Direct photon production at RHIC and LHC

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Abstract

In this work, the photon spectrum measured in RHIC and LHC experiments at $\sqrt{s_{\mathrm{NN}}} = 0.2$ and 2.76 TeV respectively has been analyzed in a hydrodynamical model. The data is compared with the calculations. The data shows enhancement even after considering all the known sources of direct photon production. Surprisingly enhancement factor is found to be more at RHIC energy than the LHC energy.

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I. INTRODUCTION

The ultra relativistic heavy ion collision experiments are performed with the aim to produce matter with very high energy density required to form quark gluon plasma (QGP). With this aim, Pb+Pb collision experiments at $\sqrt{s} = 17.6A$ GeV have been carried out at CERN SPS giving a variety of data on electromagnetic and hadronic observables [For a review see [1]]. The most interesting are the electromagnetic probes [2], which are sensitive to various stages of the evolution of the system and may contain the information about QGP formation. A considerable amount of theoretical work has been done to dig out the information on QGP from these data [For review see [4, 5]].

To explain the data with hydrodynamical models, one assumes that QGP is formed with given initial conditions which then expands hydrodynamically till it reaches the critical temperature T_C for quark-hadron phase transition. In the idealized Maxwell construction, the temperature of the system is held fixed at $T = T_C$ until the hadronization is completed. Thus in turn one assume that the latent heat obtained by the phase transition is compensating the temperature drop due to cooling. Such a picture has been widely used in literature when describing the electromagnetic signals [6]. This is a good approximation when the expansion time scales are far greater than the phase transition time scales as in the case of early universe. For the case of relativistic heavy ion collisions, there have been extensive studies of the space time evolution of QGP undergoing a first order phase transition by nucleation [7**?** –9]. As a result of rapid expansion of the system, a substantial amount of supercooling is expected and the dynamics of quark hadron phase transition becomes quite different in RHIC as compared to that in early universe [9, 11]. When the hydrodynamical equations are coupled with nucleation rate equation [9], the QGP is shown to supercool to a temperature T_S lower than T_C. The hadronization proceeds by thermal fluctuation from this metastable QGP to stable hadron phase. The system reheats due to the release of latent heat and approaches to T_C as the hadronization proceeds. Such a calculation is shown in Fig. 1. This corresponds to an equilibrium situation where the latent heat generated is going into reheating the system.

It is also possible that QGP supercools to a temperature, the barrier between the metastable QGP and the stable hadron phase minima completely vanishes leading to a point of inflection at $T = T_S$ known as spinodal instability [12]. In this case, the rapidly quenched system leaves the region of metastability and enters the highly unstable spinodal region before a substantial amount of nucleation begins. If it happens, then one can not define the phase transition rate by thermal fluctuation.

The spinodal decomposition has also been suggested as a possible mechanism of phase conversion for a rapidly expanding system of quarks and gluons [12–14]. This hadronization process is much faster than the nucleation and is also referred as explosive decomposition [15]. The QGP breaks up into small droplets of plasma, which will form hadrons. This occurs in a short time and the system may not be able to undergo further reequilibration and would freeze out at this point. Such a picture has been presented in literature many times and referred as 'a fast shock like hadronization' in Refs. [16] and a 'sudden hadronization scenario' in Ref. [17]. The signature of such a scenario will be very short life time [18] of the system measured through HBT data [20**?**] and should combine with no mass shift observed in ρ and ϕ.

When most of the QGP volume has been converted to hadrons, the already nucleated hadron bubbles would tend to join together and the QGP droplets will be trapped inside. At such a point, fluctuation theory is no more applicable. The system is highly unstable at this point and may simply breaks up into fragments: hadronic clusters and small droplets of plasma which then form the final state hadrons [10].

As all these scenarios exist in the literature, it is worthwhile to see their manifestation in the measured photon spectrum which is the best probes of space time evolution of quark-gluon plasma (QGP) possibly produced in relativistic heavy-ion collisions. Direct photon spectra have been measured by the WA98 collaboration at the SPS [2].

In the present work, the contribution of thermal photons are calculated and compared with SPS data, assuming the QGP formation which expands and goes through supercooling.

II. MODEL

We consider that QGP is formed at some initial temperature T_i and initial time τ_i and starts cooling by Bjorken hydrodynamics. sTransverse expansion is not taken into account considering short life time of the system. To get the equations of state it is assumed that QGP is a massless 2 flavour parton gas and hadronic phase is a massless three pion gas.

When the QGP cools to the critical temperature T_C we invoke following four scenario for the calculations:

(1) Idealized Maxwell construction (from T_i to T_f.): The temperature of the system is held fixed at $T = T_C$ until the hadronization is completed. Afterwards the hadron gas cools to T_f by hydrodyanmics.

