Photons from Pb-Pb Collisions at CERN SPS

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High energy photon emission rate from matter created in Pb + Pb collisions at CERN SPS energies is evaluated. The evolution of matter from the initial state up to freeze-out has been treated within the framework of (3+1) dimensional hydrodynamic expansion. We observe that the photon spectra measured by the WA98 experiment are well reproduced with hard QCD photons and photons from a thermal source with initial temperature $\sim 200$ MeV. The effects of the spectral changes of hadrons with temperature on the photon emission rate and on the equation of state are studied. Photon yield for Au + Au collisions at RHIC energies is also estimated.

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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 microscopic 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 [4,5,6]. While in Ref. [6], the contribution from hard photons and the effects of transverse expansion on the thermal photons were neglected, in [7] the thermal contribution was not taken into account. Again, in [6,7] the intrinsic $k_T$ distribution of partons and thermal shift of hadronic masses were ignored. In this letter we present the results of an analysis of the photon spectra in a realistic framework using a reasonable set of parameters and consistently taking into account all the effects mentioned above. 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 [8] 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. $\pi$, $\rho$, $\omega$ and $\eta$.

It has been emphasized that the properties of vector mesons may change appreciably because of interactions among the hadrons at high temperatures and/or densities (see the reviews [9–13]). 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 [13], we examine two possibilities for the hadronic phase in this paper: (i) no medium modifications of hadrons, and (ii) the scenario of the universal scaling hypothesis of the vector meson masses [11]. In principle, we can think of a third scenario (iii) the large collisional broadening of the vector mesons [3]. 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 [3]. 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. We will see that the resulting photon spectra reproduce the experimental data quite well.

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.

We start with the direct QCD photons originating from hard scattering of partons embedded in the nucleons of the colliding nuclei in the very early stages of the collision. We will see later that they make a significant contribution to the total photon yield. These are estimated using perturbative QCD as

\[ E \frac{dN}{dp} = T_{AA}(b = 0) E \frac{d\sigma_{pp}}{dp} \]

where \( T_{AA}(b) \) is the nuclear thickness at impact parameter \( b \). Its value at \( b = 0 \) is taken as 220/fm² [3]. \( \sigma_{pp} \) includes the pp cross-section for Compton and annihilation processes among the partons. At SPS energies one should include the effects of intrinsic \( k_T \) distribution of partons [4] to account for the fact that the colliding partons might have some initial transverse momenta with respect to the incoming hadrons (analogous to the Fermi motion of nucleons in the nucleus). This leads to substantial enhancement in the photon spectra [5]. In practice such an effect is implemented by multiplying each of the parton distribution functions appearing in the right hand side of the above equation by a Gaussian function of the type \( f(k_T) = \exp\left(-k_T^2/(\langle k_T^2 \rangle)\right)/\pi(\langle k_T^2 \rangle) \) and integrating over \( d^2k_T \). We use CTEQ5M partons [15] and \( \sigma_{pp} \) of 0.9 GeV² [3] for evaluating the hard QCD photons (\( \sqrt{\langle k_T^2 \rangle} = 0.8 \) GeV is taken in [3]). The photons from hard QCD processes have been used to normalize the p-p data. The higher order effects has been taken into account through a K-factor \( \sim 2 \). An enhanced production in A-A collisions compared to p-p will presumably mark the presence of a thermal source [3].

The lowest order processes contributing to hard thermal photon emission from quark gluon plasma are the QCD Compton and annihilation processes [16]. It has been shown recently [17] that the two-loop contribution leading to bremsstrahlung and \( qq \) annihilation with scattering is of the same order as the lowest order processes. The total rate of emission per unit four-volume at temperature \( T \) is given by

\[ E \frac{dR}{d^3p} = \frac{5}{9} \frac{\alpha_s}{2\pi^2} \exp(-E/T) \left[ \ln \left( \frac{2.912 E}{g^2 T} \right) + 16 \frac{(J_T - J_L)}{\pi^2} \ln(2 + \frac{E}{3T}) \right] \]

(2)

where \( J_T \approx 4.45 \) and \( J_L \approx -4.26 \). The QCD coupling, \( \alpha_s \), is given by,

\[ g^2/4\pi \equiv \alpha_s = \frac{6\pi}{29\ln(8T/T_c)} \]

(3)

for two quark flavours [18]. For photon energies in the range \( 1 \leq E \) (GeV) \( \leq 5 \), the static emission rate given by Eq. (1) at \( T \sim 200 \) MeV is about an order of magnitude larger than the rate due to Compton and annihilation processes [16]. We will see below that within the present framework the space time integrated photon yield from quark matter is less than that from hadronic matter due to the smaller life time of the QGP phase as a result of a moderate value of the initial temperature considered. Therefore, the overall thermal photon yield remains largely unaffected by the two loop contribution.

