SINGLE PHOTONS FROM RELATIVISTIC HEAVY ION COLLISIONS AND QUARK-HADRON PHASE TRANSITION

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Abstract

The present status of theoretical expectations of studies of single photons from relativistic heavy ion collisions is discussed. It is argued that the upper limit of single photon radiation from S+Au collisions at CERN SPS obtained by the WA80 collaboration perhaps rules out any reasonable description of the collision process which does not involve a phase transition to quark gluon plasma. Predictions for single photons from the quark-matter likely to be created in collision of two lead nuclei at RHIC and LHC energies are given with a proper accounting of chemical equilibration and transverse expansion. Finally, it is pointed out that, contrary to the popular belief of a quadrilateral dependence of electromagnetic radiations ($N_\gamma$) from such collisions on the number of charged particles ($N_{ch}$), we may only have $N_\gamma \propto N_{ch}^{1.2}$.

1 INTRODUCTION

Relativistic heavy ion collisions are expected to lead to observation of a QCD phase transition from hadronic matter to quark matter and an ephemeral formation of Quark Gluon Plasma (QGP). Single photons and dileptons have long been considered as excellent probes of the early stages of relativistic heavy ion collisions. Their usefulness stems from the fact that - once produced - they hardly ever interact and leave the system with their energy and momentum unaltered. Their production cross-section is also known to increase rapidly with temperature and they should provide valuable information about the hot and dense - the truly exotic- stage of the matter likely to be created in such collisions. These early expectations have been considerably refined in recent times. It is now realized that we have to obtain a quantitative understanding of the various sources of single photons and dileptons before we are ready for an experimental identification of the thermal radiations from QGP. By now, it has also become evident that - at least - at the SPS energies, the
initial temperatures are not likely to be very high. Thermal radiations are emitted at every stage of the evolution of the interacting system. Thus for an expanding system, the radiations from the late hadronic phase can easily overwhelm the radiations from the initial QGP phase if the initial temperatures are not very high. This will be more so at lower transverse momenta.

The experimental identification of single photons gets very difficult due to the huge background of photons originating from the decay of $\pi^0$ and $\eta$ mesons. While there is some hope that it may be possible to isolate single photons at RHIC and LHC energies on an event by event basis; at the SPS energies this separation can only be attempted on a statistical basis.

The only guiding factor at the moment is the upper limit for single photons from S+Au collisions at SPS energies obtained recently by the WA80 collaboration [1]. The situation is quite lively, on the other hand, for the case of lepton pairs as a number of experiments have reported excess production of lepton pairs, both from sulphur and lead induced collisions [2] at the same energies. This already provides for a very important conclusion, which is often missed, viz.; the mechanism for the production of dileptons and single photons being similar, if there is an excess production of dileptons, there must be a production of single photons. We have to assess the experimental situation against the backdrop of these considerations.

The theoretical understanding of the production of single photons has three essential inputs, the rate of production of single photons from quark matter, the rate of production of single photons from hadronic matter, and the mechanism for the evolution of the interacting system. Recent years have witnessed enormous developments on all these fronts. Thus, the rate of production of single photons from quark matter has been calculated by a number of authors; with addition of soft and hard contribution using the Bratten - Pisarski resummation method to shield the singularity for a baryon free plasma [3, 4], for a plasma with a finite baryochemical potential [5], and for a non-equilibrated plasma [6] (see also [7, 8, 9, 10] for additional work in this connection). The rate of production of single photons from a hot hadronic matter due to a host of reactions has been studied by a number of authors [3, 4, 11, 12, 13, 14, 15]. The early works [16] on estimating single photons used the boost-invariant hydrodynamics of Bjorken [17] without transverse expansion extensively. The other extremes of Landau hydrodynamics [18] and a free streaming expansion [19, 20] have also been used. More recent studies have properly accounted for the transverse expansion of the plasma [21, 22, 23, 24, 25, 26, 27, 28]. Radiation of thermal photons from chemically equilibrating plasma has also been evaluated recently [10, 29, 30].

