Photons from Pb + Pb and S + Au collisions at CERN SPS energies

Sourav Sarkar, Pradip Roy and Jan-e Alam
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064 India
Bikash Sinha
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064 India
Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Calcutta 700 064 India

Abstract

The effects of the variation of vector meson masses and decay widths on photon production from hot strongly interacting matter formed after Pb + Pb and S + Au collisions at CERN SPS energies are considered. It has been shown that the present photon spectra measured by WA80 and WA98 Collaborations can not distinguish between the formation of quark matter and hadronic matter in the initial state.

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Nucleus-Nucleus collisions at ultra-relativistic energies offer a unique opportunity to create and study a new state of strongly interacting matter called Quark Gluon Plasma (QGP). Photons and dileptons can probe the entire volume of the plasma without almost any interaction and as such are better markers of space time history of the evolving matter [1]. However, apart from QGP, photons can originate from the primary interactions among the partons of the colliding nuclei, which dominate the high momentum region of the spectra, and these photons could be evaluated reliably by applying perturbative QCD (pQCD). At smaller values of the transverse momentum, meson decays (mainly π^0 and also η) dominate the spectrum. Due to their long life time π^0 decays into two photons outside the hot zone and photons originating from this decay can be reconstructed through invariant mass analysis. But there is no method by which the thermal photons from hadronic reactions and decays within the hot zone of the thermalised system can be identified experimentally. In an ideal scenario where all the photons from π^0 decays are reconstructed and the photons from hard QCD processes are identified and subtracted from the data, then only thermal photons will be left in the data.

Irrespective of whether QGP is formed or not, hadronic matter (HM) formed in Ultra-relativistic Heavy Ion Collisions (URHIC) is expected to be in a highly excited state of very high temperature and/or density. Thus it is of primary importance to understand the change in hadronic properties *e.g.* mass, life time etc at finite temperature and density. One of the most important aspects, spontaneously broken chiral symmetry, a property of hadrons in their ground state, is expected to be restored at high temperature, which should manifest itself in the thermal shift of hadronic masses as well as decay widths. Changes in the hadronic properties could be probed most efficiently by studying the thermal spectrum of real and virtual (dilepton pairs) photons. The thermal photon yield from S + Au collisions has been studied by many authors [2, 3, 4, 5] without taking medium effects into account. In this work we evaluate the transverse momentum distribution of photons emitted from a strongly interacting system with initial conditions expected to be realised at CERN SPS energies for Pb + Pb and S + Au collisions, taking in-medium effects on hadronic properties into account.

In a phase transition scenario, thermal photons originate both from QGP and hadronic phase as the latter is realised when the temperature of the system cools down to the critical temperature (T_c) due to expansion. However, if the system does not go through a phase transition, then obviously, the thermal photons originate from hadronic interactions only. We have studied the thermal photon spectra from both the scenarios.

The thermal emission rate of real photons can be expressed in terms of the trace of the retarded photon self energy ($\Pi^R_{\mu\nu}$)at finite temperature [6]

$$E\frac{dR}{d^3p} = -\frac{2g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(p)\frac{1}{e^{E/T}-1} \tag{1}$$

where $g_{\mu\nu}$ is the metric tensor and T is the temperature of the thermal medium. In the quark matter (QM) the lowest order contribution to the trace of the imaginary part of the retarded self energy $\mathrm{Im}\Pi^R_{\mu\nu}(p)$ comes from the two loop diagrams corresponding to QCD Compton and annihilation processes, the total rate for which is given by [7],

$$E\frac{dR}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2\exp(-E/T)\,\ln(\frac{0.2317E}{4\pi\,\alpha_s T}) \tag{2}$$

where α is the fine structure constant, $\alpha_s = 6\,\pi/(33-2n_f)\ln(8\,T/T_c)$ [8] is the strong coupling constant.

