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ESTIMATES OF ELECTROMAGNETIC SIGNALS FROM DECONFINED MATTER PRODUCED IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS *

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INTRODUCTION

Electromagnetic signals, i.e., real and virtual photons, have proven to be experimentally accessible probes of highly excited, strongly interacting matter in intermediate and relativistic heavy-ion collisions, both for Bevalac energies¹ and for SPS energies.² Indeed, at SPS in CERN the three large dilepton experiments, which measure the decay products of the virtual photons either as electron - positron pairs (CERES) or muon - anti-muon pairs (NA38, HELIOS-3), have detected an 'excess' of observed dileptons, i.e., a larger number of pairs in certain phase space regions than it could be explained by simple superpositions of known hadron decay sources or individual pp collisions. This is particularly tempting, since it indicates interesting features at nucleon - nucleon center-of-mass energies of $\sqrt{s} = 20$ GeV already for such light projectile - target combinations as S + S, S + U, and O + U.

There are interpretations of the data which point to precursors of the chiral symmetry restoration in dense and hot hadron matter.³ Other interpretations rely on the assumption of the achievement of the deconfinement transition to a quark-gluon plasma in these violent collisions.⁴

The appearance of the deconfinement transition in sufficiently hot hadron matter is predicted by evaluating properties of the equation of state on space-time lattices within quantum chromodynamics (QCD).⁵ The transition from hadron matter to deconfined matter seems to appear as an unavoidable consequence of QCD. In deconfined matter

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the quarks and gluons represent the relevant degrees of freedom. Since present day lattice calculations are still hampered by difficulties in handling the quark degrees of freedom and finite size effects, a final understanding of the differences of hadron matter versus deconfined matter is still lacking. Also the properties of hadron matter at temperatures below the deconfinement transition are yet matter of debate,⁶ and often one relies on simplified models to uncover the expected physical behavior.

If, according to QCD predictions, the appearance of the quark-gluon plasma is a necessary fact, one has to ask whether it can be experimentally identified. Generally, in central collisions of sufficiently large nuclei at sufficiently high bombarding energy the transient excitation of deconfined matter is expected. Among the long list of specific signals of the quark-gluon plasma the electromagnetic probes are considered as promising. Due to the electromagnetic interaction the production cross sections of real and virtual photons are small, and also their interaction cross sections are so small that these photons, once created, leave the strongly interacting matter nearly unaffected. Indeed, a simple estimate gives a mean free path of $\Lambda \sim \hbar \alpha^{-2} T^{-1} \sim 3.7 \cdot 10^6 T_{MeV}^{-1} \text{ fm}$, i.e., a value which is much larger than the typical nuclear dimensions. This estimate assumes that the mean free path is $\Lambda^{-1} \sim n \langle \sigma v \rangle$ with particle density $n \sim (T/\hbar)^3$, cross section $\sigma \sim \alpha^2 \hbar^2 / \hat{s}$, velocity $v \sim 1$, and relative energy $\sqrt{\hat{s}} \sim T$ (T is the temperature of the medium); $\alpha \approx \frac{1}{137}$ is the electromagnetic coupling constant. Therefore, electromagnetic signals represent direct messengers from hot QCD matter.

Since dileptons arise in the decay of a virtual photon $\gamma^* \rightarrow \mu^+ \mu^-$, a pair might be characterized by its four-momentum $Q \sim (M_\perp \cosh Y, M_\perp \sinh Y, \vec{q}_\perp)$, or invariant mass M , transverse momentum \vec{q}_\perp (which is a two dimensional quantity) and rapidity Y . The transverse mass is defined by $M_\perp = \sqrt{M^2 + q_\perp^2}$. Here we consider dileptons with $M > 2 \text{ GeV}$ in the so-called continuum region. In estimating the dilepton yield we follow the standard schematic picture of ultrarelativistic heavy-ion collisions: Nuclei are considered as swarms of partons. During the collision the coherence of the partons is destroyed. At RHIC and LHC energies ($\sqrt{s} = 200$ and 6400 GeV) a significant part of the produced transverse energy stems from the hard parton collisions, which can be treated by means of perturbative QCD and are named min-jets. These mini-jet produced partons populate, among other phase space regions, the mid-rapidity region and, due to their high density, they evolve rapidly towards local thermal equilibrium. According to detailed studies, these partons at mid-rapidity are mainly gluons with a few quarks immersed. The intriguing point is here, that even the distributions in momentum space look like thermalized, chemical equilibrium is not achieved.^{7,8,9} Inelastic soft interactions of quarks (q) and gluons (g) of the type $gg \leftrightarrow ggg$ and $gg \leftrightarrow q\bar{q}$ drive the system towards chemical equilibrium, while the elastic binary collisions $gg \leftrightarrow gg$, $qq \leftrightarrow qq$, $qg \leftrightarrow qg$ and so on, act keeping the thermalization.

