Effect of quark-jet energy loss on direct photons in ultrarelativistic heavy-ion collisions

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We discuss the transverse momentum distribution of thermal and prompt photons in ultrarelativistic heavy ion collisions. The prompt photons are mostly produced by fragmentation of quark jets (bremsstrahlung). If these quark jets suffer a large energy loss in heavy-ion reactions, prompt photons are significantly suppressed. Thermal electromagnetic radiation from the quark-gluon plasma and the hadron gas might then dominate the intermediate \(k_T\)-range. In central Au+Au collisions at \(\sqrt{s} = 200A\) GeV, and in the range \(2\) GeV < \(k_T\) < \(4\) GeV, the inverse slope of the thermal radiation is \(360 – 460\) MeV, while that of the QCD photons is \(500 – 1000\) MeV. This large difference might allow to disentangle the various sources of direct photons experimentally. At \(\sqrt{s} = 5.5A\) TeV, nuclear shadowing and quark-jet quenching suppresses the QCD-photons strongly for \(k_T < 5\) GeV. Thermal radiation dominates in this \(k_T\)-region.

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In central collisions of heavy nuclei at ultrarelativistic energies a very hot and dense system of strongly interacting matter can be produced. By detecting produced particles like real and virtual photons or $J/\Psi$ mesons one hopes to probe this short-lived hot and dense state (see e.g. [1]).

Electromagnetic radiation is of particular interest since (once produced) it leaves the hot and dense region without further interactions [2]. Thus, it can provide information about the state of the source (e.g. its temperature or expansion velocity, in case of thermal radiation) at the space-time point of emission.

In particular, it has been suggested [3–5] that thermal photons might be detectable in the transverse momentum window $k_T = 2–5$ GeV, provided that photons from final-state decays of light mesons can be reliably identified and subtracted. However, even at the BNL-RHIC energy, $\sqrt{s} = 200$ A GeV, prompt photons (produced initially in reactions between the partons of the incoming nuclei) might dominate over the thermal radiation down to $k_T = 2$ GeV [6,7]. Only at the CERN-LHC energy, $\sqrt{s} = 5.5A$ TeV, might thermal radiation be dominant for $k_T = 2–5$ GeV, which is due to higher initial temperature of the plasma, and shadowing of the nuclear parton distributions.

If quark-jet quenching is absent in ultrarelativistic heavy-ion collisions, fragmentation of quark jets into a collinear photon and a quark (i.e. Bremsstrahlung) contributes significantly to the transverse momentum spectrum of prompt photons at midrapidity [3,4], in addition to the QCD-Compton and quark-antiquark annihilation processes.

On the other hand, in the high-multiplicity environment expected at the future heavy-ion colliders RHIC and LHC, the newly produced partons in the central region might materialize very rapidly [5]. In this case, produced quark jets could suffer a substantial energy loss while propagating through the hot and dense central region [6,7]. This energy loss is caused by
induced gluon radiation. Consequently, their fragmentation into high-$k_T$ photons would be inhibited.

The prompt photon spectrum should therefore also be a sensitive probe of energy-loss effects. Moreover, it is not sensitive to gluon jets and can thus be used to study in particular quenching of quark-jets. To give a first estimate of the maximal effect that can be expected, we compare the prompt photon spectrum with and without the contribution from quark-jet Bremsstrahlung. The latter corresponds to the case of fully quenched quark jets, i.e. complete energy loss. More detailed investigations of the bremsstrahlung spectrum as a function of the quark-jet energy loss will be presented elsewhere.

