Dilepton and Photon Production in the "Hot-Glue" Scenario

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(Received 8 January 1993)

Perturbative analysis of parton kinetics for high energy nuclear collisions shows that thermal equilibration of gluons happens very fast, while quark production is much slower. A simple "minimal model" is proposed which includes only incoming quarks and antiquarks. We have found that a smaller quark number is more than compensated by the fact that they are imbedded into the hotter glue. Predicted yield of dileptons and photons in the interesting kinematic region are larger than considered before, and are quite observable at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider.

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

The main objective of the future experimental heavy-ion program at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) is the production and studies of a new form of matter, the so-called *quark-gluon plasma* (QGP) [1], which is expected to exist during the first few fm/c of the collisions. Extrapolations from lower energies are difficult, because for heavy ion collisions at RHIC and LHC energies one is entering a new dynamical regime, in which the so-called *semihard* processes, involving partons with momenta (and momenta transfer) $p \sim$1–3 GeV, can no longer be considered as isolated rare events, but are involved in some complicated, cascade-type processes.

Early discussions of parton kinetics taking place *after the primary collisions* can be found in [1], and that of "partonic saturation" effects occurring *before the collision* can be found in [2]. The role of few-GeV partons (known also as "mini-jets") in nuclear collisions was discussed in [3–5]. Among important recent developments are estimates of parton energy losses in QGP (see [6] and references therein), which for the gluons reach $\tau_g dE/dx \approx$2–3 GeV/fm. Thus, contrary to some earlier claims, most of the mini-jets should be trapped in the fireball, created in central collisions, and therefore contribute to equilibration processes.

One open question is whether the main amount of produced entropy is due to complicated partonic substructure of nuclei themselves, and this entropy is just "liberated" at the collision moment, or it is produced in a more conventional manner, due to rescattering and production processes *after* the primary collisions took place. *Assuming* that perturbative QCD and parton model to be applicable down to 1 GeV scale ($x \sim$0.01, at RHIC), one may come to the former conclusion [5]. If gluonic structure functions are indeed so "dense," that one can speak about QGP as soon as partons are separated from each other after the first collision, at the time scale $\tau_{\text{separation}} \sim 1/p_t \sim 0.2$ fm/c. Consequences of this (the most optimistic) scenario for dileptons were recently discussed in [7]; it leads to very high initial temperatures and very big yields. However, we do not think such a regime can be dynamically sustained (at least, not if one is using perturbative cross sections).

The specific "hot-glue" scenario to be discussed below was recently suggested by one of us [8]. An ambitious program to study "partonic cascades," tracing the system all the way from the structure functions to equilibrated QGP, was recently started [9]. The results of the simulations have essentially supported the hot-glue scenario. In particular, the time during which most of the entropy is produced was found to be $\tau_{\text{entropy}} \approx 1/2$ fm/c for RHIC conditions, momenta distribution approach thermal ones, and also gluons clearly outnumber quarks.

For such a new scenario one has to reconsider all previously suggested QGP signatures. As a benchmark, we use the so-called standard scenario, which implies *complete* equilibration of QGP by the time $\tau_0 = 1$ fm/c. In this case the estimated initial temperatures (see details, e.g., in recent review [10]) should be $T_i \approx 240$ MeV (RHIC), $T_i \approx 290$ MeV (LHC), to be compared to much higher initial temperature T_i =400–500 MeV in the hot-glue case. Some consequences of this picture, like the *enhanced charm production* were already considered in [8], and in this paper we concentrate on dilepton and photon production.

Let us start with considering the initial conditions. We adopt a relatively conservative point of view (common for most mini-jet-related works) that at least 2–3 GeV parton momentum is needed in order to apply perturbative QCD. If so, the incoming partons are not yet saturated at RHIC, but gluons are effectively rescattered and soon become equilibrated. By their "equilibration time" $\tau_g \sim$ 1/3–1/2 fm/c we mean the time at which each secondary gluon has been in average *rescattered once* [8]. The problem is that quarks are not sufficiently numerous inside the parton "sea," and the relevant production processes are too slow to be operative at the few-fermi time scale [8]. Therefore, we are left with a *relatively small quark admixture* imbedded into the hot (and quickly equilibrated) glue.

