Single Photon Production in Relativistic Heavy Ion Collisions and Quark Hadron Phase Transition

Dinesh Kumar Srivastava

Variable Energy Cyclotron Centre,
1/AF Bidhan Nagar, Calcutta 700 064, India

Abstract

We discuss the recent developments in the study of single photon production in relativistic heavy ion collisions. In particular their production at SPS, RHIC, and LHC energies is re-examined in view of the results of Aurenche et al which show that the rate of photon production from quark gluon plasma, evaluated at the order of two loops far exceeds the rates evaluated at 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 out-shine those from the hadronic matter in certain ideal conditions. We further show that the earlier results lending support to the possibility of quark-hadron phase transition from the measured yield of single photons in $S + Au$ collisions at CERN SPS remain valid when an account is made for these developments.

1 Introduction

Single photons can be counted among the first signatures [1] which were proposed to verify the formation of deconfined strongly interacting matter- namely the quark gluon plasma (QGP). Along with dileptons- which will have similar origins, they constitute electro-magnetic probes which are believed to reveal the history of evolution of the plasma, through a (likely) mixed phase and the hadronic phase, as they do not re-scatter once produced and their production cross section is a strongly increasing

---

1Invited talk given at National Seminar on Nuclear Physics, July 26-29 1999, Institute of Physics, Bhubaneswar, India
function of temperature. During the QGP phase, the single photons are believed to originate from Compton ($q (\bar{q}) g \rightarrow q (\bar{q}) \gamma$) and annihilation ($q \bar{q} \rightarrow g \gamma$) processes [2, 3] as well as bremsstrahlung processes ($q q (g) \rightarrow q q (g) \gamma$). Recently in the first evaluation of single photons within a parton cascade model [4], it was shown [5] that the fragmentation of time-like quarks ($q \rightarrow q \gamma$) produced in (semi)hard multiple scatterings during the pre-equilibrium phase of the collision leads to a substantial production of photons (flash of photons!), whose $p_T$ is decided by the $Q^2$ of the scatterings and not the temperature, as in the above mentioned calculations.

The upper limit for production of single photons in $S + Au$ collisions at SPS energies [6] has been used by several authors to rule out simple hadronic equations of states [7] and the final results for the $Pb + Pb$ collisions at SPS energies are eagerly awaited.

In a significant development Aurenche et al [8] have recently evaluated the production of photons in a QGP up to two loops and shown that the bremsstrahlung process gives a contribution which is similar in magnitude to the Compton and annihilation contributions evaluated up to the order of one loop earlier [2, 3]. This is in contrast to the ‘expectations’ that the bremsstrahlung contributions drop rapidly with energy (see Ref. [9, 10] 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 anti-quark, 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.

In the following we first discuss the results of Srivastava [11] for $Pb + Pb$ collisions at SPS, RHIC, and LHC energies in view of the recent findings of Aurenche et al. Next, we discuss the reanalysis of the $S + Au$ data at SPS energy by Srivastava and Sinha [12].

If confirmed, these results provide a very important confirmation of the occurrence of quark hadron phase transition in relativistic heavy ion collisions.

2 Results of Aurenche et al.

Let us briefly recall the results of Aurenche et al and also earlier work on single photon production from the quark matter.

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

$$E \frac{dN}{d^4x} = \frac{1}{2\pi^2} \alpha \alpha_s \left( \sum_f e_f^2 \right) T^2 e^{-E/T} \ln\left( \frac{cE}{\alpha_s T} \right)$$  \hspace{1cm} (1)$$

where the constant $c \approx 0.23$. The summation runs over the 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:

$$E \frac{dN}{d^4x} = \frac{8}{\pi^5} \alpha \alpha_s \left( \sum_f e_f^2 \right) \frac{T^4}{E^2} e^{-E/T} (J_T - J_L) I(E, T)$$  \hspace{1cm} (2)$$

where $J_T \approx 4.45$ and $J_L \approx -4.26$ for 2 flavours and 3 colour of quarks. For 3 flavour
of quarks, $J_T \approx 4.80$ and $J_L \approx -4.52$. $I(E, T)$ stands for:

$$I(E, T) = \left[3 \zeta(3) + \frac{\pi^2}{6} \frac{E}{T} + \left(\frac{E}{T}\right)^2 \ln(2) + 4 Li_3(-e^{-|E|/T}) + 2 Li_2(-e^{-|E|/T}) - \left(\frac{E}{T}\right)^2 \ln(1 + e^{-|E|/T})\right],$$  \hspace{1cm} (3)

and the poly-logarithm functions $Li$ are given by:

$$Li_a(z) = \sum_{n=1}^{+\infty} \frac{z^n}{n^a}. \hspace{1cm} (4)$$

And finally the contribution of the $q\bar{q}$ annihilation with scattering obtained by them is given by:

$$E \frac{dN}{d^3x} = \frac{8}{3\pi^5} \alpha_s \left(\sum_f e_f^2\right) ET e^{-E/T} (J_T - J_L),$$  \hspace{1cm} (5)

We plot these rates of emission of photons from a QGP at $T = 250$ 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 [8] while 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 [10]. 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.

