Single photons from Pb+Pb collisions at CERN SPS, QGP vs. hadronic gas

A. K. Chaudhuri
Variable Energy Cyclotron Centre
1/AF, Bidhan Nagar, Calcutta - 700 064

In a hydrodynamic model, we have analyzed the direct photon data obtained by the WA98 collaboration in 158 A GeV Pb+Pb collisions at CERN SPS. The transverse expansion of the system was taken into account. Two scenarios, (i) formation of quark-gluon plasma and (ii) formation of hot hadronic gas, were considered. Both the scenarios describe the data equally well. However, hadronic gas scenario requires very high initial temperature (~300 MeV) and it is difficult to conceive existence of hadron gas at that high temperature. If the hadron fluid has small radial velocity (0.2c-0.3c), initially, the data are well explained in the hadronic gas scenario with reasonable initial temperatures.

Recently WA98 collaboration has published their single photon emission data for 158 A GeV Pb+Pb collisions at CERN SPS. Much interest was aroused after the publication of the WA80 preliminary results of the S+Au single photon data. As it was hoped that they can be a conclusive probe of the much debated quark-gluon plasma (QGP), expected to be produced in relativistic heavy ion collisions. The preliminary data were analyzed by several authors. Xiong and Shuryak analyzed the data assuming a mixed phase formation and found excess photons. Srivastava and Sinha analyzed the data considering two possible scenarios after the collision, one with the phase transition to QGP, the other without it. It was claimed that the data were explained only in the phase transition scenario. We had also analyzed the preliminary versions of the WA80 direct photon data. It was shown that formation of viscous hadron gas in the initial state, can explain the data. The revised version of the data were also analyzed by several authors including us. It was concluded that the data are not sensitive enough to discriminate between the two alternate pictures, e.g. formation of quark-gluon plasma and formation of hot hadronic gas.

Several authors have analyzed the recent WA98 single photon data. Peressounko et al concluded that the data could be explained only with a small initial radial velocity. Also the data could not distinguish between a QGP and a hot hadronic gas scenario. Srivastava et al could fit the data in the QGP scenario, without initial radial velocity. But the two loop photon rate used by them was not corrected for a factor of 4. They did not consider the hadronic scenario. They argued that in the pure hadronic scenario, initial temperature of the hadronic fluid will be large. Hadronic density will be ~10 hadrons/fm$^3$. It is unphysical to consider hadronic gas at such a high density. Initial Hadronic scenario was considered in [2]. It was concluded that only hadronic model with medium modification (hadrons were formed with zero mass) could explain the data.

In the present paper we analyze the WA98 single photon data in the no phase transition (NPT) scenario. A hot hadronic gas is assumed to be formed in the initial state. It expands, cools and freezes out at freeze-out temperature ($T_F$). It will be shown that WA98 single photon data could be well explained in this scenario, with reasonable hadron density, if one assumes a small initial fluid velocity. In [11] initial velocity distribution was assumed to be linearly increasing. We assume that at the beginning of one fluid hydrodynamic stage, initial radial velocity follows the distribution of initial energy density, which we assume to be of Woods-Saxon form, with radius and diffuseness parameters, $R = 6.4$fm and $a = 0.54$fm. In [11] hadronic equation of state comprises all the hadrons in the particle data book. We choose to use hadrons up to mass 2 GeV. The cut off is arbitrary. The resulting equation of state is reasonably well described by $p_h = a_h T^4$, with $a_h = 59.5 \pi^2/90$. Fig.1 compares the analytic expression with numerical results. Analytic expression overestimate the pressure in the temperature region of 200-400 MeV. However, we have used the analytic expression only to obtained the initial temperature of hadron gas, and the error introduced due to the approximation is around 10-15%. To be complete, we also analyze the data in the phase transition (PT) scenario, when QGP is formed in the initial state. 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 bag constant $B$ was obtained from the Gibbs condition $p_{QGP}(T_c) = p_{had}(T_c)$.