The aim of the present contribution is to follow the evolution of the thermalized deconfined matter (which we loosely call parton matter) up to the confined matter (i.e., hadrons) through a possible mixed phase. We address here the question of the relationship of the dilepton radiation from deconfined matter to the dilepton radiation from hadron matter.

The motivation of doing so is the following one:

(i) In the previous standard estimates for deconfined matter one considered mainly the electromagnetic quark - anti-quark annihilation via $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+ \mu^-$. However, when quarks are very rare, one should expect considerable contributions from the QCD Compton like process $qg \rightarrow q\gamma^* \rightarrow q\mu^+ \mu^-$ (and the analog process where the quark q

is replaced by an anti-quark \bar{q}).

(ii) A recent study¹⁰ estimated a very high dilepton emission rate from hadron matter. The question therefore arises whether deconfined matter might shine out.

SPACE-TIME EVOLUTION OF MATTER

We consider here the mid-rapidity region of colliding nuclei, where possible longitudinal gradients of the matter distribution might be neglected, and we assume for simplicity charge-symmetric matter. The transverse expansion is treated within the scheme of global relativistic hydrodynamics¹¹ and turns out to be very important.

The chemical evolution of the deconfined matter is followed by a set of rate equations.^{9,11} The lowest-order perturbative QCD estimates of the chemical reaction rates show that a chemically off-equilibrium parton gas would have little chance to come to equilibrium before the confinement transition.⁹ However, higher order and possible non-perturbative processes can effectively increase the rates.¹² Various examples of the evolution of the temperature, the degree of phase space occupancy of the partons and the effects of the transverse expansion are documented in Ref.¹¹

The equation of state is parametrized according to the bag model in the deconfined phase, while the hadron matter is described by an ideal gas of (approximately) massless hadrons with 3 (for pions) or 6.6 (as effective number for many hadron species; this causes a strongly reduced latent heat) degrees of freedom. The confinement region of the hadronizing parton matter is modeled by a mixture phase in terms of the Maxwell construction. For details we refer the interested reader to our previous work.¹¹

DILEPTON RATES

Within the framework of kinetic theory the dilepton rate of parton matter per space-time volume d^4x and momentum volume d^4Q might be written as

$$\frac{dN_{ll}^{(i)}}{d^4x d^4Q} = \frac{1}{(2\pi)^8} \int \frac{d^3p_1}{2E_1} \frac{d^3p_2}{2E_2} \frac{d^3p_3}{2E_3} f_1(p_1, x) f_2(p_2, x) [1 \pm f_3(p_3, x)] \times \quad (1)$$

$$\delta^{(4)}(p_1 + p_2 - p_3 - Q) |M_i|^2,$$

where M_i represent the amplitudes for the corresponding processes $1 + 2 \rightarrow 3 + \mu^+ \mu^-$. The factor $[1 \pm f_3]$ accounts for the Pauli suppression or Bose enhancement related to the phase space occupation seen by the outgoing parton 3. The f 's represent the thermal distribution functions $f(p, x) \propto \lambda(\tau, x_\perp) [\exp\{\frac{p \cdot u(\tau, x_\perp)}{T(\tau, x_\perp)}\} + S]^{-1}$ with $S = \pm 1$ for Fermions/Bosons. According to the above assumed propositions on the space-time symmetry, the temperature T and the four-velocity u of the thermalized matter depend only on the proper time τ and the transverse distance x_\perp to the longitudinal axis. Since we consider charge-symmetric matter, the chemical potential obeys $\mu \equiv 0$. λ is the fugacity, i.e., the ratio of actual particle density to chemical equilibrium density ($\lambda = 1$ means full phase space saturation).

The rate for the electromagnetic process $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+ \mu^-$ looks similar, but without the phase space integral on d^3p_3 and the factor $[1 \pm f_3]$.¹¹

In the hadron phase the rate can be written as

$$\frac{dN_{l\bar{l}}}{d^4x d^4Q} = \frac{\alpha^2}{48\pi^2} F_h(M) \exp\left\{-\frac{Q \cdot u}{T}\right\}, \quad (2)$$

where we adopt an effective formfactor F_h .¹⁰ This formfactor exceeds the so-called ρ pole formfactor at $M > 2$ GeV by two orders of magnitude. The often used ρ pole approximation relies on the pion annihilation process within the vector dominance model $\pi^+\pi^- \rightarrow \gamma^* \rightarrow \rho \rightarrow \mu^+\mu^-$. In the hadron phase we assume phase space saturation.