3 \textit{Pb + Pb collisions at SPS, RHIC, and LHC}

How much of this dominance does survive when we integrate the radiation of photons over the history of evolution of the system, specially as the QGP phase occurring in the early stages of the evolution necessarily occupies smaller four-volume compared the hadronic matter, which is known to have an emission rate similar to the quark matter 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 collision of lead nuclei at SPS, RHIC and LHC energies. We assume that a chemically and thermally equilibrated quark-gluon plasma is formed at $\tau_0 = 1 \text{ fm}/c$ at SPS and at 0.5 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 at around $\tau_0$ chosen here [4], 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 scatterings 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. The self-screened parton cascade [13] on the other hand attempts to remove these cut-offs by estimating the screening offered by the partons which have larger $p_T$ (and hence materialize earlier) to the partons which have 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 the time $\tau_0$ such that the initial temperature is obtained from the Bjorken condition [15];

$$\frac{2\pi^4}{45\zeta(3)} \frac{1}{\pi p_T^2} \frac{dN}{dy} = 4aT_0^3 \tau_0$$

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

We assume the phase transition to take place at $T = 160$ MeV, and the freeze-out to take place at 100 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 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 $\pi - \rho$ 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 a integration over history of evolution is performed [16].

In Fig. 2 we show our results for central collision 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) labeled as QM and that of the hadronic matter (from the mixed phase and the hadronic phase) separately. We see that if we use
the rates obtained earlier by Kapusta et al, 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 out-shine the hadronic matter up to $p_T = 2$ GeV, from these contributions alone. Note that by tracking the history from $\tau_0 = 1$ fm/$c$ onward, 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 out-shines 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 very larger initial energy) should be much larger here and we may have the exciting possibility that the quark matter may out-shine the hadronic matter over a very large window indeed.

4 Reanalysis of $S + Au$ collision at SPS

The publication of the upper limit of the production of single photons in $S + Au$ collisions at CERN SPS [6] by the WA80 group has been preceded and followed by several papers exploring their connection to the so-called quark-hadron phase transition. Thus an early work by Srivastava and Sinha [7], e.g., argued that the data is consistent with a scenario where a quark-gluon plasma is formed at some time $\tau_i \approx 1$ fm/$c$, which expands and cools, gets into a mixed phase of quarks, gluons, and hadrons, and ultimately undergoes a freeze-out to a state of hadronic gas consisting of $\pi$, $\rho$, $\omega$, and $\eta$ mesons. On the other hand, when the initial state is assumed to consist of (the same) hadrons, the resulting large initial temperature leads to a much larger production of single photons, in a gross disagreement with the data.

Since then, several authors have looked at the production of single photons in such collisions, using varying evolution scenarios, and including the effects of varying
Figure 2: Radiation of photons from central collision 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 while using the rates obtained by Kapusta et al and Aurenche et al, and those from hard QCD processes are shown separately.
Figure 3: Same as Fig. 2 for RHIC energies.
Figure 4: Same as Fig. 2 for LHC energies.
Figure 5: Single photon production in $S + Au$ collision at CERN SPS. An equilibrated (chemically and thermally) quark-gluon plasma is assumed to be formed at $\tau_0$ which expands, cools, gets into a mixed phase and undergoes freeze-out. QM stands for radiations from the quark matter in the QGP phase and the mixed phase. HM, likewise denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase and Sum denotes the sum of the contributions from the equilibrium phase. The histogram shows the pre-equilibrium contribution evaluated in a parton cascade model. The radiations from the quark-matter are evaluated to the order of one-loop.

Phase Transition, $T_c = 160$ MeV
$T_0 = 203$ MeV, $\tau_0 = 1$ fm/c
$S$(200 AGeV)$+Au; WA80
7.4%, most central
(baryon) density and temperature on the rate of production of photons from the hadronic matter.

