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Photon production in relativistic heavy-ion collisions using rates with two-loop calculations from quark matter

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Abstract. The production of single photons in relativistic heavy-ion collisions at CERN SPS, BNL RHIC and CERN LHC energies is re-examined in view of the recent studies of Aurenche et al., which show that the rate of photon production from quark–gluon plasma evaluated at the order of two loops by far exceeds the rates evaluated at the one-loop level, which have formed the basis of all the estimates of photons so far. We find that the production of photons from quark matter could easily outshine those from the hadronic matter under certain ideal conditions.

Single photons can be counted among the first signatures [1] which were proposed to verify the formation of deconfined strongly interacting matter, namely quark–gluon plasma (QGP). Together with dileptons – which will have similar origins – they constitute electromagnetic probes which are believed to reveal the history of the evolution of the plasma, through a (likely) mixed phase and the hadronic phase, as they do not rescatter once produced and their production cross section is a strongly increasing function of temperature. During the QGP phase, the single photons are believed to originate from Compton ($\mathrm{q}(\overline{\mathrm{q}})\mathrm{g} \rightarrow \mathrm{q}(\overline{\mathrm{q}})\gamma$) and annihilation ($\mathrm{q}\overline{\mathrm{q}} \rightarrow \mathrm{g}\gamma$) processes [2,3] as well as from bremsstrahlung processes ($\mathrm{qq(g)} \rightarrow \mathrm{qq(g)}\gamma$). Recently, in the first evaluation of single photons within a parton cascade model [4], it was shown [5] that the fragmentation of timelike quarks ($\mathrm{q} \rightarrow \mathrm{q}\gamma$) produced in (semi)hard multiple scattering during the preequilibrium phase of the collision leads to a substantial production of photons (flash of photons!), whose p_{T} is determined by the Q^2 of the scattering and not the by the temperature as in the above-mentioned calculations.

The upper limit for production of single photons in S + Au collisions at SPS energies [8] has been used by several authors to rule out simple hadronic equations of states [9], and the final results for the Pb + Pb collisions at SPS energies are eagerly awaited.

In a significant development Aurenche et al. [10] have recently evaluated the production of photons in a QGP up to two loops and they have shown that the bremsstrahlung process gives a contribution which is similar in magnitude to the Compton and annihilation contributions evaluated earlier up to the order of one loop [2,3]. This is in contrast to the "expectations" that the bremsstrahlung contributions drop rapidly with energy (see [6,7] for estimates within a soft-photon approximation). They also reported an entirely new mechanism for the production of hard photons through the annihilation of an off-mass shell quark and an antiquark, where the off-mass shell quark is a product of scattering with another quark or gluon, and which completely dominates the emission of hard photons. This process is similar to the annihilation of quarks in the presence of the chromo-electric field which may develop when two nuclei pass through each other due to colour exchange, and which can absorb the unbalanced energy and momentum to ensure the feasibility of the process which is absent in vacuum [11].

If confirmed, this has far-reaching consequences for the search of single photons from relativistic heavy-ion collisions.

The rate for the production of hard photons evaluated to the one-loop order using the effective theory based on resummation of hard thermal loops is given by [2,3]

$$E\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}^3k} = \frac{1}{2\pi^2}\alpha\alpha_{\mathrm{s}}\left(\sum_f e_f^2\right)T^2\mathrm{e}^{-E/T}\ln\left(\frac{cE}{\alpha_{\mathrm{s}}T}\right), \quad (1)$$

where the constant $c \approx 0.23$. The summation runs over the flavours of the quarks and e_f is the electric charge of the quarks in units of charge of the electron. The rate of production of photons due to the bremsstrahlung processes evaluated by Aurenche et al. is given by

$$E\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}^3k} = \frac{8}{\pi^5}\alpha\alpha_{\mathrm{s}}\left(\sum_f e_f^2\right)\frac{T^4}{E^2}\mathrm{e}^{-E/T}(J_{\mathrm{T}}-J_{\mathrm{L}})I(E,T), \quad (2)$$

where $J_{\mathrm{T}} \approx 4.45$ and $J_{\mathrm{L}} \approx -4.26$ for two flavours and three colours of quarks. For three flavours of quarks, $J_{\mathrm{T}} \approx 4.80$ and $J_{\mathrm{L}} \approx -4.52$. $I(E,T)$ stands for

