DIRECT PHOTON RADIATION FROM A RICH BARYON QUARK-GLUON-PLASMA SYSTEM

S. S. Singh

Department of Physics and Astro-Physics, University of Delhi, Delhi - 110007, INDIA

The direct photon radiation from a hot and interacting fireball system of a rich baryon quark-gluon plasma using the Boltzmann distribution function for the incoming particles and Bose-Einstein distribution for gluon and Fermi-Dirac distribution for quark, antiquark and Boltzmann distribution for gluon are discussed subsequently. The first two distribution functions are chosen for the photon production of the first case and the last two functions are considered for the second case of my photon production. The thermal photon emission rate is found that it is infra-red divergent for the massless quarks and this divergence in the quark mass is regulated using different cut-off in the quark mass. However, I remove this divergence using the technique of Braaten and Pisarski in the thermal mass of the system in my model of calculation with a coupling parameter of QGP fireball.

Thus, the production rate of the thermal photon is found to be smoothly worked by this cut-off technique of this model and the result is found to be increasing function with the increase of the variation in the value of chemical potential $\mu$.

PACS numbers: 25.75.Ld, 12.38.Mh, 21.65.+f

The study of the fundamental theory of strong interactions is very much important for the present scenarios of heavy ion collider physics. This strong interaction shows a phase transition from normal nuclear matter to very high nuclear density of deconfined phase of quark and gluon which are defined as colour exchange particles. These deconfined quark and gluon form plasma state of matter, the so called Quark-Gluon Plasma (QGP). The creation and evolution of such deconfined state of colour quark and gluon is due to the central collisions of two massive nuclei and it has now become a subject matter of present day of heavy-ion collision at the BNL Relativistic Heavy-Ion collider (RHIC) and the CERN Large Hadron collider (LHC). Moreover, the formation of this QGP is in time scale of $1 \text{ fm/c}$ after the collision. Perhaps, it is presumed that the early universe was in this state up to about a few microsecond after the Big-Bang or in the interior core matter of neutron star. Today the core program of ongoing relativistic nucleus-nucleus collision and heavy ion collision is to study the possible QGP phase of Quantum Chromodynamics (QCD) in which we study the properties of the strongly interacting matter at very high energy density and temperature. So the experimental measurement and theoretical investigation is one of the basic concepts in heavy-ion collisions. Moreover, if plasma is formed in such experiments, then there will be questions of emitting a large number of particles which consist of leptons and photons. These photons and leptons carry high energy and these electromagnetic productions are of much interest as they can not interact strongly in the subsequent process of hadronization. They have a large mean free path due to the small cross section for electromagnetic interaction in the plasma. So they carry the whole informations about the existence of the plasma and it is moreover true that over a large range of expected plasma temperature, its radiation can be observed throughout its evolution. On such aspects of electromagnetic radiation, they are considered to be the good probes for the formation of QGP.

So far, calculations of the photon production in a QGP at finite temperature have been studied and this temperature is related to the energy density $\epsilon$ given by the Stefan-Boltzmann $\epsilon \sim T^4$ and the thermodynamic relation for the system is given as $T \frac{d\rho}{dT} - p = \epsilon$; $p = \frac{1}{3} \sigma T^4 - A T$ and the linear term is the non-perturbative effect for calculation of the pressure and $'A'$ is a constant parameter. As indicated, most calculations do not involve the chemical potential in electromagnetic production even though there is no fully transparency in central midrapidity region shown by microscopic models [4,5]. Even at experiments at AGS and SPS, the chemical potential can not be neglected. In this situation, the photon production is not only the functions of temperature but also the chemical potential. Among the few calculations, Dumitru et al. [6] calculated the photon production in rich baryon density and M.Strickland[7] too, found this thermal photon using J"{a}tter distribution function. Again, Hammon[8] and coworkers have indicated that the initial QGP system produced at the RHIC energies have finite baryon density. In this way, Mujumder et al.[9] and Bass et al.[10] have pointed out the parton rescattering and fragmentation lead to a substantial increase in the net-baryon density at midrapidity region. Very recent work by He Ze-Jun et al.[11] is one of interesting results of thermal photon from this rich baryon QGP too. Thus, quark chemical potential is very much influencing factor for the calculation of this paper. As stated above, the Stefan-Boltzmann function for energy $\epsilon \sim T^4$, it is modified that the EOS for this case is expressed as:
where \( f_i \) are the particle distribution functions of \( E_i, \mu \) and \( T, \ i = 1, 2, 3 \) denotes the quark , antiquark and gluonic particles and \( |M_i|^2 \) is the amplitude for the corresponding collision which is given as : \( |M_i|^2 = \frac{d\sigma}{d\mu} (q_1 \bar{q}_2 \rightarrow \gamma \mu) \nu_{q\bar{q}} \) and \( N_s \) is degree of freedom of the quark. By plugging the corresponding distribution function in the above integration , it obtains the photon yields through annihilation process.

