Photons from Nucleus-Nucleus Collisions at Ultra-Relativistic Energies

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Abstract. We compare the photon emission rates from hot hadronic matter with in-medium mass shift and Quark Gluon Plasma (QGP). It is observed that the WA98 data can be well reproduced by hadronic initial state with initial temperature $T = 200$ MeV if the universal scaling of temperature dependent hadronic masses are assumed and the evolution of temperature with time is taken from transport model or (3+1) dimensional hydrodynamics. The data can also be reproduced by QGP initial state with similar initial temperature and non-zero initial radial velocity.

INTRODUCTION

Ultra-Relativistic collisions of heavy nuclei have brought us within reach of creating and studying various aspects of quark-gluon plasma (QGP), which so far was believed to exist in the microsecond old universe or possibly in the cores of neutron or quark stars. We are at a very interesting situation in this area of research where the Super Proton Synchrotron (SPS) era has drawn to a close and the first results from the Relativistic Heavy Ion Collider (RHIC) have started to appear. Already from the results of the Pb run at the SPS quite a few of the signatures of QGP, e.g., $J=\Psi$ suppression, strangeness enhancement etc., are reported to have “seen” unmistakable hints of the existence of QGP [1]. Electromagnetic probes, viz., photons and dileptons have long been recognized as the most direct probes of the collision [2]. Owing to the nature of their interaction they undergo minimal scatterings and are by far the best markers of the entire space-time evolution of the collision.

The single photon data obtained from Pb-Pb collisions at CERN SPS reported by the WA98 Collaboration [3] have been the focus of considerable interest in recent times. Here we emphasize the effects of in-medium modifications of hadrons on the photon spectra considering the fact that as yet it has not been possible to explain the observed low-mass enhancement of dileptons measured in the Pb+Au as well as S+Au collisions at the CERN SPS in a scenario which does not incorporate in-medium effects on the vector meson mass (see [4] for a review).

Let us first identify the possible sources of “excess” photons above those coming from the decays of pseudoscalar $\pi^0$ and $\eta$ mesons, as provided by the data. Firstly, one has the prompt photons coming from the hard collisions of initial state partons in the colliding nuclei. These populate the high transverse momentum region and can be estimated by perturbative QCD. The thermal contribution depends on the space-time evolution scenario that one considers. In the event of a deconfinement phase transition, one first has a thermalized QGP which expands and cools, reverts back to hadronic matter, again expands and cools and eventually freezes out into hadrons most of which are pions. Photon emission in the QGP occurs mainly due to QCD annihilation and Compton processes between quarks and gluons. In order to estimate the emission from the hadronic matter we will consider a gas of light mesons viz. $\pi$, $\rho$, $\omega$, $\eta$ and $a_1$.

It has been emphasized by several authors that the properties of vector mesons may change appreciably because of interactions among the hadrons at high temperatures and/or densities (see [5] for review). This modifies the rate of photon emission as well as the equation of state (EOS) of the evolving matter. Among various models for vector mesons available in the literature [6], we examine the following possibilities for the hadronic phase in this work: (i)
no medium modifications of hadrons, and (ii) the scenario of the universal scaling hypothesis of the vector meson masses [7]. In principle, we can think of a third scenario (iii) the large collisional broadening of the vector mesons [4]. Both (ii) and (iii) can reproduce the enhancement of the low-mass dileptons measured by CERES Collaboration at CERN SPS, but the scenario (iii) has been found to have a negligible effect on the emission rate of photons [6]. The effect of temperature dependent mass as described in case (ii) has also been incorporated in the EOS of the hadronic matter undergoing a (3+1) dimensional expansion.

There is still substantial debate on the order of the phase transition as well as the value of the critical temperature \((T_c)\). To address this aspect we will also consider a scenario where the system begins to evolve from a high temperature phase where all the hadronic masses approach zero (pion mass is fixed at its vacuum value). As the system expands and cools, the hadrons acquire masses (as in case (ii) above) till freeze out. Incorporation of medium modified masses and the EOS in this case also provides a reasonable explanation of the data.