To estimate the photon yield from the hadronic matter (HM) (see first of [4]), we have considered the reactions, \( \pi \pi \rightarrow \pi \pi, \pi \pi \rightarrow \rho \rho, \pi \pi \rightarrow \eta \gamma, \pi \pi \rightarrow \pi \gamma \) and the decays \( \rho \rightarrow \pi \pi \gamma \) and \( \omega \rightarrow \pi \gamma \). The invariant amplitudes for all these processes are given in Refs. [4]. In the present work we have also considered photon production due to the process \( \pi \rho \rightarrow a_1 \rightarrow \pi \gamma \) [13].

In Ref. [13] we have studied the effects of spectral changes of hadrons on the electromagnetic probes in detail. It was observed that the gauged linear and non-linear sigma models and the model with hidden local symmetry do not show any appreciable effect on photon emissions. In the Walecka model, the universal scaling hypothesis for the vector meson masses as well as the large collisional broadening of vector mesons produce a large enhancement in low mass dileptons. However, the photon emission rate does not suffer substantial medium effect in the latter case, since the spectral function is smeared out. Nevertheless, the scaling hypothesis with particular exponent \( \lambda = 1/2 \) (called the Nambu scaling in [1]) has been seen to enhance photon emission among the others.

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 (i), the parametrization of in-medium quantities (denoted by *) at finite \( T \) is

\[ \frac{m_V^*}{m_V} = \frac{f_V^*}{f_V} = \frac{\omega_0^*}{\omega_0} = \left(1 - \frac{T^2}{T_c^2}\right)^\lambda \]

(4)

where \( V \) stands for vector mesons, \( f_V \) is the coupling between the electromagnetic current and the vector meson field and \( \omega_0 \) is the continuum threshold. Mass of the nucleon also varies with temperature as Eq. (4). Note that there is no definite reason to believe that all the in-medium dynamical quantities are dictated by a single exponent \( \lambda \). This is the simplest possible ansatz (see [3] for a discussion). The effective mass of \( a_1 \) is estimated by using Weinberg’s sum rules [21]. We have seen earlier that the baryon chemical potential has a small effect on the photon yield [1]. Moreover, in the central rapidity region the entropy per baryon is quite large \( ~40 - 50 \) [21,22]. Thus the finite baryon density effects are neglected here.

We will assume that the produced matter reaches a state of thermodynamic equilibrium after a proper time \( \sim 1 \) fm/c [23]. 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. The (3+1) dimensional hydrodynamic equations have been solved numerically by the relativistic version of the flux corrected transport algorithm [24], assuming boost in-
variance in the longitudinal direction \[24\] and cylindrical symmetry in the transverse plane. The initial temperature \(T_i\) can be related to the multiplicity of the event \(dN/dy\) by virtue of the isentropic expansion as \[25\],

\[
\frac{dN}{dy} = \frac{45\zeta(3)}{2\pi^4} \pi R_A^2 a_k T_i^3 \tau_i
\]

where \(R_A\) is the initial radius of the system, \(\tau_i\) is the initial thermalization time and \(a_k = (\pi^2/90) g_k\); \(g_k\) being the effective degeneracy for the phase \(k\) (QGP or hadronic matter). The bag model EOS is used for the QGP phase, \(g_H(T)\), the statistical degeneracy of the hadronic phase, composed of \(\pi, \rho, \omega, \eta, a_1\) and nucleons is a temperature dependent quantity in this case and plays an important role in the EOS \[13\]. As a consequence the square of sound velocity, \(c_s^2 = [(T/g_H)(dH/dT) + 3] < 1/3\), for the hadronic phase, indicating non-vanishing interactions among the constituents (see also \[24\]). The hydrodynamic equations have been solved with initial energy density, \(\epsilon(\tau_i, r)\) \[22\], obtained from \(T_i\) through the EOS. We use the following relation for the initial velocity profile which has been successfully used to study transverse momentum spectra of hadrons \[21\] and also photons \[23\],

\[
v_r = v_0 + \frac{\delta}{2} \left( \frac{r}{R_A} \right) ^\delta \quad (6)
\]

For our numerical calculations we choose \(\delta = 1\) and sensitivity of the results on \(v_0\) will be shown. It is observed that the results do not change substantially with reasonable variation of the parameter \(\delta\) for a given value of \(v_0\).

Transition one has a mixed phase of coexisting QGP and hadronic matter which persists till the phase transition is over. Thereafter the hadronic matter expands, cools and freezes out at a temperature, \(T_f\) and radial velocity, \(v_f\). The sum total of the photon yields from the QGP phase, the mixed phase and the hadronic phase constitutes the thermal yield. The values of \((T_f, v_f)\) should in principle be obtained from the analysis of hadronic spectra. However, at present it is not possible to do so without ambiguity. In Ref. \[28\] it is shown that the experimental data from Pb + Pb collisions allow values of \((T_f, v_f)\) ranging from (180 MeV,0) to (120 MeV,0.7). In the present work we take \(T_f = 120\) MeV and the initial velocity profile of Eq.(6) with \(v_0\) as a parameter.

