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A second look at single-photon production in S + Au collisions at 200 A GeV and implications for quark–hadron phase transition

D.K. Srivastava[1], B.C. Sinha[1,2]

[1] Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064, India
[2] Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Calcutta 700 064, India

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Abstract. We reanalyze the production of single photons in S + Au collisions at CERN SPS to investigate: (i) the consequences of using a much richer equation of state for hadrons than the one used in an earlier study by us, and (ii) to see if the recent estimates of photon production in quark matter (at two-loop level) by Aurenche, et al. are consistent with the upper limit of the photon production measured by the WA80 group. We find that the data are consistent with a quark–hadron phase transition. The data are also consistent with a scenario where no phase transition takes place, but where the hadronic matter reaches a density of several hadrons per unit volume, which is rather unphysical.

The publication of the upper limit of the production of single photons in S + Au collisions at CERN SPS [1] 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 the present authors [2] argued that the data *is* consistent with a scenario where a quark–gluon plasma is formed at some time $\tau_0 \approx 1$ fm/c, expands and cools, gets into a mixed phase of quarks, gluons, and hadrons, and ultimately undergoes a freeze-out from a state of hadronic gas consisting of π, ρ, ω, and η 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; this is in gross disagreement with the data.

Since then, several authors have looked at the production of single photons in these collisions, using varying evolution scenarios, and including the effects of changing (baryon) density and temperature on the rate of production of photons from the hadronic matter.

Thus, for example, Cleymans, Redlich, and Srivastava [3] 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 a complete thermal and chemical equilibrium. In this approach, the production of photons in the phase-transition and the no-phase-transition scenarios (for Pb + Pb collisions at CERN SPS) was predicted to be quite similar. However, the authors also noted that the no-phase-transition scenario necessitated hadronic matter; 2–3 hadrons had to be accommodated within a volume of ≈ 1 fm^3, in which the hadronic picture should surely break down (see also [4]).

All the above studies were performed by the use of the (one-loop) evaluation of single photons from the quark matter [5,6] and hadronic reactions using varying effective Lagrangians. An attempt was also made to evaluate the single photons, which arise from the quark matter because of the bremsstrahlung processes within the soft-photon approximation, and which were found to make a large contribution at smaller p_{T} [7,8].

A new dimension, giving new hope, has recently been added to these efforts by the evaluation of the rate of single photon production from quark matter to the order of two loops by Aurenche, et al. [9]. The two most interesting results are: (i) the dominance of the bremsstrahlung process for all momenta over the Compton plus annihilation contributions included in the one-loop calculations mentioned above, and even more importantly, (ii) a very large contribution by a new mechanism which corresponds to the annihilation of a quark (scattered from a quark or a gluon) by an anti-quark. This considerably enhances the production of single photons at SPS, RHIC, and LHC energies and is a very significant departure from the (somewhat pessimistic) belief that the dominant number of the photons are now predicted to have their origin in the quark matter [10] if the initial state could be approximated as an equilibrated plasma. While the results for a (chemically) nonequilibrated plasma are awaited, a large production of high-p_{T} photons has been predicted from the preequilibrium stage of the parton cascade model [11]. Taken in its entirety, it presents a very positive development in the field of single photons from relativistic heavy-ion collisions.

However, the above also raises an important issue. One must repeat the analysis of [2] 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. In case it overshoots the upper limit, we have to identify the reasons for the overshooting.

Let us briefly recall the sources of single photons from the quark matter. During the quark–gluon phase (QGP), the single photons originate from Compton ($q\,(\overline{q})\,g \rightarrow q\,(\overline{q})\,\gamma$) and annihilation ($q\,\overline{q} \rightarrow g\,\gamma$) processes [5,6] as well as bremsstrahlung processes ($q\,q\,(g) \rightarrow q\,q\,(g)\,\gamma$) [7, 8]. During the preequilibrium phase, which can be treated within the parton cascade model [12], the fragmentation of time-like quarks ($q \rightarrow q\,\gamma$) produced in (semi)hard multiple scatterings leads to a substantial production of photons (flash of photons), whose $p_{\rm T}$ is decided by the Q^2 of the scatterings and not the temperature, as in the calculations mentioned earlier [11]. Of course, we must now admit the suggestion of Aurenche, et al. [9] that the production of photons in a QGP evaluated up to two loops leads to a large bremsstrahlung contribution (see [7,8] for early estimates within a soft photon approximation) as well as a new mechanism for the production of hard photons through the annihilation of quarks with scattering; this mechanism completely dominates the emission of hard photons.