**PHOTON PRODUCTIONS**

We begin our discussions with the prompt photon. The prompt photon yield for nucleus-nucleus collision is given by,

\[
E \frac{dN}{d^3p} = \frac{n(\phi)}{\sigma_{in}} E \frac{d\sigma_{pp}}{d^3p}
\]

where \(n(\phi)\) is the average number of nucleon-nucleon collisions at an impact parameter \(b\) \((n(\phi) \sim 3 \text{ fm})\) 660) as shown in Fig. 1 (see [8] for details) and \(\sigma_{in} \sim 30 \text{ mb}\) is the \(p\) \(p\) inelastic cross section.

![Figure 1](image-url)  
**FIGURE 1.** Hadron multiplicity (long-dashed), effective number of nucleon-nucleon collisions (dotted) and initial temperature (solid) as a function of impact parameter calculated by using Glauber model for nucleus - nucleus collisions at SPS energies (see [8] for details).

The prompt photon contributions have been evaluated with possible intrinsic transverse motion of the partons [9, 10] inside the nucleon and multiplied by a \(K\)-factor 2, to account for the higher order effects. The CTEQ(5M) parton distributions [11] are used for evaluating hard photons. The relevant value of \(\sqrt{s}\), energy in the centre of mass for WA98 experiment is 17.3 GeV. No experimental data on hard photons exist at this energy. Therefore, the “data” at \(\sqrt{s} = 17.3\) GeV is obtained from the data at \(\sqrt{s} = 19.4\) GeV of the E704 collaboration [12] by using the scaling relation: \(E d\sigma = d^3p \gamma_{h_1+h_2} \gamma_{C+\gamma} = f(x_T = 2p_T = \sqrt{s}) = \gamma_{C+\gamma}\). This scaling is valid in the naive parton model. However, such scaling may be spoiled in perturbative QCD due to the reasons, among others, the momentum dependence of the strong coupling, \(\alpha_s\), and from the scaling violation of the structure functions, resulting in faster decrease of the cross section than \(1 = \gamma_{C+\gamma}\). Therefore, the data at \(\sqrt{s} = 17.3\) GeV obtained by using the above scaling gives a conservative estimate of the prompt photon contributions. The broadening of the intrinsic transverse momentum of the partons can play an important role both for photon [13] and neutral pion spectra [14] in nuclear collisions. We have neglected this effect here.

To evaluate the photon yield from quark gluon plasma we consider the QCD Compton, annihilation, bremsstrahlung and \(q\overline{q}\) annihilation with scattering processes [15]. To estimate the photon yield from the hadronic matter (HM) (see
first of [15] and [16]), we have considered the reactions, $\pi p \rightarrow \pi\gamma, \pi\pi, \rho\gamma, \rho\pi, \eta\gamma, \pi\eta$, $\rho\gamma$ and the decays $\pi\pi\gamma$ and $\omega \rightarrow \pi\gamma$. The invariant amplitudes for all these processes are given in Refs. [15]. Photon production due to the process $\pi p \rightarrow a_1, \pi\gamma$ is also taken into account.

To consider the effect of the spectral modifications of hadrons we adopt two extreme cases: (i) no medium modifications of hadrons, and (ii) the scaling hypothesis with $\lambda = 1=2$. In case (ii), the parametrization of in-medium masses (denoted by $m_\pi^m$) at finite $T$ is

\[
\frac{m_\pi}{m_\pi^m} = 1 + \frac{T^2}{T_c^2} \lambda;
\]

where $V$ stands for vector mesons. Mass of the nucleon also varies with temperature as Eq. (2). In this case the width remains constant to its vacuum value.

In (iii) the variation of the width of the vector meson ($\rho$) with temperature is taken as,

\[
\Gamma_\rho = \Gamma_\rho = (1 + T^2/T_c^2) \lambda;
\]

and the mass remains constant to its vacuum value. A fourth case (iv) could be the one in which both the mass and width of $\rho$ varies according to Eqs. 2 and 3.