In the hadronic matter (HM) an exhaustive set of hadronic reactions and vector meson decays involving π, ρ, ω and η mesons have been considered. It is well known [9] that the reactions $\pi\,\rho\,\rightarrow\,\pi\,\gamma$, $\pi\,\pi\,\rightarrow\,\rho\,\gamma$, $\pi\,\pi\,\rightarrow\,\eta\,\gamma$, $\pi\,\eta\,\rightarrow\,\pi\,\gamma$, and the decays $\rho\,\rightarrow\,\pi\,\pi\,\gamma$ and $\omega\,\rightarrow\,\pi\,\gamma$ are the most important channels for photon production from hadronic matter in the energy regime of our interest. The rates for these processes could be evaluated from the imaginary part of the two loop photon self energy involving various mesons. Recently it has been shown [10] that the role of intermediary a_1 in the photon producing reactions is less important than thought earlier [11, 12]. In the present work we have neglected a_1 in the intermediate state.

The full interaction Lagrangian density and the relevant matrix elements for these processes have been given in Refs. [13, 14], we do not repeat those here. The photon emission rate from HM can not be expressed in a closed form as in Eq. (2) due to the complexities arising from the nature of the hadronic interactions and reaction kinematics.

To study the medium effects on the transverse momentum distribution of photons from URHIC we need two more ingredients. Firstly, we require the variation of masses and decay widths with temperature, because the invariant matrix element for photon production suffer in-medium modifications through the temperature dependent masses and widths of the participants. As the hadronic masses and decay widths enter directly in the count rates of electromagnetically interacting particles, the finite temperature and density effects in the cross sections, particularly in the

HM are very important in URHIC. In our earlier calculations [14] we have studied the finite temperature and density effects on hadronic properties by applying finite temperature field theory within a framework of an effective Lagrangian approach. The variation of nucleon, rho and omega masses and the decay width of rho with temperature could be parametrized as

$$m_N^*/m_N = 1 - 0.0264(T/T_c)^{8.94} \tag{3}$$

$$m_\rho^*/m_\rho = 1 - 0.1268(T/T_c)^{5.24} \tag{4}$$

$$m_\omega^*/m_\omega = 1 - 0.0438(T/T_c)^{7.09} \tag{5}$$

$$\Gamma_\rho^*/\Gamma_\rho = 1 + 0.6644(T/T_c)^4 - 0.625(T/T_c)^5 \tag{6}$$

where asterisk indicates effective mass in the medium and $T_c = 0.16$ GeV. In the rho width we have included the Bose enhancement effects [14]. Note that in our calculation the nucleon, rho and omega masses decrease differently; we do not observe any universal scaling law [15]. Effects of scaling mass variation [15] on photon spectra has recently been studied by Song et al [16].

The observed photon spectrum originating from an expanding QGP or hadronic matter is obtained by convoluting the static (fixed temperature) rate, as given by Eq. (1), with expansion dynamics. Therefore, the second ingredient required for our calculations is the description of the system undergoing rapid expansion from its initial formation stage to the final freeze-out stage. In this work we use Bjorken-like [17] hydrodynamical model for the isentropic expansion of the matter in $(1+1)$ dimension. For the QGP sector we use simple bag model equation of state (EOS) with two flavour degrees of freedom. The temperature in the QGP phase evolves according to Bjorken scaling law $T^3\,\tau = T_i^3\tau_i$.

In the hadronic phase we have to be more careful about the presence of heavier particles and their change in masses due to finite temperature effects. The hadronic phase consists of π, ρ, ω, η and a_1 mesons and nucleons. The nucleons and heavier mesons may play an important role in the EOS in a scenario where mass of the hadrons decreases with temperature.