By integrations over the space-time and a few of the dilepton momentum variables one gets the various spectra discussed below.

EXAMPLES OF DILEPTON SPECTRA

We employ here the following initial conditions for thermalized parton matter: $T_0 = 550$ MeV, $\lambda_g^0 = 0.5$, $\lambda_q^0 = \frac{1}{5}\lambda_g^0$, and the transverse radius of the system is 7 fm (corresponding to central collisions of Au + Au). The thermal evolution starts at $\tau_0 = 0.32$ fm/c. These numbers are according to transport calculations⁸ and other estimates.⁷ We utilize here the equation of state with reduced latent heat and assume a fast chemical equilibration scenario, so that the deconfined matter at confinement temperature of 160 MeV is fully saturated.

Fig. 1 (full line) shows the dilepton spectrum as function of the invariant mass. Weak structures can be seen. The yield from parton matter results in a smooth continuum, while the hadron matter contribution shows pronounced structures (not separately displayed here). From this one can conclude that the radiation from parton matter in the present example dominates, but some of the dileptons from hadron matter are still observable and cause the weak structures. Going into details of the calculations one becomes aware that the parton matter spectrum is much flatter, i.e., the high-mass dileptons come from short-living hotter stages of the system, while the softer dileptons stem from long-living colder stages. However, one observes in Fig. 1 that at large values of M ultimately the Drell Yan yield[†] (see below) dominates. The dashed (dot-dashed) line in Fig. 1 illustrates the change of the spectra when varying the phase space occupancies to $\lambda_g^0 = 0.25$, $\lambda_q^0 = 0.05$ ($\lambda_g^0 = \lambda_q^0 = 1$). For full phase space saturation the radiation from deconfined matter completely dominates, while the stronger undersaturated system gives more and more contribution from hadron matter. We note, however, that one should not compare various values of $\lambda_{q,g}^0$ at fixed initial temperature T_0 , but rather keep fixed the initial entropy (or energy) density. Then also T_0 varies, and smaller fugacities are nearly compensated by higher temperatures. As consequence, the yields up to $M = 3$ GeV are above the Drell Yan background.

In Fig. 2 an example of a transverse spectrum is displayed, and the contributions of parton and hadron matter are shown separately. The parton yield gives an approximately constant spectrum; this is the so-called M_\perp scaling behavior of the quark-gluon plasma,¹³ which is here weakly violated due to the transverse expansion. The hadron gas contribution shows the pronounced structures, mentioned above, which remain below the parton matter yield, except at the kinematical boundary where the ρ pole dominates. If one would neglect the transverse expansion, the hadron matter would

[†]It is here calculated with Duke Owens structure functions, set 1.1, K factor 2, for Au + Au at $\sqrt{s} = 200$ GeV.

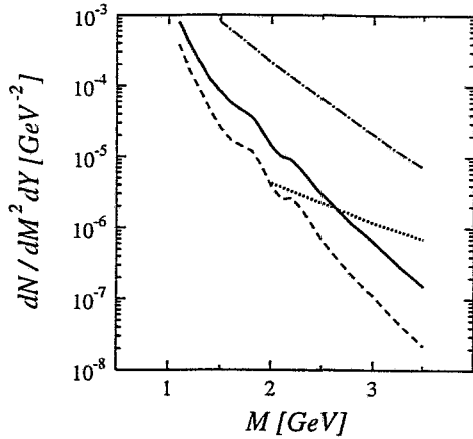


Figure 1. Dilepton spectra for various initial fugacities (dot-dashed, full, dashed lines: $\lambda_g^0 = 1, 0.5, 0.25$). The dotted line depicts the Drell Yan background.

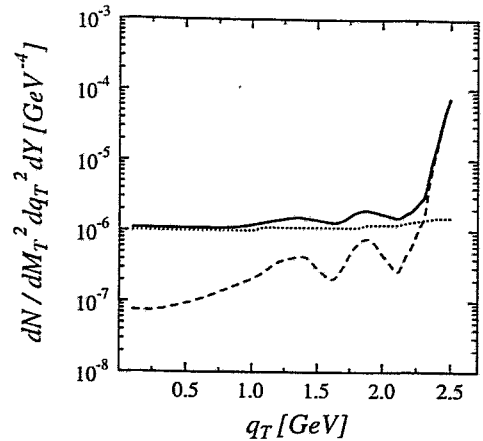


Figure 2. Transverse dilepton spectra at $M_{\perp} = 2.6$ GeV (dotted, dashed curves: contribution from parton, hadron matter; full curve: sum of these yields).