**SPACE-TIME EVOLUTION**

We will assume that the produced matter reaches a state of thermodynamic equilibrium after a proper time $1$ fm/c [17]. If a deconfined matter is produced, it evolves in space and time till freeze-out undergoing a phase transition to hadronic matter in the process. We will discuss two different models for the description of the space time evolution:

(I) the (3+1) dimensional hydrodynamic equations solved numerically by the relativistic version of the flux corrected transport algorithm [18], assuming boost invariance in the longitudinal direction [17] and cylindrical symmetry in the transverse plane. The effects of the temperature dependent hadronic masses have been taken into account in the EOS through the effective statistical degeneracy [6]. The initial temperature $T_i$ can be related to the multiplicity of the event $dN=dy$ by virtue of the isentropic expansion as,

\[
\frac{dN}{dy} = \frac{45t(3)}{2\pi^4} R^3 \langle \pi \rangle^4 4 \lambda \tau_i
\]

where $R_A$ is the initial radius of the system, $\tau_i$ is the initial thermalization time and $\lambda_k = \frac{\sqrt{k^2}}{90} g_k$; $g_k$ being the effective degeneracy for the phase $k$ (QGP or hadronic matter). The value of $dN=dy$ is 700 for impact parameter $b = 3$ fm (see Fig. 1) The bag model EOS is used for the QGP phase. $g_H$ ($'t'$), the statistical degeneracy of the hadronic phase, composed of $\pi, p, \omega, \eta, a_1$ and nucleons is a temperature dependent quantity in this case and plays an important role in the EOS [6]. As a consequence of this the square of sound velocity, $c_s^2 = \langle \langle T' = T_H \rangle \rangle' \langle \langle g_H = dT \rangle \rangle + 3) < 1=3$, for the hadronic phase, indicating non-vanishing interactions among the constituents. The hydrodynamic equations have been solved with initial energy density, $\epsilon (\tau, \rho)$ [18], obtained from $T_i$ through the EOS. We use the following relation for the initial velocity profile,

\[
\nu_r = \nu_0 \frac{r}{R_A} \delta
\]

For our numerical calculations we choose $\delta = 1$ and sensitivity of the results on $\nu_0$ will be shown.

(II) The integration over the space time history has also been performed by taking the temperature profile from the transport model [20],

\[
T (\tau) = \langle T_i \rangle, \quad T_{\infty} e^{\tau - \tau_c} + T_{\infty}
\]

The calculation is performed for $T_i = 200$ MeV, $T_{\infty} = 120$ MeV, $\tau = 8$ fm/c.

**RESULTS AND DISCUSSIONS**

First we consider the QGP initial state at a temperature $T_i = 196$ MeV. The values of the of the critical temperature $T_c$ and the freeze-out temperature $T_f$ are taken as 160 and 120 MeV respectively. In Fig. 2 (left), results for the total photon emission is shown for three different values of the initial transverse velocity with medium effects as in case
(ii). All the three curves represent the sum of the thermal and the prompt photon contribution which includes possible finite $k_T$ effects of the parton distributions. The later, shown separately by the dot-dashed line also explains the scaled $p_p$ data from E704 experiment [12]. We observe that the photon spectra for the initial velocity profile given by Eq. (5) with $v_0 = 0.3$ explains the WA98 data reasonably well. It is found that a substantial fraction of the photons come from mixed and hadronic phase. The contribution from the QGP phase is small because of the small life time of the QGP (1 fm/c).