(2) Supercooling scenario (from T_i to T_f.) At T_C, hydrodynamical equations are coupled with nucleation rate equations [12**?**]. The QGP supercools to a temperature T_S lower than T_C as shown in Fig. 1. The hadronization proceeds by thermal fluctuation from this metastable QGP phase to stable hadron phase. The system reheats due to the release of latent heat and approaches to T_C as the hadronization proceeds. When hadronization is completed, the hadron gas cools to T_f by hydrodyanmics.

(3) Spinodal decomposition followed by freeze out (from T_i to T_S.) QGP supercools to a T_S which is close to spinodal temperature [12]. The QGP breaks up into small droplets of plasma, which will form hadrons which then freezw out.

(4) Fragmentation at 95 % of hadronization followed by freeze out (from T_i to T_P.) In the nucleation scenario (2) when 95 % of the QGP volume has been converted to hadrons, the system breaks up into fragments: hadronic clusters and small droplets of plasma which then form the final state hadrons.

The total thermal photon/dilepton emission rate is given general by the sum of corresponding rates $R_{\rm QGP}$ in the QGP and $R_{\rm hadron}$ in the hadron regions integrated over space time volume element $d^4x = \tau d\tau d\eta_f \pi R^2$ as

$$R_I = \int_{\tau_i}^{\tau_f} \int_{-l}^{l} \left[(1-h(\tau))R_{\rm QGP}(T(\tau),\eta_f) + h(\tau)R_{\rm hadron}(T(\tau),\eta_f)\right] \tau d\tau d\eta_f \pi R^2 \qquad (1)$$

Here η_f is the fluid rapidity and R is the size of colliding nuclei given by $R = 1.2\,A^{1/3}$. The $h(\tau)$ is the hadronic fraction at a time τ.

The temperature $T(\tau)$ and the hadronic fractions $h(\tau)$ are obtained using above two scenario. The temperature variation in the quark phase is governed by,

$$T(\tau) = T_i \left(\frac{\tau_i}{\tau}\right)^{1/3} \qquad (2)$$

While the temperature variation in the hadron phase is governed by,

$$T(\tau) = T_h \left(\frac{\tau_h}{\tau}\right)^{1/3} \qquad (3)$$

Assuming, Bjorken scaling, the experimentally observed rapidity density dN/dy can be related to the initial conditions by

$$dN/dy = \pi R_A^2 4 a_q T_i^3 \tau_i / 3.6, \tag{4}$$

where a_q is the number of degrees of freedom in quark phase. The experimentally observed $dN/dy = 1.5\, dN_{ch}/dy$

III. THE PHOTON DISTRIBUTION

The production rate for hard thermal photons from an equilibrated QGP has been calculated in perturbative thermal QCD applying the hard thermal loop (HTL) resummation to account for medium effects.

The *Compton scattering* and *$q\bar{q}$-annihilation* contribution derived from the 1-loop HTL photon-polarization tensor [21–23] is given by

$$E \frac{dN}{d^4x\, d^3p} = \frac{5}{18\pi^2}\, \alpha\alpha_s \ln\left(\frac{0.23\, E}{\alpha_s\, T}\right) T^2\, e^{-E/T}, \tag{5}$$

The contributions from *bremsstrahlung*, and *$q\bar{q}$-annihilation with an additional scattering in the medium*, obtained from the 2-loop HTL photon-polarization tensor [24, 25] are given by

$$E \frac{dN}{d^4x\, d^3p} = 0.0219\, \alpha\alpha_s\, T^2\, e^{-E/T}, \tag{6}$$

$$E \frac{dN}{d^4x\, d^3p} = 0.0105\, \alpha\alpha_s\, E\, T\, e^{-E/T}, \tag{7}$$

All three rates are listed for a two-flavored ($N_f = 2$) QGP. Here $\alpha = 1/137$ and the strong coupling constant is $\alpha_s = 6\pi/((33 - 2N_f)\ln(8T/T_C))$ [26]. The rates (6) and (7) were *erroneously* multiplied by a factor of 4 [24], we take the rates in correct form [25].

Here $E = P_T \cosh(y - \eta_f)$ where y is the rapidity in the center of mass frame and η_f is the fluid rapidity.

The thermal photon production in an equilibrated hadron phase is determined by considering various meson interactions $\pi\pi \to \rho\gamma$, $\pi\rho \to \pi\gamma$, $\omega \to \pi\gamma$ and $\rho \to \pi\pi\gamma$ [21, 27]. By considering additionally the $\pi\rho \to a_1 \to \pi\gamma$ reaction, a strong enhancement of the rate was observed [28]. The numerical results of a detailed study of these dacays has been fitted by analytical expression as a function of temperature and photon energy as reported in Ref. [25] given as

$$E \frac{dN}{d^4x\, d^3p} = 4.8\, T^{2.15}\, e^{-1/(1.35\, T\, E)^{0.77}}\, e^{-E/T}, \tag{8}$$

where photon energy E and temperature T are to be given in GeV to obtain the rate in units of fm^{-4}GeV^{-2}.