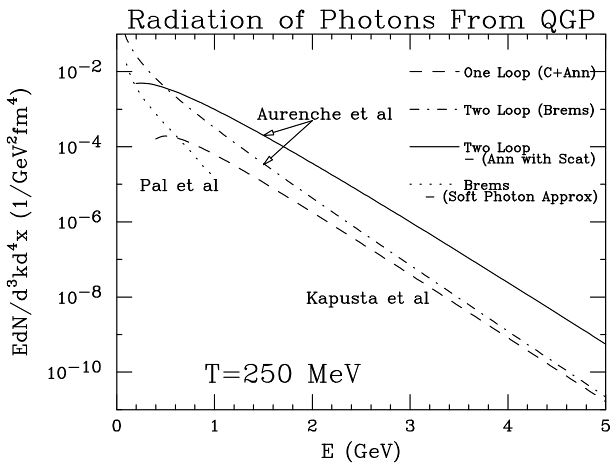

Fig. 1. Radiation of photons from various processes in the quark matter at $T = 250\,\mathrm{MeV}$

$$I(E,T) = \left[3\zeta(3) + \frac{\pi^2}{6}\frac{E}{T} + \left(\frac{E}{T}\right)^2 \ln(2) + 4\mathrm{Li}_3\left(-\mathrm{e}^{-|E|/T}\right) + 2\left(\frac{E}{T}\right)\mathrm{Li}_2\left(-\mathrm{e}^{-|E|/T}\right) - \left(\frac{E}{T}\right)^2 \ln\left(1+\mathrm{e}^{-|E|/T}\right)\right], \quad (3)$$

and the polylogarithmic functions Li are given by

$$\mathrm{Li}_a(z) = \sum_{n=1}^{+\infty} \frac{z^n}{n^a}. \quad (4)$$

Finally, the contribution of the $\mathrm{q}\overline{\mathrm{q}}$ annihilation with scattering obtained by them is given by

$$E\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}^3k} = \frac{8}{3\pi^5}\alpha\alpha_\mathrm{s}\left(\sum_f e_f^2\right) ET\mathrm{e}^{-E/T}(J_\mathrm{T} - J_\mathrm{L}). \quad (5)$$

We plot these rates of emission of photons from a QGP at $T = 250\,\mathrm{MeV}$ (Fig. 1) for an easy comparison. The dashed curve gives the contribution of the Compton and annihilation processes evaluated to the order of one loop by Kapusta et al. [2], the dot–dashed curve gives the bremsstrahlung contribution evaluated to two loops by Aurenche et al. [10], and the solid curve gives the results for the annihilation with scattering evaluated by the same authors. The dotted curve gives the results for the bremsstrahlung contribution evaluated within a soft-photon approximation (and using thermal mass for quarks and gluons) obtained by Pal et al. [7]. We see that at larger energies the annihilation of quarks with scattering really dominates over the rest of the contributions by more than an order of magnitude.

The question is how much of this dominance does survive when we integrate the radiation of photons over the history of the evolution of the system, where we should especially keep in mind that the QGP phase occurring in the early stages of the evolution necessarily occupies a smaller four-volume compared to the hadronic matter, which is known to have an emission rate similar to the quark matter emission rate at a given temperature [2], at least when only the Compton and the annihilation terms are used.