The last statement together with the current uncertainty of the critical temperature $T_c$ [19] poses the following question: Is the existence of the QGP phase essential to reproduce the WA98 data? To study this problem, we have considered two possibilities: (a) pure hadronic model without medium-modifications, and (b) pure hadronic model with scaling hypothesis according to Eq.(2). In the former case, $T_i$ is found to be $250$ MeV for $\tau_i = 1$ fm/c and $dN/dy = 700$, which appears to be too high for the hadrons to survive. Therefore this possibility should be excluded. On the other hand, the second case with an assumption of $T_i = T_c$ (which is for simplicity) leads to $T_i = 200$ MeV, at $\tau_i = 1$ fm/c, which is not unrealistic. In this case, the hadronic system expands and cools and ultimately freezes out at $T_f = 120$ MeV. The masses of the vector mesons increase with reduction in temperature (due to expansion) according to Eq.(2). The results of this scenario for zero initial radial velocity (including the prompt photon contribution) are shown in Fig. ?? (right, solid curve). The experimental data is well reproduced in this case also. This indicates that a simple hadronic model is inadequate. Either substantial medium modifications of hadrons or the formation of QGP in the initial stages is necessary to reproduce the data. It is rather difficult to distinguish between the two at present.

In Fig. 2 (right) the $p_T$ distribution of photons (prompt+thermal) is compared with the WA98 data, within the framework of the transport model, the data is well reproduced when the hadronic masses are allowed to vary according to the Eqs. 2 (long-dash line). Photon spectra for scenarios (iv) and (ii) give similar results and hence (iv) is not shown separately. However, when scenario (iii) is considered for thermal photons the experimentally observed “excess” photon in the region $1.5 \ p_T \ (GeV) \ 2.5$ (dashed-dot line) is not reproduced. The dotted line indicates results with vacuum masses and widths (scenario (i)).

![FIGURE 2](image-url)

**FIGURE 2.** Left panel: Total photon yield in Pb + Pb collisions at 158 A GeV. The theoretical calculations contain hard QCD and thermal photons. The system is formed in the quark matter phase with initial temperature $T_i = 196$ MeV. Right panel: Total (prompt+thermal) photon yield in Pb + Pb collisions at 158 A GeV at CERN-SPS. The theoretical calculations contain hard QCD and thermal photons. The system is formed in the hadronic phase with initial temperature $T_i = 200$ MeV; ‘trans’ indicates the results for the cooling law (6).

The agreement between the results obtained with two different types of evolution scenarios (transport model and hydrodynamics) can be explained as follows. We find that the variation of temperature with time (cooling law) in eq. 6 is slower than the one obtained by solving hydrodynamic equations. As a consequence the thermal system has a longer life time than the former case, allowing the system to emit photons for a longer time. In case of hydrodynamics this is compensated by the transverse kick experienced by the photon at large $p_T$ due to radial velocity of the expanding matter.

In spite of the above encouraging situation, a firm conclusion about the formation of the QGP at SPS necessitates a closer look at some pertinent but unsettled issues. The hard photon contribution has been normalized to reproduce the scaled $p_p$ data of E704 collaboration. However, among other uncertainties, the scaling we discussed before may not be
valid. It is extremely important to know quantitatively the contribution from the hard processes. Again, the assumption of complete thermodynamic equilibrium for quarks and gluons may not be entirely realistic for SPS energies; lack of chemical equilibrium will further reduce the thermal yield from QGP. We have assumed $\tau_i = 1 \text{ fm/c}$ at SPS energies, which may be considered as the lower limit of this quantity, because the transit time (the time taken by the nuclei to pass through each other in the CM system) is $1 \text{ fm/c}$ at SPS energies and the thermal system is assumed to be formed after this time has elapsed. In the present work, when QGP initial state is considered, we have assumed a first order phase transition with bag model EOS for the QGP for its simplicity, although it is not in complete agreement with the lattice QCD simulations. As mentioned before, there are uncertainties in the value of $T_c$, a value of $T_c < 200 \text{ MeV}$ may be considered as an upper limit. Moreover, the photon emission rate from QGP considered here is obtained by using the hard thermal loop approximation [15] which is strictly valid for $g < < 1$ whereas the value of $g$ is $2$ at $T = 200 \text{ MeV}$. At present it is not clear whether the rate obtained from HTL approximation is valid for such a large value of $g$ or not.

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