Direct photons from relativistic heavy ion collisions at CERN SPS and at RHIC

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Assuming QGP as the initial state, we have analyzed the direct photon data, obtained by the WA98 collaboration, in 158 A GeV Pb+Pb collisions at CERN SPS. It was shown, that for small thermalisation time, two loop rate contribute substantially to high p_T photons. We argue that for extremely short thermalisation time scale, the higher loop contribution should not be neglected. For thermalisation time 0.4 fm or greater, when higher loop contribution are not substantial, the initial temperature of the QGP is not large and the system does not produce enough hard p_T photons to fit the WA98 experiment. For initial time in the ranges of 0.4-1.0 fm, WA98 data could be fitted only if the fluid has initial radial velocity in the range of 0.3-0.5c. The model was applied to predict photon spectrum at RHIC energy.

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Ever since possible existence of deconfining phase transition from hadrons to quark gluon plasma (QGP) was predicted by the Quantum Chromodynamics (QCD), nuclear physicists are eagerly looking for the experimental evidences of QGP, the new state of matter [1]. It has even been claimed that, evidence of the new state of matter is already seen at CERN SPS in Pb+Pb collision [2]. The claim was based mainly on the experimental J/ψ suppression and strangeness enhancement, in Pb+Pb collisions. Due to intrinsic ambiguities in disentangling the similar effects arising from hadronic processes, their claim is rather considered controversial [3]. On the other hand, it may be noticed that electromagnetic signals (dileptons and photons), were not considered in establishing the claim, even though, photons and dileptons are well recognized probes of QGP. They suffer minimal final state interactions and can give information about the early stage of the collisions. Experimentally however, it is a challenge to obtain precision photon data from huge background. Recently WA98 collaboration has published their single photon emission data for 158 A GeV Pb+Pb collisions at CERN SPS [4]. Several authors have analyzed the WA98 single photon data [5–9], but their conclusions are not convergent. It seems that the data could be explained in a QGP or in a hadronic gas scenario, with or without initial radial velocity.

In the present paper, we further analyze the WA98 data in the initial QGP scenario. We first assume that the thermalisation time τ_i, beyond which hydrodynamics is applicable, is larger than 0.4 fm. The reason for this is the uncertainty in the elementary photon production rate. For smaller τ_i, higher loops contributions can be substantial, ruining any agreement obtained with data. If $\tau_i > 0.4$ fm is the case, we then confirm the analysis of Peressounko et al [8] that the data require an initial radial velocity. It was also shown that the high p_T photon spectra depend quite strongly on the initial radial velocity distribution. For realistic (surface peaked) velocity distribution, initial radial velocity in the range of 0.3-0.4c is required.

Procedure for obtaining photon spectra in a hydrodynamic evolution is well known [10]. We have solved the hydrodynamic equations $\partial_\mu T^{\mu\nu} = 0$ for a baryon free gas assuming cylindrical symmetry and boost-invariance. The equation of state for QGP was assumed to be $p_q = a_q T^4 - B$ with $a_q = 42.25\pi^2/90$. The hadronic equation of state was generalized to include all the mesonic resonances with mass < 2 GeV. The cut off 2 GeV is rather arbitrary and we verify that the results do not depend on the value of cut-off significantly. The bag constant B was obtained from the Gibbs condition $p_{QGP}(T_c) = p_{had}(T_c)$. The critical temperature (T_c) and the freeze-out temperature (T_F) were assumed to be 180 MeV and 100 MeV respectively.