The rate for the production of hard photons evaluated to one-loop order by the use of the effective theory based on resummation of hard thermal loops is given by [5,6]:

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

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

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

where $J_{\rm T} \approx 4.45$ and $J_{\rm L} \approx -4.26$ for two flavors and three quark colors. $I(E,T)$ stands for

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

and the polylogarithmic functions Li are given by

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

Finally, the contribution of the $q\overline{q}$ annihilation with scattering obtained by them [9] is given by:

$$E\frac{{\rm d}N}{{\rm d}^4x\,{\rm d}^3k} = \frac{8}{3\pi^5}\,\alpha\alpha_s\,\left(\sum_f e_f^2\right) \times ET\,{\rm e}^{-E/T}\,(J_{\rm T}-J_{\rm L}) \tag{5}$$

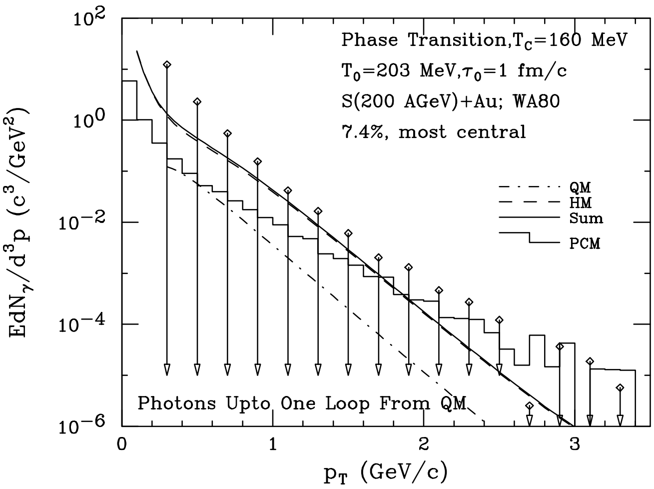

Fig. 1. Single-photon production in S + Au collision at CERN SPS. An equilibrated (chemically and thermally) quark–gluon plasma is assumed to be formed at τ_0 that expands, cools, gets into a mixed phase, and undergoes freeze-out. QM stands for radiations from the quark matter in the QGP and the mixed 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 preequilibrium contribution evaluated in a parton cascade model. The radiations from the quark matter are evaluated to the order of one loop.

A comparison of these contributions is already given in Fig. 1 of [10]. It is worthwhile to remember that these derivations are made under the assumption that the quark–gluon plasma is described by thermal quantum chromodynamics and that the effective theory obtained after resummation of hard thermal loops is a valid framework for handling the production of photons. It remains to be seen, however, whether the still higher-order (three or more loops) corrections will give only a decreasing contribution to the rate of production of photons [9].

We assume that a chemically and thermally equilibrated quark–gluon plasma is produced in such collisions at the time $\tau_0 = 1$ fm/c, and that one could use the Bjorken condition [13]

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

to get an estimate of the initial temperature. We have chosen the particle rapidity density as 225 for the S + Au collision at the CERN SPS energy, with the transverse dimension decided by the radius of the S nucleus and have taken $a = 37\pi^2/90$ for a plasma of massless quarks (u and d) and gluons. In the case of no phase transition, we estimate the temperature to yield the same entropy as in the above [3].

We assume the phase transition to take place at $T = 160$ MeV, and the freeze-out to take place at 120 MeV. We use a hadronic equation of state consisting of *all* the

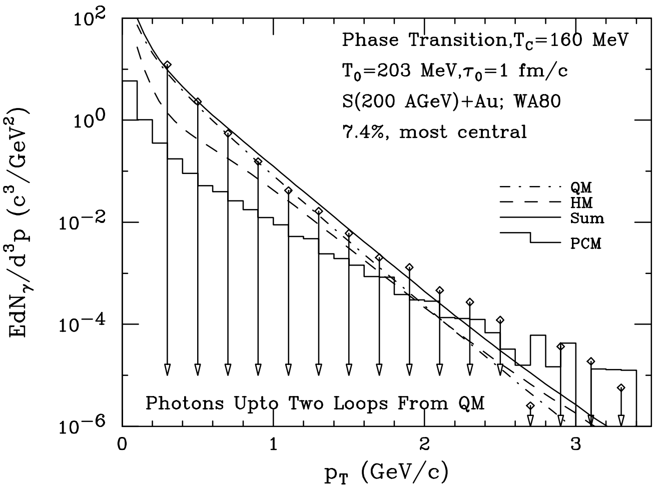

Fig. 2. Same as Fig. 1, with the radiations from the quark matter evaluated to the order of two loops.