We suggest a "minimal model," an obvious *lower bound*, including only the incoming sea quarks (and antiquarks) from the colliding nuclei. Using proton structure functions (a particular parametrization can be found, e.g., in [11]), and adding together u, d, s sea quarks and antiquarks we evaluate their number as

$$N_{q+\bar{q}} = 2\int_{x_{\rm min}} dx[u_{\rm sea}(x) + d_{\rm sea}(x) + s_{\rm sea}(x)] \approx 1.1 \pm 0.1 \,, \tag{1}$$

where the minimal value is dictated by the applicability of perturbative QCD, and we take $x_{\rm min} = 0.02$. (Actually this integral should also be cut off at some upper limit, which should be determined dynamically, excluding high-x partons which cannot be "dragged" to the central rapidity window by rescattering, but high momenta sea quarks are few anyway.) For example, for central AuAu collisions at RHIC the number of quarks and antiquarks is then $N_{q+\bar{q}}^{\rm AuAu} > 440$, while for gluons it is $N_g^{\rm AuAu} > 800$.

Looking at the problem "from the end" and normalizing gluons to some prefixed standard entropy value (our conservative choice is $dN_\pi/dy = 1400$ for AuAu central collisions at RHIC), one finds that if the gluonic plasma is *thermally* equilibrated in volume ($\pi R_A^2 \tau_g$) for $\tau_g = 0.3$ fm, its temperature should be $T \approx 500$ MeV (see details in [8]). The total number of gluons happen to be comparable to those "entering" the collision, as estimated above on the basis of known structure functions.

Including the minimal quark admixture evaluated above, one reduces the initial temperature to $T_0 = 460$ MeV. However, the *equilibrated* QGP plasma at such conditions would contain about $N_{q+\bar{q}}^{\rm AuAu} \sim 1700$, which is much larger than the number of quarks which have entered the fireball. Since in terms of momentum distribution quarks are equilibrated, one can estimate rates of any quark-related processes by simply substituting the proper power of the *quark suppression factor* $\xi \sim 1/4$ into the known rates, corresponding to the equilibrium plasma.

Let us now address the dilepton production, which is traditionally considered to be one of the best probes for QGP [1] (see recent review in [12]). In the dilepton mass "window" of interest, M=2–5 GeV, the main production mechanism is just electromagnetic $q\bar{q}$ annihilation, which has the following production rate:

$$\frac{dR_{l^+l^-}}{dM} = \xi^2 \frac{2\alpha^2}{3\pi^3} M^2 T K_1(M/T) \,, \tag{2}$$

where $K_1(x)$ is a Bessel function, and ξ is the quark suppression factor discussed above.

We have evaluated the dilepton yield in two ways. One is based on the simplest scale-invariant one-dimensional expansion picture, assuming adiabatic "cooling" of the matter. By integrating the production rate with the "temperature profile function" over the temperature as in [1], one gets

$$\frac{dN}{dy\,dM} = \xi^2 3\pi R_A^2 \tau_0^2 T_0^6 \int_{T_i} \frac{dT}{T^7} \frac{dR_{l^+l^-}}{d^4x}(T) \tag{3}$$

(in principle, the upper integration limit is the critical temperature T_c, but it leads to negligible contribution for high-mass dileptons to be discussed). The resulting invariant mass spectra are presented in Fig. 1(a), the solid curve for the hot-glue scenario ($\tau_0 = 0.3$ fm, $T_0 = 460$ MeV, $\xi = 1/4$) and the dashed curve for the standard scenario ($\tau_0 = 1$ fm, $T_0 = 240$ MeV, $\xi = 1$). The total amount of produced dileptons reflect the number of quarks involved, while the slopes of the two curves at high masses reflect the initial temperatures, so it is not surprising that the two curves cross. At large masses the thermal production yield becomes smaller than that due to direct the Drell-Yan mechanism of dilepton production, shown by the dotted line. One may therefore conclude that in the window M=2–3 GeV the new scenario leads to the dilepton yield, which *exceeds* that for the standard scenario and is above or comparable with that due to the Drell-Yan process. Although other possible backgrounds should also be considered (e.g., charm decay) before one can definitely conclude whether it is experimentally observable, the hot-glue prediction looks much more promising.