The energy density and pressure for such a system of mesons and nucleons is given by,

$$\epsilon_H = \sum_{i=mesons} \frac{g_i}{(2\pi)^3} \int d^3p\, E_i\, f_{BE}(E_i,T) + \frac{g_N}{(2\pi)^3} \int d^3p\, E_N\, f_{FD}(E_N,T) \tag{7}$$

and

$$P_H = \sum_{i=mesons} \frac{g_i}{(2\pi)^3} \int d^3p \frac{p^2}{3\,E_i} f_{BE}(E_i,T) + \frac{g_N}{(2\pi)^3} \int d^3p \frac{p^2}{3\,E_N} f_{FD}(E_N,T) \tag{8}$$

where the sum is over all the mesons under consideration and N stands for nucleons and $E_i = \sqrt{p^2 + m_i^2}$. The entropy density is given by

$$s_H = \frac{\epsilon_H + P_H}{T} \equiv 4a_{\rm eff}(T)\,T^3 = 4\frac{\pi^2}{90} g_{\rm eff}(m^*(T),T)T^3 \tag{9}$$

where $g_{\rm eff}$ is the effective statistical degeneracy.

Thus, we can visualise the finite mass of the hadrons having an effective degeneracy $g_{\rm eff}(m^*(T),T)$. The variation of temperature from its initial value T_i to final value T_f (freeze-out temperature) with proper time (τ) is governed by the entropy conservation

$$s(T)\tau = s(T_i)\tau_i \tag{10}$$

The initial temperature of the system is obtained by solving the following equation self consistently

$$\frac{dN_\pi}{dy} = \frac{45\zeta(3)}{2\pi^4}\pi\, R_A^2 4a_{\rm eff}T_i^3\tau_i \tag{11}$$

where dN_π/dy is the total pion multiplicity, R_A is the radius of the system, τ_i is the initial thermalisation time and $a_{\rm eff} = (\pi^2/90)\,g_{\rm eff}(m^*(T_i),T_i)$. The change in the expansion dynamics as well as the value of the initial temperature due to medium effects enters the calculation of the photon emission rate through the effective statistical degeneracy.

We consider Pb + Pb collisions at CERN SPS energies. If we assume that the matter is formed in the QGP phase with two flavours (u and d), then $g_k = 37$. Taking $dN_\pi/dy = 600$ as measured by the NA49 Collaboration [18] for Pb + Pb collisions, we obtain $T_i = 180$ MeV for $\tau_i = 1$ fm/c. The system takes a time $\tau_Q = T_i^3\tau_i/T_c^3$ to achieve the critical temperature of phase transition (T_c=160 MeV in our case). In a first order phase transition scenario the system remains in the mixed phase up to a time $\tau_H = r\,\tau_Q$, *i.e.* T remains at T_c for an interval $\tau_H - \tau_Q$, where r is the ratio of the statistical degeneracy in QGP to hadronic phase. At τ_H the system is fully converted to hadronic matter and remains in this phase up to a proper time τ_f. We have taken $T_f = 130$ MeV in our calculations.

In Fig. (1) we demonstrate the variation of temperature with proper time for different initial conditions. The dotted line indicates the scenario where QGP is formed initially at $T_i = 180$ MeV and cools down according to Bjorken law up to a temperature T_c at which a phase transition takes place; it remains constant at T_c up to a time $\tau_H = 8.4$ fm/c after which the temperature decreases as $T = 0.241/\tau^{0.19}$ to a temperature T_f. If the system is considered to be formed in the hadronic phase the initial temperature is obtained as $T_i = 230$ MeV (270 MeV) when in-medium effects on the hadronic masses are taken into account (ignored), the corresponding cooling laws are $T = 0.230/\tau^{0.169}$ ($T = 0.266/\tau^{0.2157}$) are displayed in Fig. (1) by solid and dashed lines respectively. The above parametrizations of the cooling law in the hadronic phase have been obtained by solving Eq. (10) self consistently.