We shall not attempt a review of these developments. Instead, as indicated earlier, we shall try to use the upper limit of single photons seen by the WA80 collaboration to constrain the theoretical description attempted in the literature. First, we briefly discuss the treatment of Srivastava and Sinha [31]. We discuss the assumptions and give predictions for Pb+Pb collisions at SPS energies from the recent work of Cleymans, Redlich, and Srivastava [28]. Then we summarize our conclusions for SPS energies. Next we give the predictions for RHIC and LHC energies for single photons from a chemically equilibrating QGP [30]. Finally we describe a scaling behaviour between the number of single photons and the number
Figure 1: A comparison of theoretical predictions of Srivastava and Sinha with the upper limit of single photons from central collisions of S+Au system obtained by WA80 collaboration. The no-phase transition scenario, when the resulting hot hadronic gas is assumed to consist of $\pi$, $\rho$, $\omega$, and $\eta$ mesons, is seen to clearly excluded by the upper limits of the data of charged particles, seen from our analysis [32].

2 RESULTS FOR SPS ENERGIES

2.1 S+Au Collisions

Consider [31] central collisions of the S+Au system and assume an interacting system having an initial transverse radius $R_T$ equal to the radius of the sulphur nucleus and $dN_{\text{charge}}/dy = 150$ at $y = 0$. Assuming an isentropic expansion one can relate the particle rapidity density $dN/dy \approx 1.5 \times dN_{\text{charge}}/dy$, the initial temperature ($T_i$), and the initial time ($\tau_i$) as [33],

$$T_i^3 \tau_i = \frac{2\pi^4}{45\zeta(3) \pi R_T^2} \frac{dN}{4a_k dy}$$

(1)

where $a_k = a_Q = 37\pi^2/90$ if the system is initially in the QGP phase, consisting of (massless) ‘u’ and ‘d’ quarks, and gluons. If, however, the system is initially in a
Figure 2: Transverse momentum distribution of photons at $y = 0$ produced from the collision of lead nuclei at CERN SPS. The hadronic matter is assumed to consist of $\pi$, $\rho$, $\omega$, and $\eta$ mesons with (dashed lines) and without (full lines) phase transition hadronic phase, consisting of $\pi$, $\rho$, $\omega$, and $\eta$ mesons, we have $a_k = a_H \approx 4.6\pi^2/90$ appropriate for temperatures in the range 100–400 MeV. For the initial time $\tau_i$ we take the canonical value of 1 fm/c.

Thus, if the system is formed in the QGP phase at $\tau_i = 1$ fm/c, we have $T_i = 203.4$ MeV. On the other hand, if we assume the system to be produced in the hot hadronic phase, with the same entropy density as before at $\tau_i = 1$ fm/c, we get $T_i = 407.8$ MeV. Thus we consider two different scenarios. In the first scenario we assume the matter to be formed in a QGP phase at the initial time $\tau_i$ and initial temperature $T_i$, which then expands and cools, and goes into the mixed phase at the transition temperature $T = T_c$. When all of the quark matter has adiabatically converted into hadronic matter, it cools again and undergoes a freeze-out at $T = T_f$.

In the second scenario we consider the system to be formed in a hadronic phase with the same entropy density as before, at the initial time $\tau_i$ and an initial temperature $T_i$ which expands, cools, and undergoes a freeze-out at $T_f$, without admitting a QCD phase transition.

