explanation of the energy dependence of not only the central rapidity density, moderate-p_T inclusive spectra, two-particle correlation functions, and violation of Koba-Nielsen-Olesen (KNO) scaling, but also the flavor and multiplicity dependence of the average transverse momentum [8]. In addition we showed [3] that the available data on $p+A$ and $A+A$ at moderate energies $\sqrt{s} \le 20A$ GeV are consistent with the multiple collision framework based on the binary collision approximation and Glauber geometry used in HIJING.

In this Letter we emphasize two novel nuclear effects on multiparticle production in $A+A$ as predicted by HIJING for $\sqrt{s} \gtrsim 200A$ GeV due to (1) gluon shadowing [9] and (2) jet quenching [10]. From deep-inelastic scatterings [11], it is well known that the quark structure functions with small $x \lesssim 0.1$ fractional momenta are depleted in a nucleus relative to a free nucleon. This depletion, usually referred to as nuclear shadowing, is also expected for the gluon structure function although there is no clear experimental evidence for that yet. Gluon shadowing is of interest in high-energy nucleus-nucleus collisions because it could influence significantly the initial conditions in such reactions [12]. In addition, it is of fundamental interest in its own right as it pertains to the nuclear structure at the parton level not accessible via deep-inelastic reactions. Jet quenching, on the other hand, is of interest because it provides information on the final-state interaction processes that may lead to partial thermal and chemical equilibration in the produced dense partonic system [10,13]. Jet quenching results from the energy loss, dE/dl, of a high-p_T parton as it traverses the dense matter. PQCD estimates [14] indicate that induced gluon bremsstrahlung may dominate the energy loss mechanism and that $dE/dl \propto \alpha_s \mu_D^2 \ln^2(E/\mu_D) \sim 1$–$3$ GeV/fm depends sensitively on the infrared (Debye) screening scale μ_D of the medium. Jet quenching therefore provides information on that interesting scale, which may vary significantly in the vicinity of the quark-gluon plasma transition.

Because of the copious minijet production at collider energies, conventional jet analysis to determine jet quenching in nucleus-nucleus collisions may be very difficult [15,16]. Therefore, it is essential to look for alternate means to observe that effect. In this Letter we consider the sensitivity of moderate-p_T, $\lesssim 8$ GeV/c, *single*-particle inclusive spectra. Since both parton shadowing and jet quenching lead to a suppression of those spectra, it is important to be able to calculate the complete event structure and incorporate both effects simultaneously in order to test if the two phenomena can be distinguished. Using HIJING, we show that a systematic study of the A dependence of moderate-p_T inclusive spectra in both $p+A$ and $A+A$ should make it possible to disentangle these novel nuclear phenomena.

For a detailed description of the HIJING Monte Carlo model and its extensive tests we refer to [3,7,8]. We recall here that jet production with initial- and final-state radiation is included along the lines of the PYTHIA model [6]. Soft beam jets are modeled by quark-diquark strings with gluon kinks along the lines of the DPM and FRITIOF models [4,5]. For nuclear interactions, exact diffuse nuclear geometry is used. Multiple minijet production at the pp level is calculated in the eikonal formalism. The cross sections for production of 0 and $j \geq 1$ number of jets production with $p_T > p_0$ are given by [17]

$$\sigma_0 = \int d^2b [1 - e^{-\sigma_{\rm soft} T_N(b)}] e^{-\sigma_{\rm jet} T_N(b)} , \qquad (1)$$

$$\sigma_j = \int d^2b \frac{[\sigma_{\rm jet} T_N(b)]^j}{j!} e^{-\sigma_{\rm jet} T_N(b)} . \qquad (2)$$

Their sum is the total inelastic cross section $\sigma_{\rm in}$. $\sigma_{\rm jet}(p_0)$ is the total inclusive jet cross section with $p_T \geq p_0$ calculated via PQCD, $\sigma_{\rm soft}$ is the phenomenological inclusive cross section for soft interactions, and $T_N(b)$ is the partonic overlap function between two nucleons at impact parameter b. We use the Fourier transform of a dipole form factor as the partonic density for each nucleon [17]. The default parameters employed in HIJING are $p_0 = 2$ GeV/c and a *constant* $\sigma_{\rm soft} = 57$ mb for $\sqrt{s} > 100$ GeV.

For nuclear interactions, we assume the validity of the binary collision approximation for both soft and hard processes. For a given binary interaction between two (possibly excited) nucleons at an impact parameter b, the interaction cross section and the number of parton scatterings are determined as above. The PYTHIA 5.3 program [6] is then used to determine the kinetic variables of the produced partons according to PQCD, including the initial- and final-state radiation associated with each hard scattering. The soft interactions are incorporated phenomenologically by a *minimal* two-string excitation model (beam jets). A gluon is represented by a kink in one of the beam quark-diquark strings. Hadronization is performed via the Lund JETSET 7.2 [18] program.