Obtaining the finite temperature effects on hadronic properties and the cooling law we are ready to evaluate the photon spectra from an $(1+1)$ dimensionally expanding system. The transverse momentum distribution of photons in a first order phase transition scenario is given by,

$$\begin{aligned} E\frac{dN}{d^3p} &= \pi\, R_A^2 \int \Bigg[\left(E\frac{dR}{d^3p}\right)_{QGP}\Theta(\epsilon-\epsilon_Q) \\ &+ \Bigg[\left(E\frac{dR}{d^3p}\right)_{QGP}\frac{\epsilon-\epsilon_H}{\epsilon_Q-\epsilon_H} \end{aligned}$$

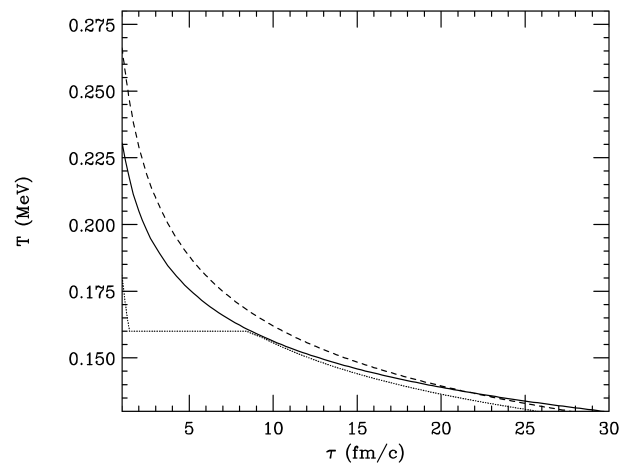

Figure 1: Variation of temperature with proper time. The dotted line indicates the cooling law in a first order phase transition scenario. The solid (dashed) line represents temperature variation in a 'hadronic scenario' with (without) medium effects on the hadronic masses.

$$+ \left(E\frac{dR}{d^3p}\right)_H \frac{\epsilon_Q - \epsilon}{\epsilon_Q - \epsilon_H}\Bigg] \Theta(\epsilon_Q - \epsilon)\Theta(\epsilon - \epsilon_H)$$
$$+ \left(E\frac{dR}{d^3p}\right)_H \Theta(\epsilon_H - \epsilon)\Bigg] \tau\, d\tau\, d\eta \qquad (12)$$

where $\Theta(M) = \Theta(\epsilon_Q - \epsilon)\Theta(\epsilon - \epsilon_H)$, ϵ_Q (ϵ_H) is the energy density in the QGP (hadronic) phase at T_c, η is the space time rapidity, R_A is the radius of the nuclei and Θ functions are introduced to get the contribution from individual phases.

In Fig. (2) we compare our results of transverse momentum distribution of photons with the preliminary results of WA98 Collaboration [19]. The experimental data represents the photon spectra from Pb + Pb collisions at 158 GeV per nucleon at CERN SPS energies. The transverse momentum distribution of photons originating from the 'hadronic scenario' (matter formed in the hadronic phase) with (solid line) and without(short-dash line) medium modifications of vector mesons outshine the photons from the 'QGP scenario' (matter formed in the QGP phase, indicated by long-dashed line) for the entire range of p_T. Although photons from 'hadronic scenario' with medium effects on vector mesons shine less bright than those from without medium effects for $p_T > 2$ GeV, it is not possible to distinguish clearly between one or the other on the basis of the experimental data.

In Fig. (3) we compare thermal photon spectra with the upper bound of WA80 Collaboration [20]. The experimental data stands for S + Au collisions at 200 GeV per nucleon at SPS. In this case the pion multiplicity, $dN_\pi/dy = 225$. Our calculation shows that maximum number of photons originate from the 'hadronic scenario' when the medium effects on vector mesons are ignored. For such a scenario the photon spectra has just crossed the upper bound of the WA80 data and more likely such a scenario is not realised in these collisions. This is in line with the analysis of the preliminary WA80 data of Ref. [3]. It should be noted for completeness that the temperature variation of the degeneracy factor was not considered in Ref. [3]