Thus for example, Cleymans, Redlich, and Srivastava [16] used a hadronic equation of state which included all hadrons having a mass of up to 2.5 GeV, from the particle data book in complete thermal and chemical equilibrium. In this approach, the production of photons in phase-transition and no-phase transition scenarios (for Pb + Pb collisions at CERN SPS) was predicted to be quite similar in magnitude. However, the authors also noted that, the no-phase transition scenario necessitated a hadronic matter, where 2–3 hadrons had to be accommodated within a volume of $\approx 1 \text{ fm}^3$, where the hadronic picture should surely break-down.

All the above studies were performed using the (one-loop) evaluation of single photons from the quark matter [2, 3] and hadronic reactions using varying effective Lagrangians.

The findings of Aurenche et al provide a new dimension to these studies. We have already seen that these findings provide that the dominant number of the photons are now predicted to have their origin in the quark matter if the initial state could be approximated as an an equilibrated plasma.

This also raises a very important issue. The analysis of Ref. [7] has to be repeated to see if the newly identified processes contributing to the single photons from the quark matter remain consistent with the upper limit of the WA80 data. We now discuss the outcome of this natural step, first taken by Srivastava and Sinha [12].

These authors assumed, as in Ref. [7], that a chemically and thermally equilibrated quark-gluon plasma was produced in the $S + Au$ collision at the time $\tau_0 = 1 \text{ fm/c}$. The Bjorken condition [15] (Eq. 6) was then used to get an estimate of the initial temperature. In the case of no phase transition the temperature was obtained by demanding an yield of the same entropy as when a QGP was assumed to be formed [16]. The rapidity density was taken as 225, and the transverse dimension was decided by the radius of the $S$ nucleus. Rest of the analysis followed along the lines discussed above.

In Fig. 5 we show the results of Srivastava and Sinha [12] for the phase transition scenario. As remarked in the figure caption there, the dot-dashed curve gives the contribution of the quark-matter evaluated to the order of one loop, the dashed curve gives the contribution of the hadronic matter, and the solid curve gives the sum of the two. The pre-equilibrium contribution evaluated within a parton cascade model [5] is also given. It is interesting to see that the non-exponential component apparent in the measured upper limit can be identified with the pre-equilibrium contribution.
Figure 6: Same as Fig. 5, with the radiations from the quark-matter evaluated to the order of two loops.

Phase Transition, $T_c = 160$ MeV

$T_0 = 203$ MeV, $\tau_0 = 1$ fm/c

$S(200 \text{ AGeV}) + \text{Au}; \text{ WA80}

7.4\%, \text{ most central}

$E \Delta N / d^3 p$ (c$^3$/GeV$^2$)

$p_T$ (GeV/c)

Photons Upto Two Loops From QM
It is seen that the photon yield stays below the upper limit at all $p_T$, and most significantly, the dominant contribution is from the radiation from the hadronic matter.

The corresponding results with rates evaluated to the order of two-loops are given in Fig. 6 using similar notations. We now see that the evaluated photon yield has a dominant contribution from the quark-matter, as remarked earlier [11]. We also note that the predicted yield closely follows the shape of the measured upper limit over the entire range of $p_T$.

Note that the evaluated photon yield exhausts the upper limit at all $p_T$. However, considering that the measurements represent an upper limit, it still leaves a scope for a discussion of scenarios which may reduce the yield of single photons. The foremost consideration, and which is also most likely, would be an initial state where the quark-gluon plasma is not in chemical equilibrium.

In Fig. 7 we have shown the predictions for the scenario when no phase transition takes place. We again see that at least beyond $p_T$ equal to 1 GeV/$c$, the estimated single photon yield is consistent with the upper limit, though it is smaller than the upper limit both at the lower and the upper end of the $p_T$ spectrum. However, we have to emphasize that this description involves a hadronic gas which has a number density of several hadrons/fm$^3$, which is rather un-physical, and we have reservations about this description. We may also add that for such high hadronic densities almost all prescriptions for accommodating finite size effects in the hadronic equation of state will either break-down or imply a very high energy density to overcome the so-called hard-core repulsion of the hadrons at very short densities. We can thus be fairly confident that the picture leading to the Fig. 6 (or 5) is more likely.

Before concluding, it is of interest to add a comment on the shape of the predicted spectra (Figs. 5–7) in comparison to the measured upper limit. We have already remarked that the predictions lie considerably below the upper limit in Figs. 5 and 7, at lower $p_T$. Recall that the hadronic reactions considered in the study include the process $\pi\pi \rightarrow \rho\gamma$ which is known to be equivalent to the bremsstrahlung process $\pi\pi \rightarrow \pi\pi\gamma$ (see Ref. [9, 10]). Thus we realize that the bremsstrahlung process in the quark matter contained in the two-loop evaluations of Aurenche et al [8] plays an important role in getting the right shape of the spectrum at lower $p_T$. We do not have to repeat that the pre-equilibrium contribution leads to the right shape at higher $p_T$.