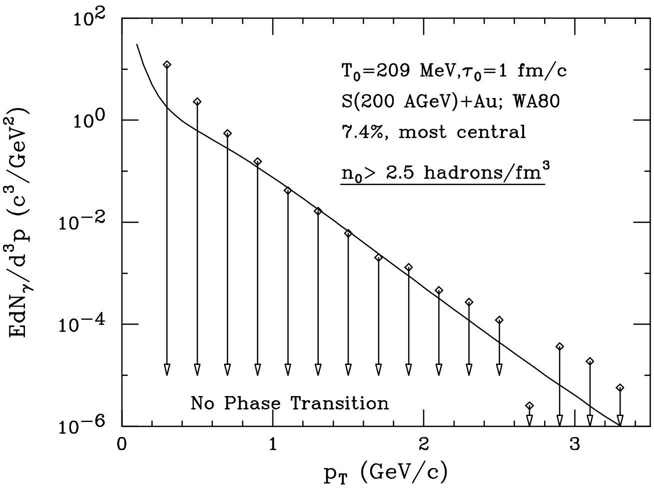

Fig. 3. Same as Fig. 1, but without a phase transition; i.e., a hot hadronic gas is assumed to be formed at τ_0. Note, however, that in this case the initial density of hadrons exceeds several hadrons/fm^3.

hadrons and resonances from the particle data table which have a mass less than 2.5 GeV [3]. The rates for the hadronic matter have been obtained [5] from a two-loop approximation of the photon self-energy by the use of 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. [14]. The relevant hydrodynamic equations are solved by the use of the procedure [15] discussed earlier, and an integration over history of evolution is performed [3].

In Fig. 1, we show our results 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. We have also separately given the *preequilibrium* contribution evaluated within a parton cascade model [11]. This is estimated by the normalization of the corresponding predictions for S + S collision at the SPS energy with the ratio of the nuclear thicknesses $T_{\rm SAu}/T_{\rm SS}$ at $b = 0$. It is gratifying to see that the nonexponential component present in the data is closely reproduced by the preequilibrium contribution.

It is seen that the photon yield stays below the upper limit at all p_T, and most significantly, it gets a dominant contribution from the radiations in hadronic matter.

The corresponding results with rates evaluated to the order of two loops are given in Fig. 2 with similar notations. We now see that the evaluated photon yield gets the dominant contribution from the quark matter, as was remarked earlier [10]. We also note that the predicted yield closely follows the shape of the data over the entire range of p_T and that the preequilibrium contribution dominates the large p_T domain.

We see that the evaluated photon yield exhausts the upper limit at all p_T. However, considering that the data represent an upper limit, this still leaves scope for a discussion of scenarios which may reduce the yield of single photons. The foremost consideration, and that which is also most likely, would be an initial state where the quark-gluon plasma is *not* in chemical equilibrium. In fact, several studies at RHIC and LHC energies do suggest that the initial state of the plasma may not be in a state of chemical equilibrium [12], though thermal equilibrium may be attained rather quickly [16].

In Fig. 3, we have shown our predictions for the scenario in which no phase transition takes place. We again see that at least for values of p_T beyond 1 GeV/c, the single photon yield estimated by us 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 having a number density of several hadrons/fm^3, which is rather unphysical; thus we have reservations about this description. We reiterate that the picture leading to Fig. 2 (or 1) is more likely. We also add that for such high hadronic densities, almost all the 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 conclude 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 that are in agreement with the upper limit of the data obtained by the WA80 group for the S + Au collisions at CERN SPS and support a description where a quark–gluon plasma is formed.

We add that, considering that the data represent the upper limit, we can in principle admit a scenario in which a chemically nonequilibrated plasma at time τ_0 leads to a smaller radiation of photons from the quark phase.

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