Prompt Photons. Dumitru et al. [29] estimate the contribution of prompt photons which employs the pQCD with inclusion of the effect of intrinsic transverse momentum of the partons. Their results for Pb+Pb collision $\sqrt{s} = 17.4A$GeV for $< K_T^2 >= 1.8$ GeV^2 including additional broadening from nuclear effects can be parameterized as

$$E\frac{d^3N}{d^3p} = \exp(a + bP_T + cP_T^2 + dP_T^3) \tag{9}$$

where $a = -4.1506$, $b = -1.9845$, $c = 0.0744$, and $d = -0.0383$.

In the work of Gallmeister [30] hard photon yield is generated by the event generator PYTHIA and are parameterized same as Eq. (9) with the coefficients $a = -5.9883$, $b = 2.0934$, $c = -1.6015$ and $d = 0.1432$. The WA98 direct photon data analysis of Gallmeister et al. obtained in a model describing a *spherically* symmetric expansion [30].

It is also possible to reproduce the WA98 direct photon data analysis of Srivastava et al. [6], which does not necessitate prompt photons but instead initial conditions that are rather extreme for SPS, i.e. a very small thermalization time of $\tau_0 = 0.2$ fm and a very high initial temperature of $T_0 = 335$ MeV. The effective degrees of freedom in the hadron gas has been increased from the actual value of $g_h = 3$ to an effective one of $g_h = 8$ in order to achieve the fit in the HHG thermal photon spectrum. This reduces the life of mixed phase and hence reducing the contribution from hadron phase.

For *typical* parameters $\tau_i = 0.8$ fm, $T_i = 210$ MeV, $T_c = 160$ MeV, $T_f = 140$ MeV, nucleon number $A = 208$ (corresponding to Pb + Pb collisions) we have obtained the photon spectrum.

IV. THE DILEPTON DISTRIBUTION

The dilepton emission rate in the quark sector considering the processes ($q\bar{q} \to e^-e^+$) is given [32, 33] by

$$\begin{aligned} \frac{dN}{d^4xd^2p_Tdy dM^2} &= \frac{3}{(2\pi)^5}M^2\sigma(M^2)\exp\left(-\frac{E}{T}\right), \\ &= \frac{\alpha^2}{8\pi^4}\left(\sum e_q^2\right)\exp\left(-\frac{E}{T}\right). \end{aligned} \tag{10}$$

Here, $\sigma(M^2) = 4\pi\alpha^2/3M^2$ and $F_q = \sum e_q^2 = 5/9$.

The dilepton emission rate from hadron phase is given by

$$\frac{dN}{d^4xd^2p_TdydM^2} = \frac{\alpha^2}{8\pi^4} F_h \exp(-\frac{E}{T}), \tag{11}$$

For the hadrons, if we assume $\pi\pi \to \rho \to l^+l^-$ is the dominant channel,

$$F_h = \frac{1}{12}\frac{m_\rho^4}{(m_\rho^2 - M^2)^2 + m_\rho^2\Gamma_\rho^2} \tag{12}$$

The parameters used are m_ρ=768 MeV, Γ=151 MeV. The detail form factors can be obtained from Ref. [34]

We get, the p_T distribution as

$$\frac{dN}{d^4xdydM^2p_Tdp_T} = \frac{\alpha^2}{4\pi^3}F \exp\left(-\frac{\sqrt{M^2+p_T^2}cosh(y-\eta)}{T}\right) \tag{13}$$

and the invariant mass distribution

$$\frac{dN}{d^4xdydM} = \frac{\alpha^2}{2\pi^3}F\, M^3 \left(\frac{1}{x^2} + \frac{1}{x}\right) \exp(-x), \tag{14}$$

where

$$x = \frac{M\cosh(y-\eta)}{T}. \tag{15}$$

Here M, p_T and y are the mass, transverse momentum, and rapidity of the lepton pair and η is the rapidity of the fluid with temperature T.

V. RESULTS AND DISCUSSIONS

The total thermal photon emission rate is given by the sum of corresponding rates in the QGP and in the hadron regions integrated over space time volume obtained from above four scenario. The photon production rates are taken from the parameterized forms of Ref. [25]. The contribution of prompt photons has been obtained by the PYTHIA calculations [30], while photons from the decay of hadrons after freeze-out are already subtracted in the experimental analysis.

Figure 2 demonstrates how the thermal photons contributions due to different evolutions compare with SPS data. From this figure, scenario (3) seems the most appropriate evolution scenario. It must be noted that these calculations depend on the initial conditions, equation of state, photon rates and hydrodynamical expansion but, would certainly be helpful to understand the various evolution scenarios and their manifestation in photon spectrum.

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