Photon radiation from hot and dense matter of quark gluon plasma

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Abstract. We work on photon radiation from hot and dense matter of quark gluon plasma (QGP). The total photon spectra of leading order (LO) process is produced in relativistic mass collisions of two nuclei using various value of quark phenomenological flow parameter dependent on quark chemical potential in quark mass. The total photon measurement is strongly increasing function of quark flow parameter ranging $2\gamma_q \leq \gamma_q \leq 8\gamma_q$ and also find appreciable enhancement at the Relativistic Heavy Ion Collider (RHIC) at BNL and the Large Hadron Collider (LHC) at CERN as a result of high temperature and chemical potential using quark phenomenological flow parameter. The results obtained are presented on the study of photon production of leading order process. Thus, the study of photon radiation from hot and dense matter provides a valuable information in the formation and evolution of QGP and in the subsequent investigation of its properties. The results are compared with other theoretical work.

1. Introduction

Since long, the study of massive nuclear collisions at RHIC and LHC have become an important and unique situation to study the QGP. The experiments in heavy ion collision explore a new form of quantum chromodynamics matter where the net baryon density is non-vanishing with unusual properties in the early stage called the quark-gluon plasma (QGP) \cite{1,2}. Now, this field has entered into a new era of measurements, it is therefore important to consider the non vanishing chemical potential in a hot and dense nuclear matter of QGP. In order to deal with hot and dense matter of QGP, a precise study of heavy ion phenomenology is required\cite{3}. Although there are many phenomenological models used to describe the properties of QGP, a perfect evidence is still not confirmed.

The experiments have searched for a variety of signatures of a quark-gluon plasma. Many indirect signatures have been suggested. Among all, photon radiation is one of the important phenomenological tool to study hot and dense matter of quark gluon plasma. These photons are emitted throughout the evolution of a heavy-ion collision \cite{4,5}. Since these valuable probes suffer little interaction with the QGP or hadronic matter, they carry information deep inside the hot and dense QGP. These particles do not experience the strong force, suffer little final state interactions and having large mean free path in strongly interacting medium. This makes the photons an ideal probe of the QGP \cite{6-18}.

Therefore photons provide direct information via electromagnetic interaction from the collision zone of plasma and escape to the detector undistorted through the hot and dense
medium [5, 19]. The theoretical calculations find a dominant contribution of the photons produced in the QGP to the direct photon spectrum [20 – 22]. Apart from these advantages, these probes have some difficulties due to massive pollution from different sources.

In past decade, the works on photon radiation have been studied by ignoring the quark chemical potential [23 – 28]. After the confirmation of chemical potential at RHIC energies [29, 30], the thermodynamic equilibrium is a function of both the temperature and chemical potential that in turn lead to the modification of photon production. Physicists calculated the photon rate of a QGP at finite chemical potential [31, 32]. For more review on photon production in the context of finite quark chemical potential see Ref. [33 – 42]. Also Biro, Strickland and their co-workers [43, 44] studied the photon emission in a chemically equilibrating baryon free QGP system.

Many observables have been proposed to probe the QGP. Here we extend our work by considering the LO processes for photon radiation. In this phenomenological model, we use finite quark mass that generated due to the interaction among quarks and/or gluons [23, 45, 46]. At non vanishing chemical potential, this quark mass depends on temperature as well as chemical potential using flow parameters and used to avoid infrared divergences. The photon emission rate is observed using various initial condition taken from RHIC and LHC energies. The quark mass is suitably modified using Ref. [23, 45]:

\[ m_q^2(T, \mu_q) = \gamma_q \left( 1 + \frac{\mu_q^2}{\pi^2 T^2} \right) g^2(k) T^2. \]  

Here, \( g^2(k) = 4\pi \alpha_s \) with QCD strong coupling constant \( \alpha_s \) defined as:

\[ \alpha_s = \frac{4}{(33 - 2N_f) \ln(1 + \frac{k^2}{\Lambda^2})}. \]

In the above expression, \( k \) is defined as:

\[ k = \left[ \frac{\gamma N^{1/2} T^2 A^2}{2} \right]^{1/4}. \]

The parameter \( N \) is given as, \( N = \frac{16\pi}{33 - 2N_f} \).

The earlier value \( \gamma_q \) is modified as \( \gamma_q [1 + \mu_q^2/\pi^2 T^2] \) for the good approxiamtion of temperature [47]. On the other side, we put gluon parameter remain same i.e. \( \gamma_g \) as \( \gamma_q \). The value of \( \gamma_q \) is fixed as 1/3. The parametrization factor \( \gamma^2 = 2[\gamma_q^2 + \gamma_g^2] \). We fix the range of \( \gamma_q \) as \( \gamma_q = 2\gamma_g \) to \( 8\gamma_g \) and \( \gamma_g = 1/3 \) in our calculation [47]. \( T \) is the temperature and \( g(k) \) is first order QCD running coupling constant [23, 45]. Using modified quark mass, we study the photon radiation of leading order process in relativistic massive collisions of two nuclei using various value of quark phenomenological flow parameter dependent on quark chemical potential with flavor \( N_f=2 \).