Hydrodynamic models require, as inputs, the initial time (τ_i) and initial energy density or equivalently the temperature (T_i) of the fluid. τ_i is the thermalisation time, beyond which quasi-equilibrium is established and hydrodynamics is applicable. τ_i and T_i are parameters of the model, unless one obtains them from some microscopic transport models. In order to reduce parameters, one further assume that the fluid flow is isentropic. Then for a given τ_i the initial temperature T_i of the fluid (QGP) can be obtained by relating the entropy density with the observed pion multiplicity (assuming pion decoupling to be adiabatic) [11],

$$T_i^3 \tau_i = \frac{1}{\pi R_A^2} \frac{c}{4a_{q,h}} \frac{dN}{dY}(b=0) \tag{1}$$

where $c = 2\pi^4/45\zeta(3)$ and R_A is the transverse radius of the system (assumed to be 6.4 fm for Pb+Pb collisions). $b=0$ corresponds to central collisions. In table 1, initial temperature of the QGP, for certain values of the initial time τ_i are shown. Rapidity density was assumed to be dN/dY=750 [5]. It can be seen that choice of initial time is of crucial importance. QGP is formed at higher temperature for low values of the thermalisation time. High p_T photon production rate depends strongly on the initial temperature and it is possible to increase its yield by arbitrarily reducing the thermalisation time and correspondingly increasing the initial temperature of the QGP fluid.

For the single photons from hadronic gas we include the following processes,

(a) $\pi\pi \rightarrow \rho\gamma$, (b) $\pi\rho \rightarrow \pi\gamma$, (c) $\omega \rightarrow \pi\gamma$, (d) $\rho \rightarrow \pi\pi\gamma$
(e) $\pi\rho \rightarrow A_1 \rightarrow \pi\gamma$
rates for which are well known [12,13].

Rate of production of hard photons from QGP were evaluated by Kapusta et al [14]. To one loop order,

$$E\frac{dR}{d^3p} = \frac{1}{2\pi^2}\alpha\alpha_s \sum_f e_f^2 T^2 e^{-E/T} \ln(\frac{\xi E}{\alpha_s T}) \tag{2}$$

where $\xi \sim 0.23$ is a constant. The summation runs over the flavors of the quarks and e_f is the electric charge of the quarks in units of charge of the electron.

Recently Aurenche et al [15] evaluated the production of photons in a QGP. At two loops level Bremsstrahlung photons ($qq(g) \rightarrow qq(g)\gamma$ found to be dominating the compton and annihilation photons.

The rate of production of photons due to Bremsstrahlung (corrected for the factor of 4 [17,16]) was evaluated by them as,

$$E\frac{dR}{d^3p} = \frac{1}{4}\frac{8}{\pi^5}\alpha\alpha_s \sum_f e_f^2 \frac{T^4}{E^2} e^{-E/T} (J_T - J_L) I(E,T) \tag{3}$$

where $J_T \sim 4.45$ and $J_L \sim -4.26$ for two flavors and 3 colors of quarks. For 3 flavor quarks, $J_T \sim 4.8$ and $J_L \sim -4.52$. $I(E,T)$ stands for,

$$\begin{aligned} I(E,T) = [&3\zeta(3) + \frac{\pi^2}{6}\frac{E}{T} + (\frac{E}{T})^2 \ln 2 + 4Li_3(-e^{-|E|/T}) \\ &+2Li_2(-e^{-|E|/T}) - (E/T)^2 \ln(1+e^{-|E|/T})] \end{aligned} \tag{4}$$

and the poly-logarith functions Li are given by,

$$Li_a(z) = \sum_{n=1}^{\infty} \frac{z^n}{n^a} \tag{5}$$

Aurenche et al [15] also calculated the contribution of the $q\bar{q}$ with scattering, which should also be corrected for the same factor of 4. The corrected rate is,

$$E\frac{dR}{d^3p} = \frac{1}{4}\frac{8}{3\pi^5}\alpha\alpha_s \sum_f e_f^2 E T e^{-E/T} (J_T - J_L) \tag{6}$$

We would like to call attention to the fact that two-loop photon rate from QGP is not complete. Higher loops contribute to the same order [18]. Also Landau-Migdal-Pomeranchuk effect has been neglected [19]. Questions naturally arise how can then one obtain a reliable estimate of photon yield in the QGP scenario. In Fig.1, we have shown the ratio of photon yield obtained with one+two loop rate and one loop rate, for initial times τ_i =0.2,0.4,0.6,0.8 and 1 fm. It can be seen for the lowest thermalisation time (τ_i=0.2 fm) two loop rate contribute more that 70% to the high p_T photons. If the higher loops contribute to the same order as the two-loop rate, their inclusion can change the two loop results drastically. In the given circumstances, it will be unwise to apply these results if the thermalisation time scale is as small as 0.2 fm.