To test the sensitivity of minijet and particle production to gluon shadowing, we consider the possibility that both quarks and gluons are shadowed by the same amount in the small-x region. Motivated by geometrical considerations [12] and constrained by European Muon Collaboration data [11], we parametrize the impact-parameter-dependent parton structure function in a nucleus as

$$\frac{f_A(x)}{A f_N(x)} = 1 - a(x)(A^{1/3} - 1)\frac{4}{3}\left(1 - \frac{r^2}{R_A^2}\right)^{1/2} , \qquad (3)$$

where $a(x) \approx 0.1 \exp(-x^2/0.01)$ describes the behavior of parton depletion at small $x \lesssim 0.1$ (see [3] for the complete form at moderate and high x). In Eq. (3), R_A is the nuclear radius and r is the transverse position of the parton's parent nucleon relative to the nuclear center.

Jet quenching in HIJING is implemented by a simplified gluon splitting algorithm to simulate induced gluon radiation [14]. The transverse coordinates of interaction points are first determined assuming a cylindrical geometry and a constant mean free path λ_s. If Δl is the distance between two interaction points, the total radiated energy is then estimated to be $\Delta E = \Delta l \, dE/dl$. Since the prehadronization state in HIJING is represented by connected quark-diquark strings with gluon kinks, induced radiative energy loss can be modeled by transferring part (ΔE) of the gluon energy from one string to another. The string to which the new gluon kink is added is the one with the transverse coordinate closest to the interaction point. This mechanism conserves exactly the energy and momentum and simulates the energy degradation of a high-p_T parton for an assumed dE/dl and λ_s. While this jet quenching mechanism is obviously very schematic, it is sufficient in order to estimate the order of magnitude of the effects that are likely to result from final-state interactions. More quantitative estimates will require the development of a microscopic parton shower and cascade model as proposed in Ref. [19].

The calculated results for central Au+Au collisions at $\sqrt{s} = 200A$ GeV are shown in Fig. 1. The left panel shows the pseudorapidity distributions of charged particles. Note that without minijets (dotted line), the $2A$ soft beam jets in our model lead to $dN_{AA}/d\eta \approx A\, dN_{pp}/d\eta$. Each beam jet contributes about 0.75 to the central rapidity density almost independently of energy [7]. Without gluon shadowing (dash-dotted line), minijets are found to approximately triple the rapidity density due to beam jets. However, if gluon shadowing is of the same magnitude as that for quarks and antiquarks, then the minijet contribution to the rapidity density is reduced by approximately half (dashed line). The solid histogram shows that the effect of jet quenching on the rapidity density is small for $dE/dl = 2$ GeV/fm and $\lambda_s = 1$ fm.

In the middle panel of Fig. 1, we plot the ratio

$$R^{AB}(p_T) = \frac{d^2N_{AB}/dp_T^2 d\eta}{d^2N_{pp}/dp_T^2 d\eta} \qquad (4)$$

of the inclusive p_T spectrum of charged particles in central Au+Au collisions to that of $p+p$. For $p_T > 2$ GeV/c, both shadowing and quenching are seen to reduce dramatically the inclusive hadron production. In the absence of shadowing and jet quenching (dash-dotted line) the ratio approaches the number of binary pp collisions in the reaction. Shadowing alone (dashed line) suppresses moderate p_T hadrons by a factor of about 2. Inclusion of jet quenching with $dE/dl = 2$ GeV/fm reduces that yield by another factor of about 3–5. It is remarkable and encouraging that the *singles* inclusive hadron spectrum appears so sensitive to nuclear effects on jet production. Clearly higher-order correlations, e.g., high-p_T back-to-back hadron pairs, will be even more sensitive to these effects.

From the above, however, we see that $A+A$ data alone would not be sufficient to disentangle the effects of shadowing and jet quenching. To separate the two, $p+A$ collisions *must* be studied at the same energy. In those reactions, the density of comoving hadrons is so low that final-state interactions leading to jet quenching should be negligible. Therefore, any observed suppression of moderate-p_T hadrons could be attributed to gluon shadowing alone. The right-hand panel in Fig. 1 shows the

