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

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In a hydrodynamic model, we have analysed 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. Equally well description to the data were obtained in both the scenarios. However, hadronic gas scenario require very high initial temperature ($\sim$ 300 MeV) and it is difficult to conceive existence of hadron gas at that high temperature. If the hadronic fluid has small radial velocity (0.2c-0.3c) initially, the data are well explained in the hadronic gas scenario with reasonable initial temperatures.

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Recently WA98 collaboration has published their single photon emission data for 158 A GeV Pb+Pb collisions at CERN SPS [1]. Much interest was aroused after the publication of the WA80 preliminary results of the S+Au single photon data [2], as it was hoped that the 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 analysed by several authors. Xiong and Shuryak [3] analysed the data assuming a mixed phase formation and found excess photons. Srivastava and Sinha [4] analysed 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 analysed the preliminary version of the WA80 direct photon data [5]. It was shown that formation of *viscous* hadron gas in the initial state, can explain the data. The revised version of the data [6] were also analysed by several authors including us [7]. 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.

The recent WA98 single photon data were analysed meticulously by Srivastava and Sinha [8]. Data were found to be excellently described in a QGP formation scenario. One important difference from earlier SPS photon data was noticed. WA98 data prefer a thermalisation time of $\sim$ .2 fm, rather than the canonical 1 fm. They did not consider the alternate scenario i.e. that of hadronic gas formation in the initial state. They argued that in the pure hadronic scenario, initial temperature of the hadronic fluid will be large. Hadronic density will be $\sim$ 10 hadrons/fm^3. It is unphysical to consider hadronic gas at such a high density.

In the present paper we analyse 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. To be complete, we also analyse the data in the phase transition (PT) scenario, when QGP is formed in the initial state. Initial QGP expands, cools undergoes 1st order phase transition at critical temperature (T_c), enters a mixed phase, remain in the mixed phase till all the quark matter is converted into a hadronic matter then cools to freeze-out temperature. As told earlier WA98 data were analysed in this scenario [8]. However, we will have minor differences from their model e.g. the initial energy density profile and the hadronic equation of state. Srivastava and Sinha used hadronic equation of state comprising all the hadrons with mass less than 2.5 GeV. In the present calculation, hadronic equation of state was generalised to include hadrons with mass less than 2 GeV. The cut-off mass (2 GeV) is purely arbitrary. The equation of state for hadronic gas comprising hadrons with mass less the 2 GeV can be 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. 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 $p_{QGP}(T_c) = p_{had}(T_c)$. The initial energy density profile was assumed to follow wounded nucleon distribution in ref. [8]. However we choose to use conventional Woods-Saxon distribution with appropriate central density. As will be shown, the WA98 data are not sensitive enough to distinguish finer details of the calculations.

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 [9,10] and are not reproduced here. The input of the hydrodynamic equations are the initial energy density or temperature (T_i) and radial velocity (v_r^{ini}) at (proper) time τ_i. τ_i is the thermalisation time beyond which hydrodynamics became applicable. For a given τ_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) [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., we have shown the initial temperatures as obtained from eq.1 in the two considered scenarios, the QGP and the hot hadronic gas. dn/dY was assumed to be 750. It can be seen, in both the scenarios, initial temperatures are comparable. Corresponding hadron density are also shown in table 1.. For τ_i=0.2 and 0.4 fm, it is $\sim$ 10 and 2.9 hadrons per fm^{-3} respectively. It is unlikely than at such high density hadrons can retain their identity. For larger τ_i, initial temperatures are comparatively small and the densities have acceptable values. The other parameter for the hydrodynamic evolution with transverse expansion is the initial radial velocity v_r^{ini}. It is customary to assume that the initial v_r^{ini}=0. However, it is possible that the fluid (QGP or hadronic gas) possess some small radial velocity at initial time τ_i. As will be shown here, initial small radial velocity can affect the photon spectra considerably.

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,

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

where the constant $c \sim 0.23$. The summation runs over the flavours 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 was evaluated by them as,

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

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

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

and the poly-logarith functions Li are given by,

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

Aurenche et al also calculated the contribution of the $q\bar{q}$ with scattering,

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

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 MeV. Data were found to be insensitive to the exact value of T_c. The initial radial velocity (v_r^{ini}) was assumed to be zero. In fig.2, computed photon spectra for different initial times τ_i=.2,.4,.6 and .8 fm are shown. Also shown is the WA98 data. We find that for thermalisation time of .2 fm, the QGP scenario describe the data excellently well. For higher thermalisation times, the data are not well described particularly at high p_T side. The initial temperatures are low enough to produce requisite number of high p_T photons. As expected the results are similar to those obtained by Srivastava and Sinha [8]. We donot 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. [8] 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, very good fit to data indicate that 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 LHC energy, data will be sensitive on these details.

The results obtained in the no phase transition scenario, when hadronic gas is assumed to be formed in the initial state are presented in fig.3. We have presented photon spectra for different initial times, τ_i=.2,.4,.6,.8 fm. For τ_i=0.2 fm, hadronic gas scenario describe the data very well. For higher thermalisation times, the description gets poorer specially in the high p_T sector. The results are not surprising. As told earlier, with resonance hadronic gas, the degrees of freedom are comparable to the QGP. Thus initial temperatures are nearly same either in hadron gas or in QGP. It was noted quite early that hard photon production rate are nearly same in hadronic gas or in QGP [14]. It would seem that the WA98 single photon data equally well described in PT as well as NPT scenario. However, existence of hadronic gas at a temperature of 300 MeV is extremely unlikely. At this temperature, hadron density is very large $\sim 10 fm^{-3}$. It is unlikely that at such a high density hadrons can retain their identity. Hadronic gas scenario at such a high density is unphysical. For higher thermalisation time τ_i=0.6 fm, when the initial temperature and density are 211 MeV and 1.3 hadrons per fm^{-3}, though the scenario is physical, the data gets underpredicted.