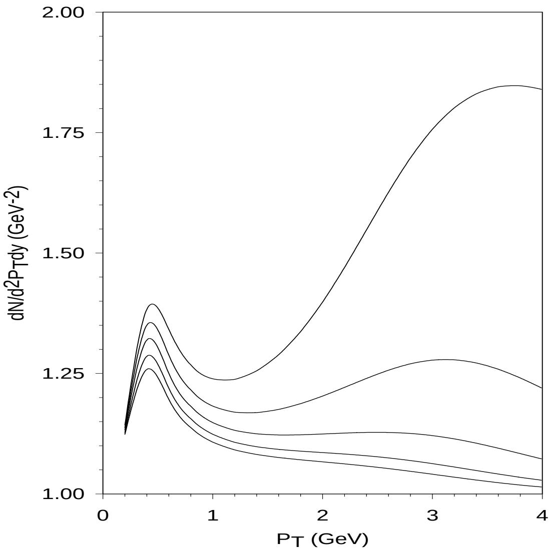

FIG. 1. Ratio of photon yield in QGP scenario obtained with one+two loop rate and one loop rate, for different initial times. The lines, from top to bottom corresponds to τ_i=0.2, 0.4, 0.6, 0.8 and 1 fm. Corresponding initial temperatures are listed in table 1. The lines are drawn with

For $\tau_i \geq .4$ fm or more, the two loop rates contribute to 25% or less to the total yield. Thus for a realistic estimate of photon yield in the QGP scenario, one must consider $\tau_i \geq .4$ fm, when contribution of two loop rate is moderate and even if higher loops contribute to the same order, it will not affect the total yield substantially. Calculations with smaller τ_i could not be relied upon. We thus assume $\tau_i \geq 0.4$fm. As will be shown later, for $\tau_i \geq$ 0.4fm, initially static QGP scenario could not explain the WA98 data. It under predicts them. However, if the fluid is assumed to have certain initial radial velocity, data could be fitted satisfactorily. Indeed, Peressounko et al [8] argued that the WA98 data could be fitted only with some initial radial velocity. Present analysis confirms the result. Source of initial radial velocity could be the collisions among the constituents of the fluid (quarks

and gluons). However, the high p_T photon yield will depend on the type of velocity distribution to be assumed. Peressounko et al [8] used linearly increasing velocity distribution. In an earlier work [9] a Woods-Saxon form for the initial velocity distribution was used. Fig.2, we have shown the computed photon yield for three types of velocity distributions,
(a) Woods-Saxon type of velocity:

$$v_r(r) = v_r^0/(1+exp((r-R_0)/a) \tag{7}$$

(b) Linearly increasing velocity:

$$v_r(r) = \begin{cases} v_r^0 r/R_0, & r \leq R_0 \\ 0 & r > R_0 \end{cases} \tag{8}$$

and (c) surface peaked velocity:

$$v_r(r) = 4v_r^0 exp((r-R_0)/a)/(1+exp((r-R_0)/a))^2 \tag{9}$$

with R_0 =6.4 fm and a =0.54 fm corresponding to Pb nucleus. In these velocity profiles, the parameter v_r^0 is chosen to be the maximum value of the distribution. We should remember that this choice of parametrization is not unique. For example, it may also be normalized to give the same average radial velocity. Due to the ambiguity of the definition of v_r^0, the absolute values of photon yield for each profile in Fig. 2 may change in different normalization, but an important fact is that p_T dependence changes and the high p_T part of the photon spectra is sensitive to the shape of the velocity distribution. Surface peaked velocity distribution is least effective for producing p_T. On the other hand, Saxon-Woods type of velocity profile produces more high p_T photons. Linearly increasing velocity lies in between.