The total photon spectra are calculated by integrating the production rate over the four-volume of the collision while taking into account the dynamics of the matter. We plot total photon production with low and intermediate transverse momentum region \( k_T \leq 5 \text{ GeV} \) at temperature \( T = 0.57 \text{ GeV} \) and \( T = 0.83 \text{ GeV} \) using various value of quark flow parameter dependent on quark chemical potential at RHIC and LHC. It is quite certain that photons in the relevant range of transverse momentum provide valuable information in the hot and dense matter of QGP. Thus, the present work is interesting and important to account for these effects in the measurements of photon radiation of LO process at the hot phase of temperatures.

Thus, we organize the paper as: In section 2, we present the photon radiation from hot and dense matter of QGP. In last section 3, we give the results and conclusion.
2. Photon radiation from hot and dense matter of QGP

The study of photons have now become an exciting field in high energy heavy ion collision. Many theoretical and experimental physicists all over the world are working in this field to understand the best signatures of the QGP formation and measuring them. The significant work has been done by many authors and lots of research is on the way to study the hot and dense matter of QGP. Since photons have been proposed as a promising signature of the QGP in relativistic heavy-ion collision, our interest lies within hot and dense nuclear matter in heavy ion collision. The complete calculation of photon radiation from a partonic medium to order of $s$ has been considered in the Ref. [24, 25, 48, 50]. The relevant LO processes include different channels like quark-antiquark annihilation, QCD compton scattering, bremsstrahlung (brems) and quark-antiquark annihilation with scattering (aws). For the present calculation, the photon rate of momentum $k$ is given by the expression [49, 50]:

$$\frac{dN}{d^4x d^3k} = 0.004 A(k) \left[ \ln \left( \frac{T}{m_q(T, \mu_q)} \right) + \frac{1}{2} \ln \left( \frac{2k}{T} \right) + C_T \left( \frac{k}{T} \right) \right]$$

The leading-log coefficient $A(k)$ is given as:

$$A(k) = 0.029 \frac{m_q^2(T, \mu_q)}{k} f_D(k)$$

Here $f_D(k)$ is the fermi distribution function. The dependence on the specific photon production process is written in the term $C_T \left( \frac{k}{T} \right)$.

$$C_T \left( \frac{k}{T} \right) = C_{2\leftrightarrow2} \left( \frac{k}{T} \right) + C_{brems} \left( \frac{k}{T} \right) + C_{aws} \left( \frac{k}{T} \right).$$

The non-logarithmic two-to-two contribution $C_{2\leftrightarrow2}$ for general $k/T$ and the rate of photon production by bremsstrahlung and annihilation with scattering are computed. This requires solving a non-trivial integral equation to determine this rate. The thermal corrections to the dispersion relations for incoming or outgoing particles can no longer be neglected in these $2 \leftrightarrow 2$ processes. The $C_T \left( \frac{k}{T} \right)$ is the non-trivial function that can only be solved numerically. All results for $C_T \left( \frac{k}{T} \right)$ are evaluated by Ref. [49, 50].

We compute above photon rates of complete leading order over the space time volume of the reaction according to Bjorken’s model at temperature $T = 0.57$ GeV and $T = 0.83$ GeV with the various value of quark flow parameter dependent on chemical potential for flavor $2$. The volume element $d^4x = d^2x_T dy d\tau d\tau$, where $\tau$ is the evolution time of the system and $y$ is the rapidity. By considering the central collisions, the integration over transverse coordinates yields a factor of $d^2x_T = \pi R_A^2$. We finally obtain the total photon spectra at hot temperature using Ref. [23, 42, 45, 50]. It is expressed as:

$$\frac{dN}{d^2k_T dy} = \pi R_A^2 \int_{\tau_0}^{\tau_f} \tau d\tau \int_{y_{nuc}}^{y_{	ext{fin}}} dy \left( k - \frac{dN}{d^2k_T dy} \right).$$

Where $\tau$ is time evolution determined with the temperature from initial to final state with corresponding rapidity value at RHIC and LHC energy. The parameter $k_T$ is the photon transverse momentum. Thus, with the values of rapidity, $k_T$ and other various set of initial condition, we obtain the total photon spectrum of LO processes at RHIC and LHC with quark flavor $N_f = 2$. 