\[
E_\gamma \frac{dN^\text{ann}}{dpd^4X} = \frac{5\alpha_e \alpha_s T^2}{27\pi^2} \exp\left(-\frac{E}{T}\right) \\
\times \left\{ \ln\left(\frac{4ET}{m_q^2}\right) - C_F - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{\ln(n)}{n^2} \right\} 
\]

and this expression is independent of the chemical potential. But in the compton process, it can be performed through these two reactions : \( gg \rightarrow \gamma g \); \( gg \rightarrow \gamma q \).

In a similar way, it does the compton process with the same frequency distribution and its photon yields as:

\[
E_\gamma \frac{dN^\text{comp}}{dpd^4X} = 4N_s N_e \sum_{f=1}^{N_f} \frac{1}{(2\pi)^6} \int d^3p_1 d^3p_2 E_\gamma \\
\times f_1 f_2 (1 + f_3) |M_i|^2 
\]

where \( f_i \) are the particle distribution functions of \( E_i, \mu \) and \( T, \ i = 1, 2, 3 \) denotes the quark , antiquark and gluonic particles and \( |M_i|^2 \) is the amplitude for the corresponding collision which is given as : \( |M_i|^2 = \frac{d\sigma}{d\mu} (q_1 \bar{q}_2 \rightarrow \gamma q) \nu_{q\bar{q}} \) and \( N_s \) is degree of freedom of the quark. By plugging the corresponding distribution function in the above integration , it obtains the photon yields through annihilation process.

\[
E_\gamma \frac{dN^\text{comp}}{dpd^4X} = \frac{5\alpha_e \alpha_s T^2}{27\pi^2} \exp\left(-\frac{E}{T}\right) \\
\times \left\{ \ln\left(\frac{4ET}{m_q^2}\right) - C_F - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{\ln(n)}{n^2} \right\} 
\]

where \( C_{Euler} \) is Euler number \( 0.577215 \). In the above equation , the first polarity \( \mp \) shown in above equation , the upper one is compton process for the quark and lower one is for antiquark and the second polarity \( \mp \) shown second in the equation is for antiquark and quark . So now the final production rate for both cases of annihilation as well as compton process is shown in Fig.1 and 2 subsequently. This calculation of photon production through annihilation for the hot QGP system as well as transition temperature is shown in the Fig. 1.

Again for the second calculation of photon yield, I proceed the same technique through annihilation and compton process by using the Fermi-Dirac distribution functions \( f_i(E_i) = \frac{1}{\exp(\frac{E_i}{T}) - 1} \); here 'd' denotes for the
quark and antiquark for strong interaction and Boltzmann distribution function indicated above is used for gluon. I like to compare this results with the previous results as mentioned in the first case. Plugging the corresponding frequency distribution in eqn. (5) and (7) for annihilation and compton process, I obtain the photon production rate per space volume and found to be as:

\[ \frac{dN^{ann}}{dP \gamma d^4X} = \frac{5\alpha_c \alpha_s T^2}{9\pi^4} \frac{1}{\exp\left(\frac{E-\mu}{T}\right) + 1} \times \left\{ \left[ \ln\left(\frac{4ET}{m_q^2}\right) - C_{Euler} - 1 \right] \right\} + \left(1 - \exp\left(\frac{\mu}{T}\right) \right) \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} \exp\left(-\frac{\mu n}{T}\right) \left\{ \ln\left(\frac{4ET}{m_q^2}\right) - C_{Euler} - 1 - \ln(n) \right\} \]

where \( C_{Euler} \) is the same Euler number and \( \alpha_e = 1/137 \).