The energy loss of high-$p_T$ jets propagating through hot and dense QCD-matter has been studied in refs. [9,10], cf. also ref. [11]. HIJING simulations have shown [12] that this energy loss might reflect in a strong suppression of high-$p_T$ pions in heavy-ion collisions as compared to proton-proton collisions (at the same center-of-mass energy per nucleon). In ref. [13] it was proposed to study jet quenching by measuring the energy of the jet fragments in the opposite direction of a tagged photon. This assumes that the high-$k_T$ photons are predominantly produced via the Compton process $gq \rightarrow \gamma q$. On the other hand, if Bremsstrahlung gives an important contribution, the energy of the photon obviously is not equal to that of the quark-jet, and thus does not allow for a direct determination of its energy loss. This study this is restricted to photon transverse momenta well above 5 GeV. The detection of this jet quenching effect is one of the issues addressed by the STAR experiment [14] at the Relativistic Heavy-Ion Collider (RHIC), and the single photons will be measured by the PHENIX experiment [15].

In this letter we do not discuss the mechanism for the energy loss itself but propose an alternative observable for the quenching of quark jets, namely prompt photons. The
interaction of high-$k_T$ photons with the hot and dense QCD medium can be neglected [16,17], they thus do not suffer any energy loss while propagating through the medium.

To calculate prompt photon production in $p + p$ reactions, we convolute the cross-section for the given elementary process with the appropriate parton distribution of the proton, cf. e.g. refs. [7,18]. We work in LO (with a $K$-factor of $K = 2$ at $\sqrt{s} = 200A$ GeV and $K = 1.5$ at $\sqrt{s} = 5.5A$ TeV to account for the contribution of higher orders in $\alpha_s$) and at the twist-2 level, and employ the GRV-95 parton distribution function parametrizations for the proton [19]. To obtain the photon spectrum in heavy ion reactions, we multiply the cross section for $p + p$ reactions with the nuclear overlap functions $T_{AuAu}(b = 0) = 29mb^{-1}$ and $T_{PbPb}(b = 0) = 32mb^{-1}$, respectively. We account for nuclear shadowing effects by multiplying with $R_{F_2}$ as parametrized in ref. [20]. The $Q^2$ dependence of $R_{F_2}$ is neglected.

We also compare these spectra to the photons from the thermalized stage of the reaction. These are computed assuming longitudinally boost-invariant and cylindrically symmetric transverse hydrodynamical expansion of the thermalized quark-gluon plasma (QGP). To obtain an upper estimate for the thermal photons, we assume a very short thermalization time and a high initial temperature ($\tau_i = 0.124 \text{ fm/c, } T_i = 530 \text{ MeV for Au+Au at RHIC, } \sqrt{s} = 200A \text{ GeV, and } \tau_i = 0.1 \text{ fm/c, } T_i = 880 \text{ MeV for Pb+Pb at LHC, } \sqrt{s} = 5.5A \text{ TeV}$). For the QGP we assume the MIT bag-model equation of state for two massless quark flavours and a bag-constant of $B = 380 \text{ MeV/fm}^3$. Thus, the total entropy at midrapidity is $dS/d\eta = 5000$ for Au+Au at RHIC, and $dS/d\eta = 18700$ for Pb+Pb at LHC.

The hadronic phase is modelled as an ideal gas of massive $\pi$, $\eta$, $\rho$, and $\omega$ mesons. The two equations of state are matched by Gibbs conditions of phase equilibrium thus leading to a first-order phase transition (at $T_C = 160$ MeV). Finally, the thermal photon production rate derived in ref. [16] is integrated incoherently over that volume of the forward light-cone
with temperature above 100 MeV. The Bremsstrahlung contribution to the thermal photon emission rate is neglected since it is important only at lower transverse momenta. For further details of the calculations of both the prompt as well as the thermal photons please refer to ref. [1].