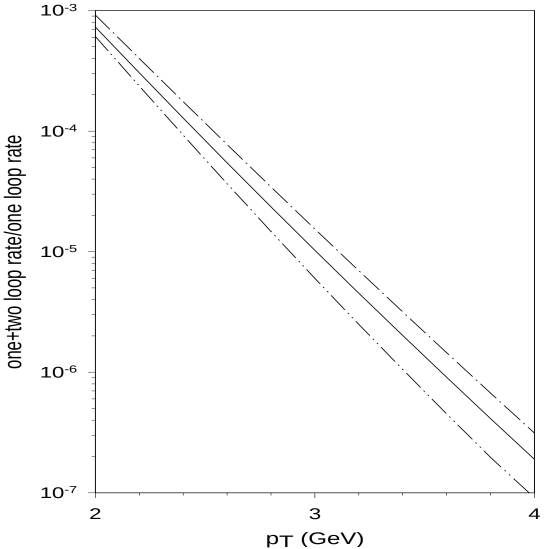

FIG. 2. Photon yield for different types of initial velocity distributions, with v_r^0=0.2c. The dash-dot-dot line is for the surface peaked initial velocity, the dash-dot line is for the Woods-Saxon type of velocity distribution and the solid line is for the linearly increasing velocity profile.

To see the physical picture of these profiles, let us consider some conserving quantity associated to the fluid. Then from the continuity equation for cylindrical symmetric case,

$$\dot{n} + \frac{1}{r}\frac{\partial}{\partial r}(rnv_r) = 0,$$

where n is the density of the conserved quantity. For example, if we take Wood-Saxon type velocity field, at $r \simeq 0$, $v_r \simeq const$, so that

$$\dot{n} \simeq -v_r(0)\left[\frac{n}{r} + \frac{\partial n}{\partial r}\right]$$

near $r \simeq 0$. Except for $n(0) \to 0$ for $r \to 0$, the density variation at the center becomes infinitely large. Thus, the Wood-Saxon type profile represents a detonation at the origin, exploding from the center whole the material outwords. The linear profile corresponds to the homologous expansion of the system, corresponding to a rather mild density change. For example, a typical solution is

$$n \simeq \frac{1}{R^2(t)} f\left(\frac{r}{R(r)}\right),$$

where f is an arbitrary function. On the other hand, when the QGP gas is initially almost at rest, and its surface area is expanding rapidly to the vacuum, similar to the early simple wave stage of the Landau model, then the velocity profile becomes surface peaked. If a nuclear collision generates initially almost static QGP fireball, the fluid velocity may be more surface peaked compared to the linear one.

Before we compare our model prediction with the WA98 experiment, we would like to make few comments on the direct QCD and pre- equilibrium photons. Direct QCD photons are produced from the early hard collisions of partons in the nuclei and in Pb+Pb collisions make significant contribution to the high p_T yield. Gallmeister et al [7] claimed that prompt photons are able to explain the high p_T data in Pb+Pb collisions. Dumitru et al [20] also arrived at a similar conclusion including the nuclear broadening effects. However, this point is still controversial due to uncertainties in prompt photon emission at AA collisions. Thus Alam et al [6] and also Srivastava and Sinha [5] calculated the prompt photon emission for Pb+Pb collisions. It was seen that for p_T >2 GeV, direct QCD photons alone can describe the data within a factor of 3-8 only.

Pre-equilibrium photons are emitted before the establishment of quasi equilibrium. Traxler and Thoma [21] calculated pre-equilibrium photons and found them order of magnitude less than the equilibrium photons. Roy et al [22] also calculated the pre-equilibrium photons.

They used Fokker-Plank equations and found that pre-equilibrium photons are less or at best equal to the equilibrium photons. The results refers to RHIC and LHC energies. At SPS one expects still lower contribution of pre-equilibrium photons. At SPS, the system is far from chemical equilibrium and number of quarks and anti-quarks will be less. Pre-equilibrium photons then can be neglected.