We assume a boost-invariant hydrodynamic expansion with transverse expansion of the system (Ref. [21, 34]). The thermal photon spectrum is obtained by convoluting the rate of emission of photons with the space-time evolution of the system, using methods which are well established by now [21]. For emission of photons from the QGP we consider the Compton plus annihilation contribution.
corrected for infrared divergences as 
\[
E \frac{dR}{d^3p} = \frac{5}{9} \frac{\alpha_s}{2\pi^2} T^2 e^{-E/T} \ln \left[ 1 + \frac{2.912 E}{g^2 T} \right] \tag{2}
\]
where \(\alpha_s\) is the strong coupling constant. For the hadronic matter we explicitly consider all the reactions involving the complete list of (nonstrange) light mesons ((\(\pi\pi \rightarrow \rho\gamma\), \(\pi\rho \rightarrow \pi\gamma\), \(\pi\pi \rightarrow \eta\gamma\), \(\pi\eta \rightarrow \pi\gamma\), and \(\pi^+\pi^- \rightarrow \gamma\gamma\)) and the decay of vector mesons (\(\omega^0 \rightarrow \pi^0\gamma\) and \(\rho^0 \rightarrow \pi^+\pi^-\gamma\)) considered by Kapusta, Lichard and Seibert \[3\]. In addition we include the contribution of \(\pi \rho \rightarrow A_1 \gamma\) through the parametrization suggested by Xiong et al. \[11\] whose results are rather similar to those of Song \[12\].

The photon spectrum is then obtained as,
\[
\frac{dN}{d^2p_T dy} = \int \left[ f_Q(r, \tau, \eta) \left( E \frac{dR}{d^3p} \right)_{QGP} + f_H(r, \tau, \eta) \left( E \frac{dR}{d^3p} \right)_{Had} \right] \tau d\tau r dr d\eta d\phi , \tag{3}
\]
where \(f_Q\) is the fraction of the quark-matter in the system and \(f_H\) is the hadronic fraction. We take \(T_c = 160\) MeV and assume the freeze-out to take place at 100 MeV. In any case the thermal photon production becomes insignificant at lower temperatures.

The results of this study are compared with the upper limit of the data seen by the WA80 group in Fig. 1 (Ref. \[1\]).

It is seen that a hadronic gas description is clearly ruled out by the upper limit of the data. Similar conclusions were reached by a number of authors \[22, 23, 24, 27\] using widely different descriptions for the expansion of the system. However, it should be emphasized that an initial temperature of about 400 MeV for the hot hadronic gas is already unacceptable from simple physical considerations as it would amount to a hadronic density in excess of 10 hadrons/fm\(^3\).

### 2.2 Predictions for Pb+Pb collisions at SPS

These conclusions on the basis of sulphur induced collisions have been closely scrutinized. Thus, it was argued that, one could consider a much richer constitution of the hadronic matter instead of limiting ourselves to only light mesons. This would bring down the initial temperature. However, there is still no published estimate of the rates for emission of photons from hadronic reactions which might involve heavier mesons and, say, baryons. One may still obtain a lower limit of hadronic description for the data by considering a much richer hadronic matter for the equation of state, but still employing the rates used earlier in Ref. \[31\]. Sollfrank et al. \[27\] have reported predictions in agreement with the upper limit of the WA80 results using such a procedure. However, one must remember that the initial energy density for this particular description in the above work \[27\] is several GeV/fm\(^3\) and the hadronic density is also several hadron/fm\(^3\), which does not inspire confidence in a hadronic description.

A good understanding of the effect of the equation of state of hadronic matter on the single photons at SPS energies is obtained from the detailed study of Cleymans, Redlich, and Srivastava \[28\]. Two extreme prescriptions for the hadronic
Figure 3: Transverse momentum distribution of photons at $y = 0$ produced from the collision of lead nuclei at CERN SPS. The hadronic matter is assumed to consist of all hadrons in particle data book, with (dashed lines) and without (full lines) phase transition matter were used. In the first case, the hadronic matter was assumed to consist of only $\pi$, $\rho$, $\omega$, and $\eta$ mesons, while in the other case all hadrons from the particle data book were assumed to populate the system in complete thermal and chemical equilibrium. Justification for the chemical equilibrium, at least at the time of freeze-out, is available from the studies of Braun-Munzinger et al. [35]. Both hadronic matter descriptions were employed with and without phase transition. In each case, the initial temperature was fixed by requiring that $dN_{\text{charge}}/dy \approx 550$ in collisions involving two lead nuclei.