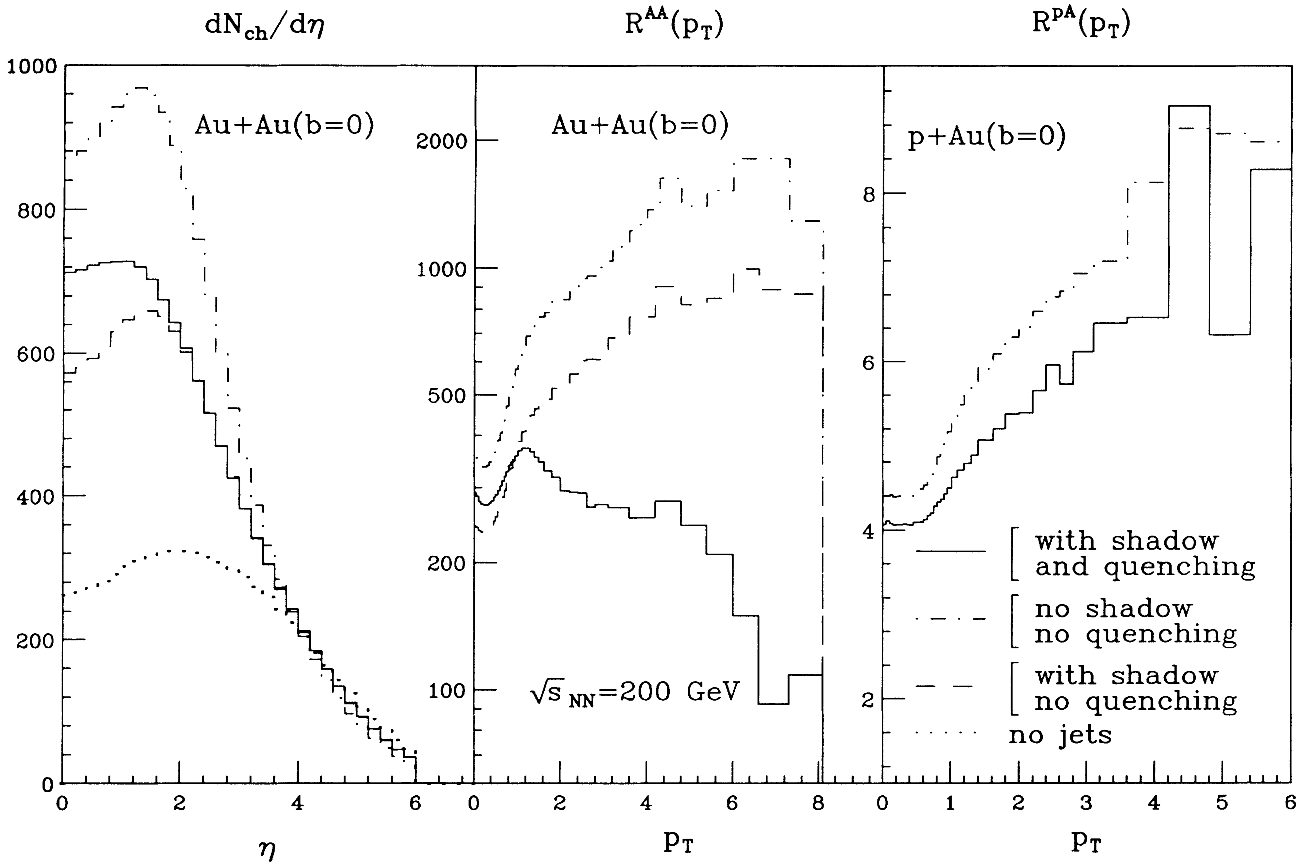

FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl=2$ GeV/fm with $\lambda_s=1$ fm. $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in $A+B$ collisions to that of $p+p$.

ratio as defined in Eq. (4) for central p+Au collisions. Without shadowing (dash-dotted line), the high-p_T limit again reaches the number of binary collisions, which is about 8 in this case. The low-p_T limit is, on the other hand, controlled by the number of *pairs* of beam jets, which is approximately 4 in central collisions. We see from this figure that the ratio $R^{pA}(p_T)$ at moderate p_T is indeed sensitive to gluon shadowing. Therefore, a systematic measurement of the inclusive hadron spectra in $p+p$ and $p+A$ at the same energy is essential in order to determine the magnitude of gluon shadowing. Since other nuclear effects on jet production in $p+A$ collisions at $\sqrt{s}\gtrsim 100A$ GeV are expected to be small [20], the spectra of moderate-p_T hadrons will provide complementary information on the gluon structure function to that deduced by the conventional direct photon technique that is limited to higher-x gluons due to the high $\pi^0\to\gamma\gamma$ background. Once the magnitude of gluon shadowing is determined, its contribution to the observed suppression of moderate-p_T hadrons in $A+A$ data can be calculated, thereby making it possible to isolate the contribution due to jet quenching.

In conclusion, calculations based on the HIJING model reveal quantitatively the important role of multiple minijet production in ultrarelativistic heavy-ion collisions. We emphasized here two novel nuclear effects which influence strongly the absolute yield of moderate-p_T hadrons, namely, gluon shadowing and jet quenching. Both effects are of fundamental interest as they pertain to nuclear structure at the partonic scale and the energy-loss mechanisms in dense matter. We showed that a systematic study of moderate-p_T singles inclusive hadron spectra in $p+p$, $p+A$, and $A+A$ collisions can be expected to provide enough information to determine the magnitude of each effect separately. The expected nuclear dependence of those spectra is large and should be readily measurable at RHIC.

We would like to thank S. J. Brodsky, K. Eskola, L. McLerran, and B. Müller for their helpful comments and discussions. This work was supported by the U.S. Department of Energy under Contracts No. DE-AC03-76SF00098 and No. DE-FG05-90ER40592.

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