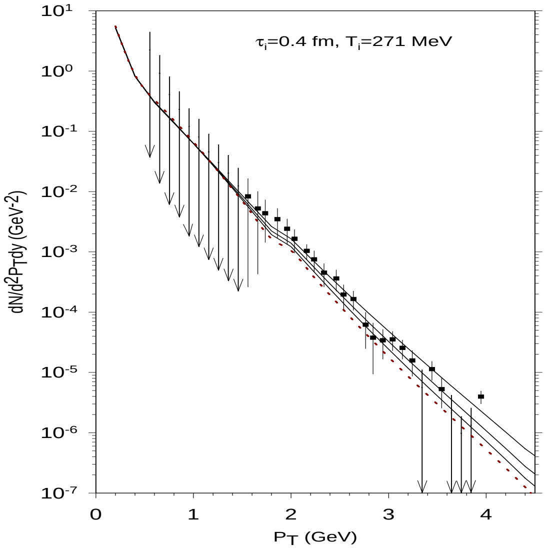

FIG. 3. Thermal plus hard QCD photons compared with WA98 experimental results. The initial time and temperature of QGP is 0.4 fm and 271 MeV respectively. The solid lines are obtained with initial radial velocity 0.2,0.3 and 0.4c (from bottom to top). The dotted line is obtained without any initial radial velocity.

In Fig.3 , we have compared the photon yield obtained in the present model with WA98 experiment. The initial time and temperature are τ_i=0.4 fm and T_i=271 MeV respectively. We have included the hard QCD photons for $p_T > 2$ GeV following Alam et al [6]. Without any initial radial velocity (the dotted line) thermal photons together with hard QCD photons could not explain the data. High p_T part of the data are underestimated by a factor of 5 or more. It is possible to obtain a reasonable fit to data for still lower initial time(e.g. τ_i=0.2 fm, T_i=341 MeV), but as emphasized earlier, the results obtained thus are not reliable. Higher loops (three and more) contributions, which are neglected here may then be significant. When we suppose that the initial temperature is not so high, then the data requires an initial radial velocity in our model. In Fig.3, the solid lines are the photon yield obtained with initial radial velocity with maximum velocity v_r^0=.2,.3,.4c. Here we take the surface peaked initial velocity profile, which corresponds to a scenario of QGP fireball with surface expansion. As expected with initial v_r, high p_T photon yield is increased and we find that the data is well describe if v_r^0 lies in the range of 0.3-0.4c. When we assume more mild QGP gas expansion represented by the linear velocity profile, then these values are little bit smaller. In Fig.4, same results are shown for initial time τ_i=1.0 fm. In this case, without any initial radial velocity, data are more under-predicted. Reasonable agreement with data is obtained again with (surface peaked) initial velocity in the range of v_r^0=0.4-0.5c. The present results are in agreement with the finding of Peressounko et al [8] that the WA98 single photon data require initial radial velocity of the fluid, at least in the surface region.

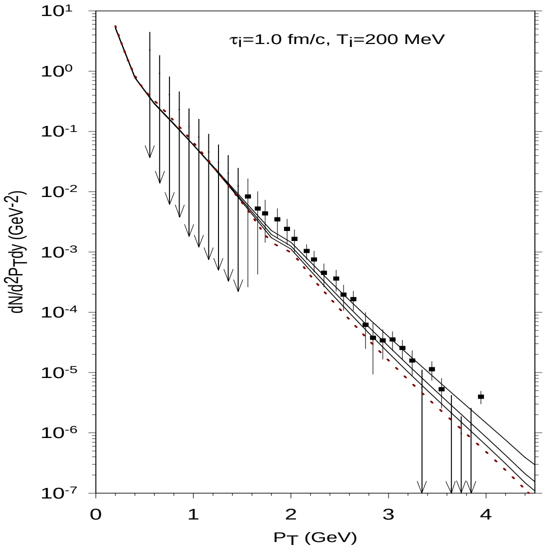

FIG. 4. Thermal plus hard QCD photons compared with WA98 experimental results. The initial time and temperature of QGP is 1.0 fm and 200 MeV respectively. The solid lines are obtained with initial radial velocity 0.3, 0.4 and 0.5c (from bottom to top). The dotted line is obtained without any initial radial velocity.