A third source of photons are the final-state decays of $\pi^0$ and $\eta$ mesons. This background contribution, which has been discussed e.g. in refs. [4,5], turns out to exceed the thermal yield in the transverse momentum range considered here. Thus, as already argued in ref. [5], these decay photons have to be identified and subtracted in order that the thermal radiation could be observable. At lower energy (Pb+Pb collisions at $\sqrt{s} = 18 A$ GeV, total central entropy $dS/dy \sim 3000 - 3500$) this has been successfully performed by the WA98 collaboration [22]. We assume that this will be possible also at the higher energies.
FIG. 1. Transverse momentum distribution of thermal (dotted curve) and prompt QCD-photons at midrapidity (solid curve: sum of compton and annihilation contributions; dashed curve: sum of compton, annihilation, and bremsstrahlung contributions); for central Au + Au collisions at RHIC energy.

Figure 1 shows that at RHIC energy the transverse momentum spectrum above $k_T \approx 2.5$ GeV is dominated by prompt photons, if quark jet quenching is absent. Thus, even if decay photons could be identified and subtracted, the thermal radiation would not be visible (in this range of $k_T$).

However, in central heavy-ion collisions the prompt photon spectrum might be modified. While nuclear shadowing effects were found to be small at this energy [6], quenching of quark jets might suppress prompt photon production. In the extreme case where the fragmentation of quark jets into photons is suppressed completely, thermal radiation shows up again in the transverse momentum range $k_T \leq 3$ GeV, cf. Fig. 1. For the very short thermalization time and high initial temperature assumed here, the thermal photon spectrum is dominated by photons from the QGP. For higher $\tau_i$ and lower $T_i$, however, the hadronic phase might contribute a similar number of real photons [6].

At this energy, the thermal and prompt photons have very different inverse slopes of the transverse momentum distributions. Even for such small thermalization times as $\tau_i = 0.124$ fm, and including collective transverse expansion, the inverse slope of the thermal photons is $T^*_th \leq 500$ MeV, for $k_T \leq 5$ GeV. $T^*$ is calculated as

$$T^* = -\frac{1}{d/dk_T \ln (d^2 N^*/k_T dk_T dy)} .$$

More specifically, we obtain $T^*_th = 360$ MeV at $k_T = 2.2$ GeV and $T^*_th = 460$ MeV at $k_T = 3.8$ GeV. On the other hand, the inverse slopes of the prompt photons are $T^*_{prompt} =$
500 MeV and $T^{*}_{\text{prompt}} = 750$ MeV at $k_T = 2.2$ GeV and $k_T = 3.8$ GeV, respectively. This large difference in $T^*$ should make it possible to distinguish thermal and prompt photons experimentally.

Due to shadowing of the nuclear structure functions, the prompt photons might be below the thermal radiation at LHC energy, cf. Fig. 2. The energy loss of quark jets reduces the non-thermal radiation even further. At $k_T = 2$ GeV, e.g., the prompt radiation is two orders of magnitude below the thermal contribution.

In summary, we have pointed out that the spectrum of prompt photons emitted in ultra-
relativistic heavy-ion collisions might be sensitive to the quark-jet energy loss in the medium. At RHIC, very strong jet quenching might suppress prompt photons to below the thermal radiation for not too high transverse momenta, $k_T \leq 3\text{ GeV}$. The photons with higher transverse momenta offer the opportunity to study quark-jet quenching in the hot and dense QCD medium. This is an independent observable of the jet-quenching effect (in addition to the proposed study of hadron spectra at high $p_T$ \cite{12}).

At the LHC energy, the conditions for detecting the thermal electromagnetic radiation (from the QGP) are even more favorable, since high initial temperatures enhance thermal emission, while nuclear shadowing and quark-jet quenching suppress prompt photon production.

The assumption that the partons formed at midrapidity essentially thermalize immediately is, of course, rather crude. In principle, one would expect that a pre-equilibrium stage exists, which would then also emit photons \cite{23}, thus “interpolating” between prompt and thermal radiation. This can be studied, e.g., within the parton cascade approach \cite{24}. According to our results, however, coherence effects \cite{10} on photon production (up to a few GeV of transverse momentum) in ultrarelativistic heavy-ion collisions are important and should be taken into account.

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