However, in this annihilation process, there are two major parts of the contribution in the photon yield. One is due to quark and another is from antiquark. This result too is shown in Fig.3 and the corresponding calculated photon yield rate through compton process is:

\[ \frac{dN^{comp}}{dP \gamma d^4X} = \frac{10\alpha_c \alpha_s T^2}{9\pi^4} \frac{1}{\exp\left(\frac{E+\mu}{T}\right) + 1} \times \left\{ \left[ \ln\left(\frac{4ET}{m_q^2}\right) - C_{Euler} + 1/2 - \ln(n) \right] \right\} \]

Again, here the polarity before the exponential function, the upper one is for quark and lower one is for antiquark. The above expressions show the computed thermal spectrum results. There is in need of setting the quark mass in all photon yield expressions as the massless quark shows divergent in the infrared region. So the quark mass is replaced by infrared cut-off which is \( 2k_c^2 \).

This replacement is being done through the technique of Braten and Pisarski \[13\] and \( k_c^2 = \frac{4\gamma^2T^2}{\Lambda^2} \) where \( \gamma \) is the phenomological flow parameter \[15\] and Bose-Einstein distribution function for the incoming quark, antiquark \( \bar{q} \), and Bose-Einstein distribution for incoming gluon \( \gamma \).

Results and Conclusions: In this present paper, I attempt to evaluate the photon production rate through two processes using the Boltzmann distribution function and Bose-Einstein distribution function for the incoming particles quark, antiquark and gluon for hot QGP system as well as just around transition phase region for different coupling parameters based on \( \gamma_g = 6\gamma_q \) or \( \gamma_q = 8\gamma_q \) in the first calculation. The photon production rate for both of these coupling parameters are found to be almost similar in both the calculations of annihilation as well as the compton process in this first case. So either this \( \gamma \) factor with \( \gamma_g = 6\gamma_q \) or \( \gamma_q = 8\gamma_q \) is very important for photon production rate in both cases with this two temperatures \[14\]. In the annihilation process of the first case, the chemical potential does not play any role for both of the temperatures but as the temperature rises, the photon production is less suppressed with the high temperature which is clearly defined in Fig.1. In the case of compton process, there is some effect in producing the photon when the chemical potential is very high compared to the temperature. There is diverging even though by the effective mass of the quark with coupling parameter at
low temperature. Only when the chemical potential is around $\mu = 0.25$ GeV, the result can be obtained at the hot QGP. At transition temperature, we can not see this photon radiation.

In the second case, the photon radiation through annihilation is found to be sharp with the chemical potential.

With the increase in the value of $\mu$, the photon radiation is increased in the hot QGP shown in Fig. 3 and still divergence is coming out for the transition temperature. But the compton process such as $q\bar{q} \rightarrow \gamma q$, the result is shown in Fig. 4 for the case of the hot QGP. Again, it follows the behaviour of the annihilation with less suppression. Now, the photon suppression for the trans-
position temperature is still higher as compared to the hot plasma in compton process of the second case of distribution function. If we use the compton process for $\bar{q}g \rightarrow \gamma \bar{q}$, there is no much distiction about the suppression with the chemical potential even at high temperature without resolution in the scale. Looking into its resolution, I can see their distiction with effect of the chemical potential $\mu$. Moreover, it is necessary to look into the case of this photon production due to the transverse momentum $P$ factor too. Only the transverse momentum $P$ plays the role in the case of annihilation process of my first calculation. There is a wide difference in their photon production with the low value of the transverse momentum. It can not observe much difference in the second case of my calculation for both annihilation and compton process. Above all, photon production or suppression is observed in both the cases of temperature for these distribution function in the second case. But it is well contributed by the hot QGP. It shows that there are emission of electromagnetic radiation in the hot QGP.

Acknowledgments

We are very thankful to Dr. R. Ramanathan and Dr. K.K. Gupta for their constructive suggestions and discussions.