We now show the prediction for RHIC energy. In Fig.5, we have shown the results obtained for Au+Au collisions at $\sqrt{s}$=130 GeV. The initial time and temperature was assumed to be τ_i=0.5 fm and T_i=300 MeV [23]. The dash-dot line is the hard QCD photons at RHIC energy. p_T broadening effect is ignored. At RHIC energy the effect is not as important as at SPS energy. The dotted lines are the thermal photons obtained for initial radial velocity v_r^0=0,0.3 and 0.5c. Solid lines show the total contribution (thermal and hard QCD photons). It can be seen that for $p_T < 2$ GeV, thermal photons dominate the spectrum. Hard QCD photons dominate at higher $p_T > 4$ GeV. In the intermediate p_T range (2 GeV-4 GeV), thermal photons contribute as copiously as the hard QCD photons. This is the range where initial fluid velocity has considerable effect. Considering the importance of hard QCD photons at RHIC energy, it is of utmost importance to determine experimentally the single photon spectra in pp collisions at RHIC energy. Only then it will be possible to comment on the possible QGP formation at RHIC energy from the single photon data.

To summarize, we have analyzed the recent WA98 single photon data assuming QGP formation in the initial state. It was shown that in order to have a reliable estimate of photon yield, initial time of the hydrodynamic evolution should be larger than 0.4 fm, otherwise neglect of three and higher loops in the photon production rate would be unjustified. They can contribute in the same order as the two loop photon rate (which is more than 70% at high p_T for an initial time of 0.2 fm). As far as $\tau_i \geq 0.4$ fm, then initially static QGP scenario underestimates the high p_T photons compared to the observed data. The data could be fitted only if some kind of initial radial velocity is present. Photon yield depend on the initial velocity distribution, changing by factor of 2-3 at the high p_T , from the surface emission scenario (surface peaked) to the detonation at the center (Woods-Saxon form). WA98 data could be fitted reasonably well if the thermalisation time τ_i, ranges between 0.4-1.0 fm (corresponding to initial temperature between 271-200 MeV), and if the QGP fluid has an initial (surface peaked) radial velocity in the ranges of 0.3-0.5c. The model was applied to predict photon spectra at RHIC energy in Au+Au collisions. It was shown that high p_T spectra is dominated by hard QCD photons. Thermal photons dominate low p_T part of the spectra and in the intermediate range of p_T thermal photons contribute comparably to hard photons. We feel it is important to measure hard QCD photons in pp collisions at RHIC energy. Only then it will then be possible to comment on possible QGP formation from the direct photon data at RHIC.

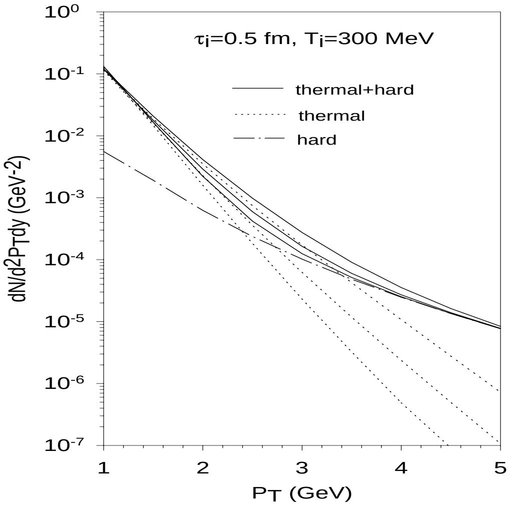

FIG. 5. Theoretical estimate of direct photons at RHIC energy for Au+Au collisions at ß=130 GeV. The dash-dot line is the hard QCD photons. The dotted lines are the thermal photons with initial radial velocity v_r^0=0,0.3 and 0.5c. The solid lines are the total contribution of hard QCD photons and thermal photons.

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TABLE I. The initial temperature of the QGP for certain initial times τ_i. dN/dY was assumed to be 750.

$\tau_i(fm)$	0.2	0.4	0.6	0.8	1.0
$T_i^{QGP}(MeV)$	341	271	237	215	200