We solve the hydrodynamic equations $\partial_\mu T^{\mu\nu} = 0$ in 3+1 dimension assuming cylindrical symmetry and boost-invariance in the longitudinal direction. The relevant equations are well known and are not reproduced here. The inputs of the hydrodynamic equations are the initial energy density or temperature ($T_0$) and radial velocity ($v(r)$) at (proper) time $\tau_i$. $\tau_i$ is the thermalisation time beyond which hydrodynamics became applicable. For a given $\tau_i$ the initial temperature $T_i$ of the fluid (hadronic gas or QGP) can be obtained by relating the entropy density with the observed pion multiplicity (assuming pion decoupling to be adiabatic).

$$T_i^{3 \tau_i} = \frac{1}{\pi R_A^2} \frac{c}{a_0} \frac{dN}{dy} (b=0)$$

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).
the following processes, considerably. Initial small radial velocity can affect the photon spectra that the fluid (QGP or hadronic gas) possess some small colors of quarks. For 3 flavor quarks, the constant $c$ is evaluated by them as, $c = 1 - 2/\pi$. 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) $\pi\rho \rightarrow A_1 \rightarrow \pi\gamma$ for which are well known \[13,14\].

Rate of production of hard photons from QGP were evaluated by Kapusta et al \[7\]. To one loop order, \[ E \frac{dR}{d^3p} = \frac{1}{2\pi^2} \alpha_s \sum_f c_f^2 T^2 e^{-E/T} \ln(\frac{E}{\alpha_s T}) \tag{2} \]

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

Recently Aurencche et al \[13\] evaluated the production of photons in a QGP. At two loops level Bremsstrahlung photons ($q\bar{q}(g) \rightarrow q\bar{q}(g)\gamma$) found to be dominating the compton and annihilation photons. However, their calculations overestimated the photon yield by a factor of 4 \[15,16\].

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

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

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,

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

and the poly-logarithm functions $Li_n$ are given by,

\[ Li_n(z) = \sum_{n=1}^{\infty} \frac{z^n}{n^n} \tag{5} \]

Aurencche et al \[18\] also calculated the contribution of the $q\bar{q}$ with scattering, which was also overestimated by the same factor of 4. The corrected rate is,

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

We would like to mention that two loop photon rate from QGP is not complete. Higher loops contribute to the same order \[23\]. Also Landau-Migdal-Pomeranchuk effect been neglected \[22\].

Before we present our results we would like to make a brief comment on the direct QCD 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 \[20\] claimed that prompt photons are able to explain the high $p_T$ data in Pb+Pb collisions. Dumitru et al \[23\] 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 \[3\] and also Srivastava and Sinha \[8\] 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 3-8 only.

We first present the photon spectra obtained in the phase transition scenario. As in ref. \[8\] we assume the critical temperature to be $T_c = 180 \text{ MeV}$. Data were found to be insensitive to the exact value of $T_c$. The initial radial velocity ($v^{ini}_{\tau}$) was assumed to be zero. In fig.2, computed photon spectra for different initial times $\tau_i = 2, 4, 6$ and 8 fm, with one+two loop order rates are shown. In the inset of Fig.1, we have compared the photon yield obtained with one loop rate and one+two loop rate. For initial time $\tau_i = 0.2$ fm, two loop contribution is more than 50% at large $p_T$. Higher loop contributing to the same order, photon rates, are not complete. But for $\tau_i > 0.2 \text{ fm}$, two loop contribution is quite less and the rates can be regarded more or less complete. We find that with corrected photon rate, QGP scenario, unlike in ref. \[8\], do not describe the data well. In \[8\], photon rates were not corrected for the factor of 4. With correct photon rate, yield is reduced by a factor of 2, compared to uncorrected rate. Consequently, while Srivastava et el \[8\] found very good fit to data for $\tau_i$-0.2 fm, presently data are underestimated by the similar factor of 2. For higher thermalisation times, the data are further underestimated particularly at high $p_T$ side. The initial temperatures are low enough to produce requisite number of high $p_T$ photons. In fig.2, the dotted line shows the contribution of direct QCD photons, as calculated by Alam et al \[8\]. For $\tau_i > 0.2 \text{ fm}$, the hard QCD photons contribute more than the thermal photons. It is evident that for thermalisation time $\tau_i=0.2 \text{ fm}$, thermal photons together with hard QCD photons describe the data satisfactorily. For higher thermalisation times, thermal photons together with hard QCD photons underpredict the
data. We do not elaborate on this scenario. Just a few comments are in order. The equation of state of the hadronic sector now consists of hadrons with mass less than 2 GeV, while in ref. 3 hadrons with mass less than 2.5 GeV were included. The other difference is the initial energy density profile. Srivastava and Sinha assumed the initial energy density profile to follow the wounded-nucleon distribution, while we have used the standard Woods-Saxon profile. Despite these differences, our results are very similar to the results obtained in 3. The data are not sensitive enough to the details of the calculations. The data can not distinguish whether hadronic sector comprised with hadron with mass less than 2.5 GeV or with mass less than 2 GeV. Also, the data are insensitive to the details of initial energy density profile so long they are not very different. May be at RHIC or insensitive to the details of initial energy density profile. The data can not distinguish whether hadronic gas is assumed to be formed in the LHC energy, data will be sensitive on these details.