[1] F. Wilczek, hep-ph/0003183; D. E. Kharzeev, J. Rau, hep-ph/0004075; S. S. Singh et al., hep-ph/0607005.
[2] D. Boyanovsky et al., Phys. Rev. D 68 (2003) 055018; D. Boyanovsky et al., Nucl. Phys. B (2005) 212.
[3] E. V. Shuryak, Phys. Lett. B 78 (1978) 15; K. Kajantie and H. I. Miettinen, Z. Phys. C 9 (1981) 341; G. Domokos and J. Goldman, Phys. Rev. D 23 (1981) 203.
[4] T. S. Biro, E. V. Doorn, B. Muller, M. H. Thomas and X. N. Wang, Phys. Rev. C 48 (1993) 1275.
[5] D. Dutta, A. K. Mohanty, K. Kumar, and R. K. Choudhury, Phys. Rev. C 61 (2000) 064911.
[6] Dumitru et al., Modn. Phys. Lett. A 8 (1993) 1291; T. Peitzmann, Pram. Jour. Phys. 60 (2003) 651; M. M. Aggarwal et al., WA98 Collaboration, Phys. Rev. Lett. 85 (2000) 3595; C. T. Traxler et al., Phys. Lett. B 346 (1995) 329; nucl-ex/0006007, nucl-ex/0008004.
[7] M. Strickland, Phys. Lett. B 331 (1994) 245; J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D 44 (1991) 2774; Phys. Rev. D 47 (1993) 4171; F. D. Steffen et al., Phys. Lett. B 510 (2001) 98; P. Aurencche, F. Gelis R. Kobes and H. Zaraket, Phys. Rev. D58 (1998) 085003; J. Alam, S. Sarkar, T. Hatsuda, T. K. Nayak, and B. Sinha, Phys. Rev. C 63 (2001) 021901(R); R. Bai, H. Nakagawa, A. Neigawa, and K. Redlich, Z. Phys. C 53 (1992) 43; S. Wang and D. Boyanovsky, Phys. Rev. D 63 (2001) 051702(R).
[8] Hammon N et al., Phys. Rev. C 61 (1999) 041901; Geiger K et al., Phys. Rev. D 47 (1993) 4905; G. D. Moore hep-ph/0403161.
[9] T. DeRafael, hep-th/9712085; V. Rusanov and Quark-Gluon Plasmas edited by R. C. Hwa, world scientific, 1991.
[10] Bass S et al., Phys. Rev. Lett. 91 (2003) 052302.
[11] G. Li et al., Phys. Rev. D 68 (2003) 054003.
[12] J. Alam, S. Sarkar, T. Hatsuda, T. K. Nayak, and B. Sinha, Phys. Rev. C 63 (2001) 021901(R); R. Bai, H. Nakagawa, A. Neigawa, and K. Redlich, Z. Phys. C 53 (1992) 43; S. Wang and D. Boyanovsky, Phys. Rev. D 63 (2001) 051702(R).
[13] Hammon N et al., Phys. Rev. C 61 (1999) 041901; Geiger K et al., Phys. Rev. D 47 (1993) 4905; G. D. Moore hep-ph/0403161.
[14] T. DeRafael, hep-th/9712085; V. Rusanov and Quark-Gluon Plasmas edited by R. C. Hwa, world scientific, 1991.
[15] Bass S et al., Phys. Rev. Lett. 91 (2003) 052302.
[16] G. Li et al., Phys. Rev. D 68 (2003) 054003.
[17] J. Alam, S. Sarkar, T. Hatsuda, T. K. Nayak, and B. Sinha, Phys. Rev. C 63 (2001) 021901(R); R. Bai, H. Nakagawa, A. Neigawa, and K. Redlich, Z. Phys. C 53 (1992) 43; S. Wang and D. Boyanovsky, Phys. Rev. D 63 (2001) 051702(R).
[18] Hammon N et al., Phys. Rev. C 61 (1999) 041901; Geiger K et al., Phys. Rev. D 47 (1993) 4905; G. D. Moore hep-ph/0403161.
[19] T. DeRafael, hep-th/9712085; V. Rusanov and Quark-Gluon Plasmas edited by R. C. Hwa, world scientific, 1991.; Bass S et al., Phys. Rev. Lett. 91 (2003) 052302.