As expected from the earlier findings of Srivastava and Sinha [31], the results for particles as well as photons were quite different for the equation of state employing a limited number of light mesons for the cases with and without phase transition. On the other hand, however, the predictions for photons as well as particle distributions were seen to be quite similar for the two scenarios - with and without phase transition - when the hadronic matter was assumed to consist of all hadrons (see, e.g., Figs. 2 & 3).

Before drawing any conclusion from Fig. 3 about the suitability of single photons for distinguishing between the scenarios which may or may not involve a phase transition, we should remember that even though the initial temperature in the hadronic gas scenario here is only about 210 MeV, which by itself may not be very
Figure 4: Distribution of thermal photons from the QGP phase at RHIC, from a chemically equilibrating and transversely expanding plasma. The initial conditions were obtained from a self screened parton cascade model. Results are also given for a purely longitudinal flow. Prompt photons, whose production is governed by structure functions are seen to dominate the yield for $p_T > 3–4$ GeV.

large, the initial number density is almost 3–4 hadrons/fm$^3$. This is obviously too large, for the hadronic description to be taken seriously. One may argue that all the hadrons may not be in chemical equilibrium at the initial time. Then, it is quite likely that the initial temperature would be much higher and lead to a much higher production of single photons. Again, we insist that, as only the limited number of hadronic reactions evaluated in Refs. [3, 11] were included in these analyses, the no-phase-transition scenario results are only a lower bound of the expected results. Finally, we add that it is often argued that, the initial time of 1 fm/c assumed in these analyses is perhaps too small. Increasing it to 2 fm/c was found to have negligible effect on the QGP scenario, due to very small space-time occupied by the QGP phase at the SPS energies, at not too large values of the transverse momenta. The hadronic gas description is affected more strongly, but the initial number density still remains too large (see Ref. [36], also for a discussions of effect of viscosity).

We may conclude therefore that the upper limit of the single photons obtained by the WA80 experiment perhaps rules out a reasonable description of the collision which does not involve a phase transition. We eagerly await the results from the Pb+Pb experiment. In any case, the two predictions given in Fig. 3 differ by a factor of 2, and hence a data accurate to better than that will hopefully be able to
Figure 5: Same as Fig. 4 at LHC. The prompt photons from fragmentation of quark jets are also shown.

clearly distinguish between the two descriptions.

We may add that the same approach is able to describe [38] the excess production of low mass dielectrons (near and beyond the $\rho$ peak) seen in $S + Au$ collisions by the CERES experiment [2] without any free parameters; which further enhances our confidence in the observation that we are perhaps witnessing the quark-hadron phase transition.

3 RESULTS FOR RHIC & LHC ENERGIES

It is generally believed that the formation of QGP at RHIC and LHC energies in collisions involving heavy nuclei is perhaps beyond doubt. The formation, thermalization, and chemical equilibration of the quark matter produced at these energies has been a subject of intense study during the last several years. Recently the initial conditions likely to be attained in such collisions have been obtained in a self-screened parton cascade model [37]. It has been found that while a thermalization of the plasma is obtained quickly, (say by $\tau = 0.25$ fm/$c$), the plasma is far from chemical equilibrium. The chemical equilibrium is likely to proceed via gluon multiplication ($gg \leftrightarrow ggg$) and quark production ($gg \leftrightarrow q\bar{q}$). The transverse expansion of the plasma has been found to impede the chemical equilibration due to enhanced cooling of the partonic matter. Single photons and dileptons will prove to be invaluable tools for probing the early stages of such matter. We give the
Figure 6: Variation of rapidity density of thermal photons with the charged particle rapidity density with the two equations of state in Fig. 3 & 4, involving phase transition. \( N_\gamma \) is seen to scale as \( KN_\text{ch}^\alpha \) with \( \alpha \approx 1.2 \). \( K \) is decided by equation of state.

predictions for production of thermal photons from such matter in Figs. 4 & 5, and invite the reader to Ref. [30] for details.