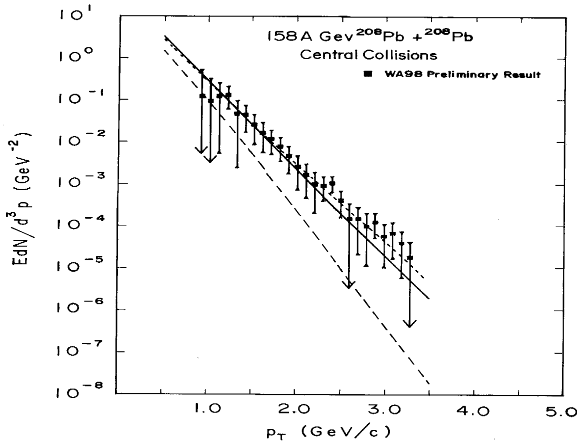

Figure 2: Total thermal photon yield in Pb + Pb central collisions at 158 GeV per nucleon at CERN SPS. The long-dash line shows the results when the system is formed in the QGP phase with initial temperature $T_i = 180$ MeV at $\tau_i = 1$ fm/c. The critical temperature for phase transition is taken as 160 MeV. The solid (short-dash) line indicates photon spectra when hadronic matter formed in the initial state at $T_i = 230$ MeV ($T_i = 270$ MeV) at $\tau_i = 1$ fm/c with (without) medium effects on hadronic masses and decay widths.

leading to quantitative differences in the theoretical predictions between the present work and Ref. [3]. Photons from 'hadronic scenario' with medium modifications of vector meson properties outshine those from the 'QGP scenario' for the entire p_T range. Considering the experimental uncertainty, no definitive conclusion can be drawn in favour of any particular scenario.

We have compared the experimental data on photon spectra from S + Au and Pb + Pb collisions at 200 GeV and 158 GeV per nucleon respectively with different initial conditions. In case of Pb + Pb collisions photons from hadronic scenario dominates over the photons from QGP scenario for the entire p_T domain. But in the hadronic scenario the photon spectra evaluated with and without in-medium properties of vector mesons describe these data reasonably well. Hence the transverse photon spectra at present do not allow us to decide between an in-medium dropping mass and a free mass scenario. For S + Au collisions the photon spectra evaluated with free masses seems to exceed the experimental upper bound. However, the photon spectra obtained by assuming hadronic matter (with in-medium effects or otherwise) in the initial state outshines the spectra evaluated with first order phase transition. Considering the experimental uncertainty, it is not possible to state, which one, between the two is compatible with the data. Experimental data with better statistics could possibly distinguish among various scenarios.

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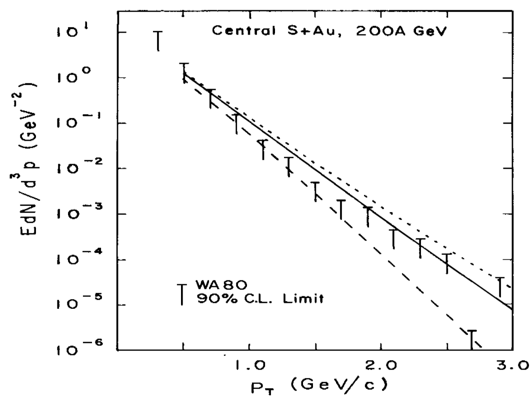

Figure 3: Total thermal photon yield in S + Au central collisions at 200 GeV per nucleon at CERN SPS. The long-dash line shows the results when the system is formed in the QGP phase with initial temperature $T_i = 190$ MeV at $\tau_i = 1.2$ fm/c. The critical temperature for phase transition is taken as 160 MeV. The solid (short-dash) line indicates photon spectra when hadronic matter formed in the initial state at $T_i = 230$ MeV ($T_i = 270$ MeV) at $\tau_i = 1.2$ fm/c with (without) medium effects on hadronic masses and decay widths.

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