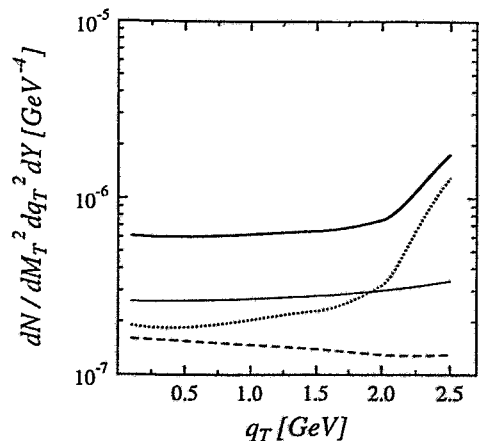
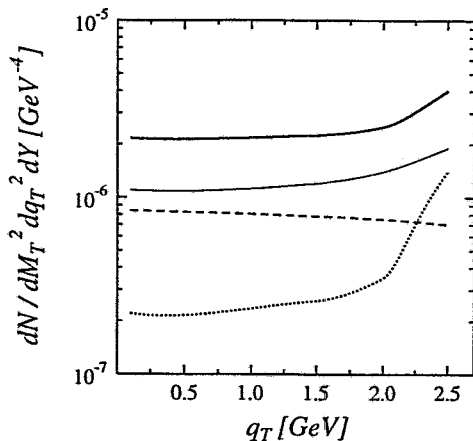


Figure 3. The contributions to the dilepton spectra from deconfined matter (thin, dashed, dotted curves: electromagnetic annihilation, QCD annihilation, QCD Compton processes; heavy full curve: sum of these processes). The left (right) panel is for fast (slow) chemical equilibration.

sine out¹¹ and the pattern of the curves would also change. We have chosen here $M_{\perp} = 2.6$ GeV, i.e., a value in the continuum region below the J/ψ peak.

Fig. 3 shows the various processes which contribute to the yield from parton matter. We employ here the QCD coupling constant $\alpha_s = 0.3$. The electromagnetic annihilation dominates in a wide range of transverse momenta. Only for a very slow chemical equilibration process (right panel; in this case the parton matter would stay far from chemical equilibration up to confinement) the QCD Compton process dominates for larger values of q_{\perp} . For the rapidly equilibrating model (left panel) the QCD annihilation is above the QCD Compton process. For the extremely small initial fugacities, as advocated in the HIJING model,⁹ the contribution of the QCD Compton process becomes more important. The main feature is obviously that the electromagnetic and QCD annihilation processes have the same relation to one another, while the QCD Compton process becomes more important with decreasing quark concentration.

PHOTON YIELDS

Examples of photon spectra within the same space-time evolution scenario are reported in Ref.¹¹ Photons obey a somewhat different kinematics, and they turn out to be more sensitive against details of the transverse expansion of the matter. As pointed out by Alam et al.,¹⁴ in the standard scenario with a bag model equation of state the photons from hadron matter would dominate. The reason is that the photon emissivities of deconfined matter and hadron matter are nearly equal.¹⁵ However, the lattice results⁵ point to a reduced latent at the confinement transition (in comparison with a bag model parametrization), and an appropriate incorporation of this fact shows that the so-called thermal photons from deconfined matter can still dominate.¹¹

SUMMARY

We present schematic estimates of photon and dilepton radiation from thermalized matter, which probably results in central ultra-relativistic heavy-ion collisions. The matter evolution is described by means of hydrodynamics and rate equations. Our goal is to clarify under which conditions the yields of deconfined matter could dominate.

For a complete calculation the decay rates from final free-streaming hadrons must be included as well as the pre-equilibrium contributions. The Drell Yan like contribution (i.e., first-chance parton collision products) can be estimated by an analog of Eq. (1) with structure functions, instead of the distribution functions f , and are dominant at large dilepton mass or photon energy. Proper pre-equilibrium contributions (i.e., when the f 's in Eq. (1) are neither the thermal distribution functions nor the structure functions) can be estimated semi-analytically only within some approximations.¹⁶ Presently we adopt a transport model⁸ to get a complete estimate on a unique footing.

Finally, we mention the recent results of Vogt,¹⁷ which show that semi-leptonic charm decays might result in dilepton numbers which exceed the thermal yields. This issue needs obviously further consideration.

Acknowledgments

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