In order to check the sensitivity of these conclusions to the assumed equilibrium momentum distribution and the one-dimensional expansion, we have also performed a different evaluation of the dilepton yield using the cascade model. It has different plasma evolution: a cascade-driven expansion is neither strictly adiabatic nor a one-dimensional one. The results are shown in Fig. 1(b), and one can see that this more realistic model leads to similar conclusions in the invariant mass window of interest. The details of those cascade simulations will be published elsewhere.

We have also evaluated the photon production, due

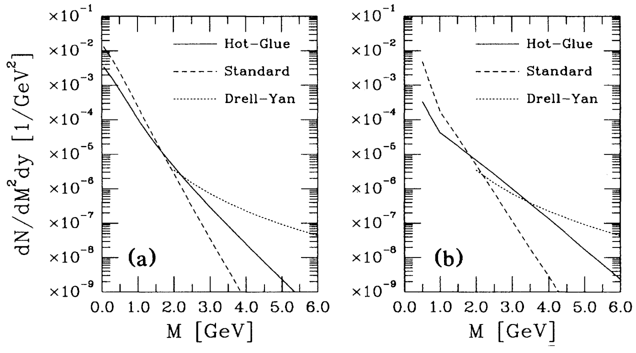

FIG. 1. The invariant mass spectrum of dilepton production from quark-antiquark annihilation during the plasma expansion in Au+Au collisions at 100+100 GeV/nucleon, calculated with (a) the hydrodynamical scale-invariant one-dimensional expansion model and (b) the parton cascade simulations. The curves are explained in the text.

to the Compton-like process $q(\bar{q})g \rightarrow q(\bar{q})\gamma$ and quark annihilation $q\bar{q} \rightarrow g\gamma$ [1], which dominates at large p_t. The thermal rate was discussed in few recent publications [13], and we use it in the form

$$E\frac{dR}{d^3p} = \xi E\frac{dR^{\text{Compton}}}{d^3p} + \xi^2 E\frac{dR^{\text{annihilation}}}{d^3p} = \frac{2}{3}\frac{\alpha\alpha_s T^2}{6\pi^2}\exp(-E/T)(\xi + 2\xi^2)\ln\frac{E}{g^2T}\,. \quad (4)$$

Integrating over the longitudinal momentum and over the expansion, assuming it to be one dimensional, we have evaluated the photon yield which is shown in Fig. 2. As for dileptons, predictions of these two scenarios, standard and hot-glue ones, are shown by the solid and dashed curves. Those should also be compared to the projected range of "direct photon" production (a range between two dash-dotted lines) and the background from $\pi^0 \rightarrow \gamma\gamma$ decay (a range between two dotted lines), which are taken from Ref. [12]. (Note, the latter background can certainly be experimentally determined and subtracted, and this should be kept in mind while comparing the curves.)

In conclusion the difference between the two scenarios for photon production is quite crucial from experimental point of view: while predictions of the standard model are hardly observable, those corresponding to the hot-glue scenario can presumably be seen in the window at p_t=3–5 GeV.

Considering the structure functions we have not included the so-called *shadowing* effect, the difference between the nuclear and nucleon structure functions. It is not yet known for sea quarks at sufficiently small x, and it can somewhat decrease the results. However, the same factor appears in the Drell-Yan process and in the quark number in our minimal model, so both thermal production and direct ones are affected by similar factor. Therefore, since their ratio is the most important experimentally, the shadowing effect does not affect most of our conclusions.