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3. Results and Conclusion

The theoretical knowledge of the production rates is an essential ingredient for the phenomenological description of photon signatures. In this contribution, we perform the calculation of LO processes for photon radiation from hot and dense matter of QGP which consist QCD Compton Scattering, quark-antiquark annihilation, bremsstrahlung and quark-antiquark annihilation with scattering using various initial condition at RHIC and LHC with the effect of phenomenological flow parameters such as $\gamma_q'$ and $\gamma_g$ dependent on quark chemical potential in quark mass.

![Figure 1. Photon Spectra at temperature $T = 0.57$ GeV using various value of quark flow parameter dependent on quark chemical potential at RHIC.](image)

The calculation of LO processes for photon radiation is extended with the suitable range of phenomenological parameter from $\gamma_q = 2\gamma_g$ to $8\gamma_g$ that dependent on finite value of quark chemical potential with temperature $T = 0.57$ GeV and $T = 0.83$ GeV for flavor $N_f = 2$. We study the total photon spectrum over the space-time evolution of QGP.

In Figure [1], we plot total photon spectra for various value of phenomenological parameter ranging from $\gamma_q = 2\gamma_g$ to $8\gamma_g$ dependent on quark chemical potential $\mu_q = 0.30$ GeV at hot temperature $T = 0.57$ GeV for flavor $N_f = 2$. We found that the total photon rate strongly increases with increases the quark phenomenological parameter at quark chemical potential $\mu_q = 0.30$ GeV and at hot temperature $T = 0.57$ GeV. Also there is uniform fall in total emission rate as a function of transverse momentum $k_T$ for all values of phenomenological parameter.

The strength of the photon radiation enhances due to the baryon rich plasma. The larger number of anticipating quarks brings more interactions, resulting enhancement in the production rate. It is also observed that the photons yield suppress more for the higher value of flow parameter and at $\gamma_q = 8\gamma_g$, suppression is more as comparison to the lower values. At closer inspection, the production rate is low for the value of flow parameter $\gamma_q = 6\gamma_g$ up to transverse momentum $k_T=2$ GeV and for $\gamma_q = 8\gamma_g$ up to $k_T=3.2$ GeV and afterwards photon rate increases.

The total rate is significantly large and more dominant in the relevant range of transverse momentum. Thus the value above $\gamma_q > 8\gamma_g$, quark flow parameters is not suitably fit to get the photon spectra. At the same time, it is also not right to take low value of quark phenomenological parameter i.e. $\gamma_q < 2\gamma_g$ since for these values the calculation for photon rate diverges. We compare our work with other theoretical work at zero chemical potential [45, 50]. Therefore, the results are much enhanced in the presence of chemical potential as comparison to zero chemical potential of other works [45, 50].

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In Figure [2], with the similar line, we plot total photon spectra for LHC at hot temperature $T = 0.83$ GeV and at fix value of quark chemical potential $\mu_q = 0.30$ GeV for flavor $N_f = 2$. It is seen that the photon rate at LHC is much higher than the RHIC data. At LHC, the enhancement in the photon yield is of the order of $10^1$ to $10^2$. So, the production rate at LHC is significantly large as comparison to RHIC energy.

Again we observe that the production rate is low for the value of flow parameter $\gamma_q = 6\gamma_g$ up to transverse momentum $k_T = 2.7$ GeV and for $\gamma_q = 8\gamma_g$ up to $k_T = 4.5$ GeV and afterwards photon rate increases. The total production rate is very large and more dominant in the relevant range of transverse momentum. Overall our model results are suitably fit for $\gamma_q = 2\gamma_g$ to $\gamma_q = 8\gamma_g$ with various sets of parameter. In this case, the results are much enhanced in the presence of chemical potential at LHC as comparison to RHIC energy and production rate of photon at non-vanishing chemical potential is much larger than the zero chemical potential.

Finally, we conclude that the total photon yield is calculated by integrating the rate over the plasma volume created by the expansion and is compared with other theoretical work [45, 50] at zero chemical potential. The measurement of leading order processes for photon production in the QGP which consist QCD Compton Scattering, quark-antiquark annihilation, bremsstrahlung, and quark-antiquark annihilation with scattering provide a good opportunity to study the photon radiation from hot and dense matter of QGP.

At both RHIC and LHC energies, total photon yield is appreciably large with the effect of quark phenomenological flow parameter and hence it is a strong increasing function at high temperature and chemical potential. So, our results are fitted well with these sets of parameter and show appreciable enhancement in the production of photon. By considering the quark flow parameter in quark mass, photon measurements may play an important role.

Overall photons are the best probe of QGP in relativistic heavy-ion collisions.

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