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 τ_i the fluid has some small radial velocity v_r^{ini}. Source of v_r^{ini} may the collisions among the constituents, which lead to the local equilibrium. In fig.4, we have shown the photon spectra in the hadronic gas scenario with initial fluid velocity v_r^{ini}=0,.1,.2,.3 (in units of c) for initial temperature of T_i=211 MeV corresponding to initial time τ_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.

To summarise, we have analysed 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 are 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 can not 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 τ_i. Also shown are the corresponding hadron density

$\tau_i(fm)$	$T_i^{QGP}(MeV)$	$T_i^{Had}(MeV)$	$\rho_i^{Had}(fm^{-3})$
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

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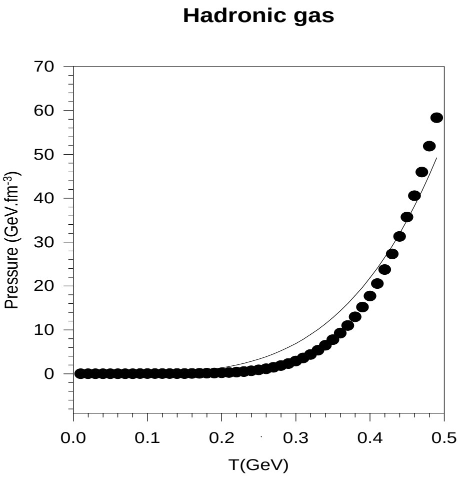

FIG. 1. Pressure as a function of temperature for th hadronic gas comprising hadrons with mass less than 2 GeV The solid line is a fit using $a_h T^4$, $a_h = 59.5$.

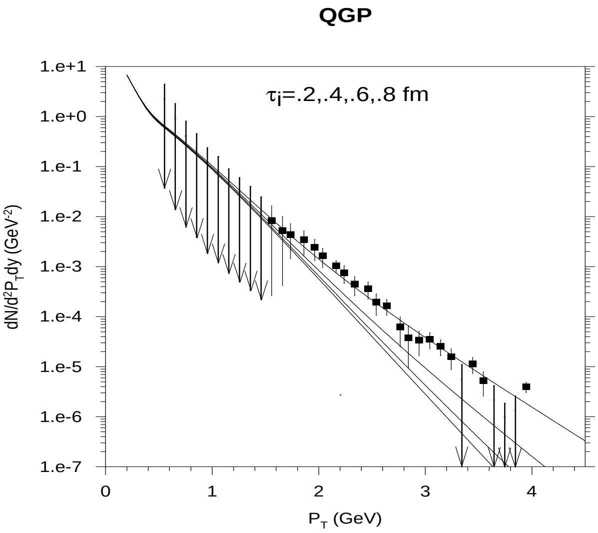

FIG. 2. The single photon yield in the phase transitio scenario for four different initial times, τ_i's, .2,.4,.6,.8 fm (fro top to bottom). Corresponding temperatures are listed i table 1. Experimental points are also shown.

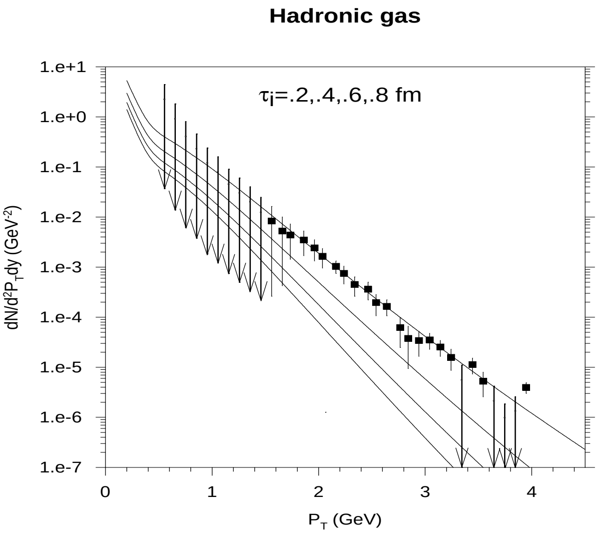

FIG. 3. The single photon yield in the no phase transition scenario for four different τ_i's, .2,.4,.6,.8 fm (from top to bottom). Corresponding tempertures are listed in table 1. Experimental points are also shown.

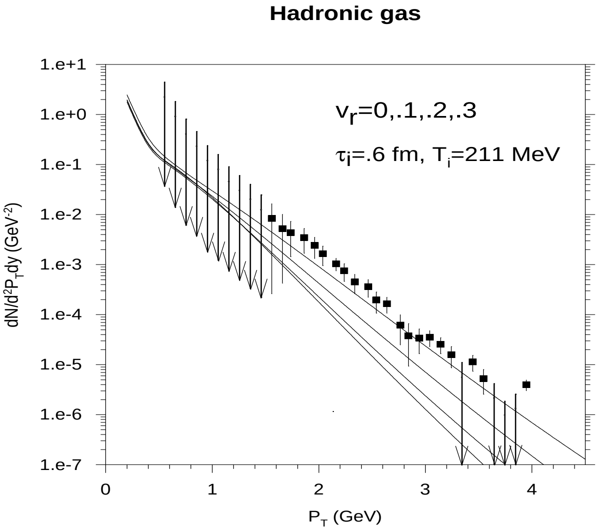

FIG. 4. The single photon yield in the no phase transition scenario for four different initial radial velocityv_r^{ini}=0,.1,.2,3 (in units of c). The initial time and temperatures are τ_i=.6 fm and T_i=211 MeV respectively.