For central collisions of Pb nuclei at 158 A GeV at the CERN-SPS, we assume that QGP is produced at \(\tau_i=1\) fm/c which expands in (3+1) dimension and undergoes a first order phase transition to hadronic matter at \(T_c=160\) MeV. Taking \(dN/dy=700\) (last of Ref. \[3\]), and \(g_k = g_{QGP}=37\) for a two-flavour QGP, the initial temperature \(T_i\) comes out as 196 MeV. In a first order phase

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{Transverse momentum distribution of thermal photons with and without medium effects.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Total 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 QGP phase with initial temperature \(T_i = 196\) MeV.}
\end{figure}
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 parton distributions. The later, shown separately by the analysis of transverse momentum spectra of hadrons and photons (see also [6]). 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).

![FIG. 3. Total 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 the hadronic masses approaching zero at initial temperature \(T_i = 205\) MeV.](image)

The last statement together with the current uncertainty of the critical temperature \(T_c\) [30] 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. (6). 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 just for simplicity) leads to \(T_i \sim 205\) 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. (6). The results of this scenario for three values of the initial radial velocity including the prompt photon contribution are shown in Fig. 3. The experimental data are well reproduced for vanishing initial transverse velocity 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.

We now show our prediction of the photon yield in central collisions of Au nuclei at 200 A GeV at RHIC in Fig. 4 for scenario (ii) with \(v_0 = 0\). Enhancement due to intrinsic motion of the partons has been ignored at RHIC, because at higher beam energies such effects are small [7]. The initial temperature and thermalization time are taken as \(300\) MeV and \(0.5\) fm/c respectively [22]. It is seen that up to \(p_T = 2\) GeV, most of the photons are emitted from the thermal source. We also observe that photons from quark matter make a substantial contribution to the thermal yield (dash-dotted line in Fig. 4), because of the higher initial temperature and larger lifetime of the QGP phase realized at RHIC compared to SPS. The effect of the transverse expansion on the QGP phase is small. However, photons from the hadronic phase (short dashed line in Fig. 4), particularly during the late stage of the evolution, receive a large kick due to the radial expansion and consequently populate the high \(p_T\) region, as shown in Fig. 4.

![FIG. 4. Photon spectra at RHIC for Au + Au collisions.](image)

In summary, we have evaluated the high energy photon yield in Pb + Pb collisions at CERN SPS energies with two different initial conditions. In the first scenario, we start with the assumption of the formation of a QGP phase at \(T_i \sim 196\) MeV and then the system continues through mixed phase and hadronic phase before freeze-out. In the second scenario, we assume a chirally symmetric phase where the hadronic masses approach zero at a temperature \(\sim 205\) MeV and then the system evolves towards freeze-out. The effects of the variation of hadronic masses on the photon yield have been considered both in the cross section as well as in the EOS. The photon spectra reported by the WA98 collaboration are well reproduced in both cases. We thus conclude that the thermal photon spectra resulting from the Pb + Pb collisions at CERN SPS energies are emitted from a source with an initial temperature \(\sim 200\) MeV. A similar value
of $T_k$ is also obtained from the analysis of photon and dilepton data from CERN SPS [3][4]. At RHIC energies the total yield of photons increases by an order of magnitude compared to SPS with a substantial contribution from QM.

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. In the evaluation of the hard photon contribution the value of the K-factor and the intrinsic $k_T$ distribution of partons are adjusted so as to reproduce the scaled p-p data of E704 collaboration. However, it is extremely important to know quantitatively the contribution from the hard processes. The possibility of $A$ and $k_T$ dependence of the K-factor [2], the energy loss of fast partons, the shadowing of the structure functions and the broadening of transverse momentum distribution of partons are some of the vital issues related to photon production in nucleus-nucleus collisions which have not been considered in the present work. Again, the assumption of complete thermodynamic equilibrium for quarks and gluons may not be entirely realistic for SPS energies; lack of complete thermodynamic equilibrium for quarks and pions 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 [21]. However, it is difficult to distinguish among different EOS with the current resolution of the photon data. As mentioned before, there are uncertainties in the value of $T_k$ [22], a value of $T_k \sim 200$ MeV may be considered as an upper limit. Moreover, the photon emission rate from QGP given by Eq. (2), evaluated in Refs. [16,17] by resumming the hard thermal loops is strictly valid for $g << 1$ whereas the value of $g$ obtained from Eq. (3) is $\sim 2$ at $T \sim 200$ MeV. At present it is not clear whether the rate in Eq. (2) is valid for such a large vaule of $g$ or not.

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