In order to ascertain this we consider central collisions of lead nuclei at SPS, RHIC and LHC energies. We assume that a chemically and thermally equilibrated quark–gluon plasma is formed at $\tau_0 = 1\,\mathrm{fm}/c$ at SPS and at $0.5\,\mathrm{fm}/c$ at RHIC and LHC energies. While there are indications that the plasma produced at the energies under consideration may indeed attain thermal equilibrium around the τ_0 chosen here [4,12], it is not quite definite that it may be chemically equilibrated. It may be recalled that the parton-cascade model which properly accounts for multiple scattering uses a cut-off in momentum transfer and virtuality to regulate the divergences in the scattering and the branching amplitudes for partons. This could underestimate the extent of chemical equilibration by a cessation of interactions when the energy of the partons is still large, which would not be the case if the screening of the partonic interactions could be accounted for. On the other hand, the self-screened parton cascade [13] attempts to remove these cut-offs by estimating the screening offered by the partons which have a larger p_T (and hence materialize earlier) to the partons which have a smaller p_T (and hence materialize later). However, it does not explicitly account for multiple scattering except for what is contained in the Glauber approximation utilized there.

In these exploratory calculations we assume a chemical equilibration at time τ_0 such that the initial temperature is obtained from the Bjorken condition [15]:

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{\pi R_\mathrm{T}^2}\frac{\mathrm{d}N}{\mathrm{d}y} = 4aT_0^3\tau_0. \quad (6)$$

Here we have chosen the particle rapidity densities to be 825, 1734, and 5625 at SPS, RHIC, and LHC energies, respectively, for central collisions of lead nuclei [14] and we have taken $a = 47.5\pi^2/90$ for a plasma of massless quarks (u, d, and s) and gluons.

We assume that the phase transition takes place at $T = 160\,\mathrm{MeV}$ and that the freeze-out takes place at $100\,\mathrm{MeV}$. We use a hadronic equation of state consisting of all the hadrons and resonances from the particle data table which have a mass less than $2.5\,\mathrm{GeV}$ [16]. The rates for the hadronic matter have been obtained [2] from a two-loop approximation of the photon self-energy using a model where π–ρ interactions have been included. The contribution of the A_1 resonance is also included according to the suggestions of Xiong et al. [18]. The relevant hydrodynamic equations are solved using the procedure [17] discussed earlier, and an integration over the history of the evolution is performed [16].

In Fig. 2 we show our results for central collisions of lead nuclei at energies which are reached at CERN SPS. We give the contribution of the quark matter (from the QGP phase and the mixed phase), labelled QM, and that of the hadronic matter (from the mixed phase and the hadronic phase) separately. We see that, if we use the

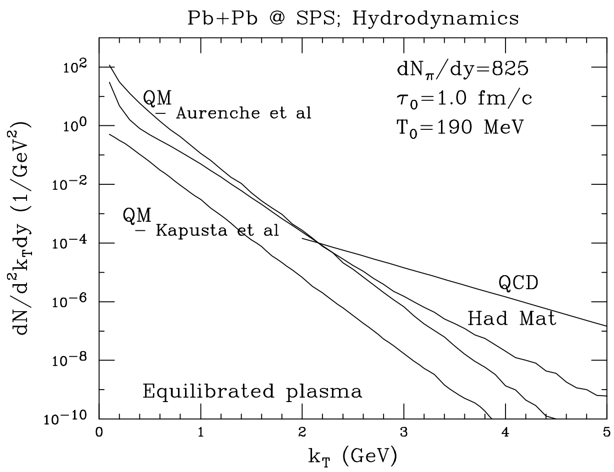

Fig. 2. Radiation of photons from central collisions of lead nuclei at SPS energies from the hadronic matter (in the mixed phase and the hadronic phase) and the quark matter (in the QGP phase and the mixed phase). The contribution of the quark matter when we use the rates obtained by Kapusta et al. and Aurenche et al., and those from hard QCD processes are shown separately