It is thus clear that the newly obtained rates for emission of photons from QGP (evaluated to the order of two loops), which are much larger than the corresponding results for the one-loop estimates yield single photons which are in agreement with
Figure 7: Same as Fig. 5, but without a phase transition; i.e., a hot hadronic gas is assumed to be formed at \( \tau_0 \). Note, however, in this case the initial density of hadrons exceeds several hadrons/fm\(^3\).

the upper limit of the data obtained by the WA80 experiment for the \( S + Au \) collisions at CERN SPS, and support a description where a quark-gluon plasma is formed.

We repeat also that, considering that the data represent the upper limit, we can, in principle, admit a scenario which has a chemically non-equilibrated plasma at the time \( \tau_0 \), and which will lead to a smaller radiation of photons from the quark phase.

5 Discussions and Summary

How will the results change if the QGP is not in chemical equilibrium? While it is not easy to perform the estimates similar to the one 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 emission of photons from 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.

We have also seen that these development continue to support the exciting possibility that the quark-hadron phase transition may have indeed taken place in $S + Au$ collisions at SPS. The preliminary data for $Pb + Pb$ collisions at SPS also seem to indicate [5] a similar possibility. This coupled with the observed excess production of dileptons, excess production of strange particles and the suppression of $J/\psi$ production, all of which constitute signatures of the quark hadron phase transition indicate that we are on the verge of very clear confirmation of the discovery of quark gluon plasma. A strong support to these observations has recently been provided by the first estimate of the colour Debye mass [21] for the partons released in heavy ion collisions evaluated within the parton cascade model. For $Pb + Pb$ collisions at SPS energies, it is found to be larger than the screening mass of $\chi_c$ signalling its dissolution and the attendant reduction in the production of $J/\psi$. For higher energies, the Debye mass is found to be much larger.

**Acknowledgments**

The author gratefully acknowledges the encouragement and thoughtful guidance he has received from Prof. L. Satpathy and Prof. M. Satpathy over the last two decades. The work described here has been done in collaboration with Bikash Sinha.
References


Pb+Pb @ SPS; Hydrodynamics

\[ \frac{dN}{d^2k_Tdy} \text{ (1/GeV}^2) \]

- QM
  - Aurenche et al
- QM
  - Kapusta et al
- QCD
- Had Mat

Equilibrated plasma

\[ dN_\pi/dy = 825 \]
\[ \tau_0 = 1.0 \text{ fm/c} \]
\[ T_0 = 190 \text{ MeV} \]
Pb+Pb @ RHIC; Hydrodynamics

$\frac{dN_\pi}{dy} = 1734$

$\tau_0 = 0.5$ fm/c

$T_0 = 310$ MeV

Equilibrated plasma

$\frac{dN}{d^2k_Tdy}$ (1/GeV$^2$)

$k_T$ (GeV)
Pb+Pb @ LHC; Hydrodynamics

\[ \frac{dN}{d^2k_T dy} \left( \frac{1}{\text{GeV}^2} \right) \]

- QM
  - Aureloche et al
- QM
  - Kapusta et al
- Had Mat
- QCD

Equilibrated plasma

- \( dN_\pi/dy = 5625 \)
- \( \tau_0 = 0.5 \text{ fm/c} \)
- \( T = 450 \text{ MeV} \)
Phase Transition, $T_c=160$ MeV
$T_0=203$ MeV, $\tau_0=1$ fm/c
S(200 AGeV)+Au; WA80
7.4%, most central

Photon distribution $\gamma$: $E dN_\gamma/d^3p$ (c^3/GeV^2)

$0 \leq p_T \leq 3$ (GeV/c)

QM, HM, Sum, PCM
Phase Transition, $T_C = 160$ MeV

$T_0 = 203$ MeV, $\tau_0 = 1$ fm/c

$S(200 A GeV) + Au$; WA80

7.4%, most central

$E_d N_\gamma / d^3 P$ (c$^3$/GeV$^2$)

$P_T$ (GeV/c)
$T_0 = 209 \text{ MeV}, \tau_0 = 1 \text{ fm/c}$

$S(200 \text{ AGeV}) + \text{Au}; \text{ WA80}$

7.4%, most central

$n_0 > 2.5 \text{ hadrons/fm}^3$

No Phase Transition