It would seem that though in NPT scenario good description of data is obtained, physical consideration (i.e. very high hadron density) will render that picture unacceptable. In the calculation presented till now, the initial radial velocity \( v_{r}^{ini} \) of the fluid was assumed to be zero. However it is possible that at initial time \( \tau_{i} \) the fluid has some small radial velocity \( v_{r}^{ini} \). Several authors 4, 11 have used initial velocity to fit the direct photon data. Source of \( v_{r}^{ini} \) may be the collisions among the constituents, which lead to the local equilibrium. Peresounko et al 25 used the high \( p_{T} \) component above 2 GeV in the \( \pi^{0} \) spectrum to argue for it. However, argument in favor of initial fluid velocity is weak. High \( p_{T} \) part of the spectrum might have come from hard processes 26. Also several hydrodynamical calculations, with out initial velocity, could explain a host of experimental data 27, 28. Apparently large \( p_{T} \) data require a initial fluid velocity.

In fig.4, we have shown the photon spectra in the hadronic gas scenario with initial fluid velocity \( v_{r}^{ini} = 0.2 \) fm, when the initial temperature \( \tau_{i} = 0.6 \) fm. \( v_{r}^{ini} \) had considerable effect on photon spectra. It enhances the \( p_{T} \). Good fit to data is obtained for \( v_{r}^{ini} = 0.3c \). It is also obvious that with \( v_{r}^{ini} \) in the ranges of 0.2 \(-\) 0.3c, it will be possible to fit the WA98 data in a hadronic gas scenario with physically acceptable initial time and temperature.

Good fit to the data with small initial velocity bring back the hadronic gas scenario into contention. It is no longer possible to say that the WA98 data indicate quark-gluon plasma formation only.

Initial fluid velocity will also affect the photon spectra in the phase transition scenario. As shown here in this scenario, WA98 data are underpredicted with initial time \( \tau_{i} > 0.2 \) fm. It will be possible to fit the data with \( \tau_{i} > 0.2 \) fm, if small initial velocity is assumed. In ref. 3, a good fit to data was obtained for \( \tau_{i} = 1 \) fm and initial velocity in the ranges 0.2 \(-\) 0.3c.

To summarize, we have analyzed the recent WA98 single photon data using a hydrodynamic model. Two scenarios were considered, the phase transition scenario where a QGP is formed in the initial state, and the no phase transition scenario where hot hadronic gas is formed initially. Both the scenarios gave good description to the data. QGP scenario require that the initial time and temperature of the QGP is 0.2 fm and 340 MeV respectively. The hadronic gas scenario also require an initial time of 0.2 fm and temperature of 304 MeV. As the hadron density is very large at this temperature, it would seem that the data is described by QGP only. However, it was shown that with small initial radial velocity in the range 0.2c \(-\) 0.3c, the WA98 data can be well described.
in the hadronic scenario with reasonable initial temperature. The present analysis thus suggests that the WA98 single photon data are not conclusive. It cannot discriminate between two alternate scenarios currently in vogue.

TABLE I. The initial temperature of the QGP and the hot hadronic gas for different initial times $\tau_i$. Also shown are the corresponding hadron density $\rho_{\text{Had}}$.

| $\tau_i$ (fm) | $T_{i,QGP}^{(\text{MeV})}$ | $T_{i,Had}^{(\text{MeV})}$ | $\rho_{i,Had}^{(f m^{-3})}$ |
|--------------|----------------|----------------|----------------|
| 0.2          | 341            | 304            | 10.41          |
| 0.4          | 271            | 242            | 2.89           |
| 0.6          | 237            | 211            | 1.32           |
| 0.8          | 215            | 192            | 0.78           |
| 1.0          | 200            | 178            | 0.52           |