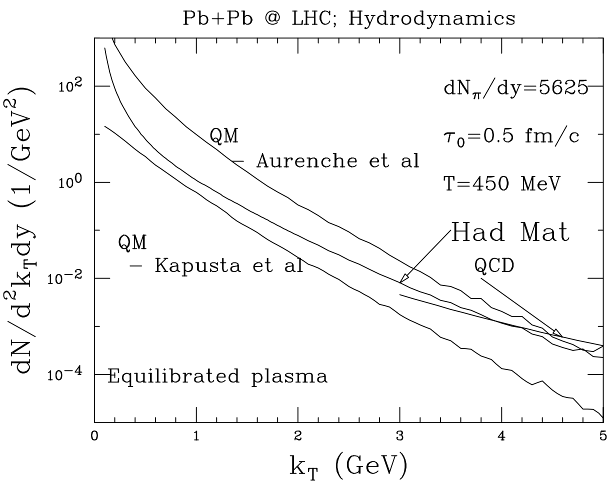

Fig. 4. The same as Fig. 2, but for LHC energies

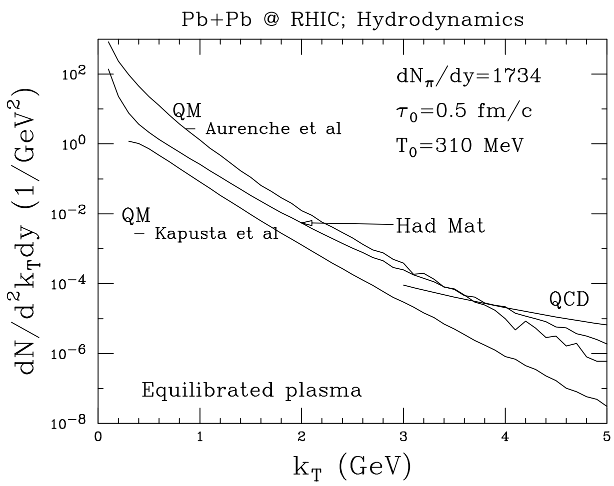

Fig. 3. The same as Fig. 2, but for RHIC energies

rates obtained earlier by Kapusta et al., then there is no window when the radiations from the quark matter could shine above the contributions from the hadronic matter. However, once the newly obtained rates are used we see that the quark matter may indeed outshine the hadronic matter up to $p_T = 2\,\mathrm{GeV}$ from these contributions alone. Note that by tracking the history from $\tau_0 = 1\,\mathrm{fm}/c$ onwards, we have not included the pre-equilibrium contributions [5] which will make a large contribution at higher momenta. The contribution of hard QCD photons [20] is obtained by scaling the results for pp collisions by the nuclear thickness.

The results for RHIC energies (Fig. 3) are quite interesting as now the window over which the quark matter outshines the hadronic contributions stretches to almost 3 GeV. Once again the addition of the pre-equilibrium contributions at larger p_T would substantially widen this window.

At LHC energies this window extends to beyond 4 GeV, and considering that perhaps the local thermalization at LHC (and also at RHIC) could be attained earlier than what is definitely a very conservative value here, these results provide the exciting possibility that, if these conditions are met, the quark matter may emit photons which may be almost an order of magnitude larger than those coming from the hadronic matter over a fairly wide window. As mentioned earlier, the pre-equilibrium contribution (due to the much larger initial energy) should be much larger here, and we may have the exciting possibility that the quark matter may outshine the hadronic matter over a very large window indeed.

How will the results change if the QGP is not in chemical equilibrium? While it is not easy to make estimates in a similar way as is done by Aurenche et al. for a chemically non-equilibrated plasma, it is reasonable to assume that the rates will fall simply because then the number of quarks and gluons will be smaller. Some of this short-fall will be off-set by the much larger temperatures which the parton cascade models predict. If one considers a chemically equilibrating plasma [19] then the quark and gluon fugacities will increase with time and at least the contributions from the latter stages will not be strongly suppressed. It is still felt that the loss of production of high p_T (from early times) photons due to chemical non-equilibration would be more than off-set by the increased temperature and the pre-equilibrium contribution, which can be quite large.

We conclude that the newly obtained rates for the emission of photons from a QGP (evaluated to the order of two loops) suggest that if chemically equilibrated plasma is produced then there will exist a fairly wide window where the photons from quark matter may outshine the photons from hadronic matter. Even in the absence of chemical equilibration these results indicate an enhanced radiation from the quark matter which is of considerable interest.

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