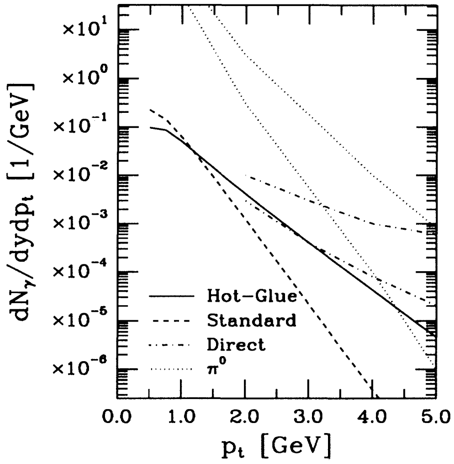

FIG. 2. The transverse momentum distribution of photons, produced from quark-gluon plasma. The curves are explained in the text.

There exist many other production mechanisms at smaller dilepton masses (or smaller photon p_t). In particular, one should be able to evaluate thermal production from the hadronic gas. Recently, the photon production from it was reconsidered [14], because it was found that the process $\pi\rho \rightarrow A_1 \rightarrow \gamma\pi$ "outshines" all others. Obviously, this process significantly contributes to small mass dilepton production as well. We will present a detailed discussion of these topics, as well as our cascade calculations elsewhere.

Recently, we have obtained a paper [15] in which dilepton yield from the nonequilibrium parton cascade is evaluated. Their findings are similar to ours, with even larger window in which plasma-related production dominates over other mechnisms.

Summarizing the paper, we have evaluated the dilepton and photon spectra at RHIC, based on the hot-glue scenario. We have found that a smaller quark fraction does not make these signals less useful. On the contrary, in the kinematical regions of interest the higher initial temperature happens to be more important, so the yields are actually *enhanced.* If so, an experimental observation of thermal dileptons and photons from the quark-gluon plasma has a better chance to succeed.

This work is partially supported by the U.S. Department of Energy under Grant No. DE-FG02-88ER40388. We also thank R. Baier and K. Redlich for helpful correspondence.

[1] E. Shuryak, Yad. Fiz. **28**, 796 (1978) [Sov. J. Nucl. Phys. **28**, 408 (1978)]; Phys. Rep. **61**, 71 (1980).

[2] L. Gribov, E. Levin, and M. Ryskin, Phys. Rep. **100**, 1 (1983).

[3] R. Hwa and K. Kajantie, Phys. Rev. Lett. **56**, 696 (1986); K. Kajantie, P.V. Landshoff, and J. Lindfors, Phys. Rev. Lett. **59**, 2527 (1987).

[4] K.J. Eskola, K. Kajantie, and J. Lindfors, Phys. Lett. B **215**, 375 (1988).

[5] J.P. Blaizot and A. Mueller, Nucl. Phys. **B289**, 847 (1987).

[6] X.-N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991); Phys. Rev. Lett. **68**, 1480 (1992); Nucl. Phys. **A544**, 559c (1992).

[7] J.L. Kapusta, L. McLerran, and D. Strivastava, "Dilepton production is big," University of Minnesota, 1992 (to be published).

[8] E. Shuryak, Phys. Rev. Lett. **68**, 3270 (1992).

[9] K. Geiger and B. Muller, Nucl. Phys. **B369**, 600 (1992); K. Geiger, Phys. Rev. D **46**, 4965 (1992); **46**, 4986 (1992).

[10] H. Satz, Nucl. Phys. **A544**, 371c (1992).

[11] M. Gluck *et al.*, Z. Phys. C **48**, 471 (1990).

[12] P.V. Ruuskanen, Nucl. Phys. **A544**, 169c (1992).

[13] Note that the results reported in literature [16–18] are actually all different, and in the review talk [12] the result is different from all of them. In addition, in [18] it is also claimed that the usual [ln(E/T)+const] form is only applicable at too high E. Thus, we only use the leading log terms here. The related uncertainty is comparable to general accuracy of a perturbative treatment (e.g., the g^2 value by itself) and may well be about a factor 2.

[14] L. Xiong, E. Shuryak, and G. Brown, Phys. Rev. D **46**, 3798 (1992).

[15] K. Geiger and J.I. Kapusta, Phys. Rev. Lett. **70**, 1920 (1993).

[16] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991).

[17] R. Baier, H. Nakkagawa, A. Niégawa, and K. Redlich, Z. Phys. C **53**, 433 (1992).

[18] A. Makhlin, Report No. SUNY NTG-93-10, 1993 (to be published).