[1] M. M. Aggarwal et al, WA98 collaboration, Phys. Rev. Lett. 85, 3595 (2000).
[2] R. Santo et al, in Proceedings of the Tenth International conference on Ultra-Relativistic Nucleus-Nucleus collisions, Borlange, Sweden, 20-24 June, 1993, edited by E. Stenhund, H. A. Gustafsson, A. Oskarsson and I. Otterlund [Nucl. Phys. A566, 61c (1994)] R. Santo et al., Report no. IKP-MS-93/0701, Muenster, 1993.
[3] E.V. Shuryak, L. Xiong, Phys. Lett. B 333, 316 (1994).
[4] D. K. Srivastava and B. Sinha, Phys. Rev. Lett. 73, 2421 (1994).
[5] A. K. Chaudhuri, Phys. Rev. C51, R2889 (1995).
[6] R. Albrecht et al, Phys. Rev. Lett.76, 3506 (1996).
[7] A. K. Chaudhuri, Phys. Scr. 61, 311 (2000).
[8] D. K. Srivastava and B. Sinha, nucl-th/0006018, Phys. Rev. C64, 034902 (2001).
[9] Jan-e Alam, S. Sarkar, T. Hatsuda, T. K. Nayak and B. Sinha, Phys. Rev. C63, 021901 (2001).
[10] K. Gallmeister, B. Kampfer and O. P. Pavlenko, Phys. Rev. C62, 057901 (2000).
[11] D.Y. Peressounko and Yu. E. Pokrovsky, hep-ph/0002063.
[12] H. von Gersdorff, M. Kataja, L. McLerran and P. V. Ruuskanen, Phys. Rev. D34, 794 (1986).
[13] Jan-e Alam, D.K. Srivastava, B. Sinha and D.N. Basu, Phys. Rev. D 48, 1117 (1993).
[14] R. C. Hwa and K. Kajantie, Phys. Rev. D 32, 1109 (1985).
[15] H. Nadeau, J. Kapusta and P. Lichard, Phys. Rev. C 45, 3034 (1992).
[16] L. Xiong, E. Shuryak and G. E. Brown, Phys. Rev. D46, 3798 (1992).
[17] J. Kapusta, P. Lichard and D. Seibert, Phys. Rev. D 44, 2774 (1991).
[18] P. Aurenche, F. Gelis, H. Zaraket and R. Kobes, Phys. Rev.D 58, 085003 (1998).
[19] P. Aurenche, private communication.
[20] P. D. Steffen and M. A. Thoma, hep-ph/0103044.
[21] P. Aurenche, F. Gelis, H. Zaraket, Phys. Rev. D61, 116001, 2000.
[22] P. Aurenche, F. Gelis, H. Zaraket, Phys. Rev. D62, 096012, 2000.
[23] A. Dumitru, L. Frankfurt, L. Gerland, H. Stocker and M. Strikman, hep-ph/0103203.
[24] C. T. Traxler and M. H. Thoma, Phys. Rev. C53(1996)1348.
[25] P. Roy, J. Alam, S. Sarkar, B. Sinha and S. Raha, Nucl. Phys. A624 (1997)687.
[26] X. N. Wang, Nucl. Phys. A661(1999)609.
[27] P. Huovinen, P. V. Ruuskanen and J. Solfrank, Nucl. Phys. A650(1999)227.
[28] P. Kolb, J. Sollfrank, P. V. Ruuskanen and U. Heinz, Nucl. Phys. A661(1999)349c.
[29] P. F. Kolb, J. Sollfrank, U. Heinz, hep-ph/0006129, Phys. Rev. Lett. 62, 054909 (2000).
FIG. 1. Pressure as a function of temperature for the hadronic gas comprising hadrons with mass less than 2 GeV. The solid line is a fit using $a_hT^4$, $a_h = 59.5$.

FIG. 2. The single photon yield in the phase transition scenario for four different initial times, $\tau_i$'s, $0.2, 0.4, 0.6, 0.8$ fm (from top to bottom). Corresponding temperatures are listed in table 1. Experimental points are also shown. The dotted line is the direct QCD photons calculated in ref. [9]. In the inset, we have compared the photon yield obtained with one loop rate (dashed lines) with the one+two loop rate.

FIG. 3. The single photon yield in the no phase transition scenario for four different $\tau_i$'s, $0.2, 0.4, 0.6, 0.8$ fm (from top to bottom). Corresponding temperatures are listed in table 1. Experimental points are also shown. The dotted line is the direct QCD photons calculated in ref. [9].

FIG. 4. The single photon yield in the no phase transition scenario for four different initial radial velocities $v_{ini} = 0, 0.1, 0.2, 0.3$ (in units of c). The initial time and temperatures are $\tau_i = 0.6$ fm and $T_i = 211$ MeV respectively. The dotted line is the direct QCD photons calculated in ref. [9].