We would like to add that at these energies, the contribution to single photons from the plasma comes mainly from the Compton scattering of quarks and gluons, as the plasma is gluon-rich and quark-poor. This brings about an interesting and unique possibility of obtaining information about the partonic distribution at very early times from a comparison of single photon and dilepton measurements, as the latter will be fully determined by the density of the quarks.

4 THE SCALING \( N_\gamma \propto N_\text{ch}^\alpha \)

It is popularly believed that the number of photons (real or virtual) radiated from relativistic heavy ion collisions, \( N_\gamma \), should scale with the number of charged particles, \( N_\text{ch} \), as \( N_\gamma \propto N_\text{ch}^2 \). It is important to examine this scaling behaviour as it is used to estimate the extent of the signal of single photons against the background of decay photons and even to figure out whether such a signal does exist at all. The two hadronic equations of state with a provision for QGP phase transition, used in Figs. 2 & 3, were employed to estimate single photons for a number of charged particle multiplicity densities [32]. As seen from Fig. 6, the number of photons scales
as $N_{\text{ch}}^{1,2}$, with the constant of proportionality decided by the equation of state. In, fact it is rather easy to understand this as follows. Consider a system consisting of $N_{\text{ch}}$ charged particles. The number of thermal photons $N_\gamma$ will be given by

$$N_\gamma \sim e^2 N_{\text{ch}} \nu$$

where $\nu$ is the number of collisions that each particle suffers. If the system lives long enough, as when it is confined in a box, every particle will have a chance to collide with every other particle, and $\nu \sim N_{\text{ch}}$. This will lead to the quadratic dependence suggested earlier. However, the number of collisions suffered by the particles will be given by $R/\lambda$, where $R$ is the size and $\lambda$ is the mean free path of the particles, for a system created in heavy ion collisions. Realizing that the number of particles will scale as $R^3$, we get a scaling behaviour as $N_{\text{ch}}^{4/3}$ which is quite similar to the behaviour seen here. We should also add that in the absence of transverse expansion, which is known to be important for systems having a large multiplicity, the life-time can become as large as several thousand fm/$c$. This would then mimic the case of particles contained in a box and lead to the scaling behaviour assumed generally.

5 OUTLOOK

In brief, the theoretical description of single photons from relativistic heavy collisions has reached a high degree of sophistication. Several approaches for the evaluation of rates and the evolution of the collision dynamics have been discussed in the literature. The only available data, namely the upper limits in the sulphur induced collisions at the SPS energies, are already indicative of unacceptability of any description which does not involve a phase transition to QGP, unless of-course we are comfortable with very high hadronic densities. Treatments invoking a phase transition provide an agreement with the upper limit in spite of the differences in the details of the evolution mechanism. The final data from Pb+Pb collisions at SPS energies are eagerly awaited. It has been argued that the dilepton excess measured by the CERES experiment requires that the mass of $\rho$ mesons reduces considerably in the dense matter produced in such collisions. If true, this will also affect the single photon considerably. This can be of great interest.

The truly clear signals of the production of single photons are expected to emerge at RHIC and LHC energies, where it may become possible to get an information about the densities of quarks and gluons at very early times, as the plasma may be far from equilibrium, but very hot. In fact, it may even become possible to measure diphotons [39] (from $q\bar{q} \rightarrow \gamma\gamma$) and even attempt a photon interferometry [40] to obtain an information about the space-time details of the early stages of the plasma.

We also feel that the scaling behaviour (Eq. 4) seen here may be useful in the determination of the equation of state of the hadronic matter, and also in deciding the actual strength of the signal of single photons.
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