Photons from Hot and Dense Hadronic Matter

Pradip Roy
Saha Institute of Nuclear Physics, Kolkata 700 064, INDIA

Abstract.

I. Introduction
Study of photon spectra emanating from hot and dense hadronic matter formed in ultra-relativistic heavy ion collisions is a field of considerable current interest. Electromagnetic probes have been proposed to be one of the most promising tools to characterize the initial state of the collisions [1]. Because of the very nature of their interactions with the constituents of the system they tend to leave the system without much change of their energy and momentum. In fact, photons (dilepton as well) can be used to determine the initial temperature, or equivalently the equilibration time. These are related to the final multiplicity of produced hadrons by isentropic expansion of the system formed due heavy ion collisions. By comparing the initial temperature with the transition temperature from lattice QCD, one can infer whether Quark Gluon Plasma (QGP) is formed or not. Furthermore, study of two photon interferometry could determine the source sizes at the very early stages of the collisions [2]. It has also been emphasized that to identify single photons from QGP, correct estimation from non-QGP sources is of utmost importance.

The hadronic matter produced in heavy ion collisions is usually considered to be a gas of the low lying mesons $\pi$, $\rho$, $\omega$, and $\eta$, $a_1$ and nucleons. Reactions between these as well as the decays of the $\rho$ and $\omega$ were considered to be the sources of thermal photons from hadronic matter [3, 4, 5]. In our quest for additional sources of thermal photons from hadronic matter we failed to find discussion on the role of baryons and a priori there is no reason for this. Hence, we consider it to be important and we shall see that these additional sources of photons contribute substantially in the thermal photon spectra.

In early nineties Kapusta et al. [4] has shown that photon emission rate from QGP is equal to that from hot hadronic matter at a fixed temperature [4]. Apparently this observation led to the conclusion that QGP photon might not be visible in a large hadronic background. Their calculation of photon emission rate from QGP was based on one-loop calculation. The next-to-leading order 2-loop calculation was done by Auranche et al. [6] and it was turned out to be of the same order in $\alpha_s$ and of the same size or larger than the 1-loop result. So the hope of observing the QGP photons was again raised. However, this calculation is incomplete in the sense that it does not incorporate $O(1)$ suppression due to multiple scattering during the emission process. This point was later clarified by the same authors in a subsequent work [7]. The complete calculation of photon emission rate from QGP to order $\alpha_s$ has recently been completed by re-summing all the contributions from all orders in the multi-loop expansion [8].
In a hot and dense hadronic environment it is expected that the properties of hadrons change due to its interactions with the constituents of the medium. There are ample experimental evidences of this fact. The measurement of invariant mass spectra of electron-positron pairs in 12 GeV $p + A$ reactions shows a significant difference below the $\omega$ meson between $p + C$ and $p + Cu$ interactions\cite{9}. This observation indicates that the spectral shape of the mesons is modified inside the nuclei. The enhancement of lepton pair yield in CERES data below the $\rho$-mass can only be explained by assuming the in-medium modifications of the $\rho$ meson\cite{10, 11}.

We organize the paper as follows. In section II we shall discuss the formalism of photon production rates along with the results from QGP and hadronic matter. In particular, we shall focus on the the role of intermediary $a_1$ meson in the $\pi \rho \rightarrow a_1 \rightarrow \pi \gamma$. Section III will be devoted to discuss the in-medium effects in the photon production rates. Finally, we summarize in section IV.

II. Photon production rates

In relativistic heavy ion collisions one might expect that QGP is produced initially, it expands, cools and undergoes a phase transition when the temperature drops down to $T_c$. Another possible scenario is that the initial state consists of pure hadrons only. In both the cases hadronic matter appears inevitably. There are various sources of photons from relativistic heavy ion collisions: (i) Photons from QGP, (ii) photons from hadronic matter, (iii) photons from decay of $\pi^0 (\eta) \rightarrow \gamma \gamma$ and (iv) hard photons ($A + B \rightarrow \gamma X$). Decay photons are generally subtracted from the data and hence, we shall not discuss it here. Hard photon yield can be reliably calculated using perturbative quantum chromodynamics. Therefore, we shall discuss the thermal photon yield from hot hadronic matter in somewhat detail and shall be very brief while discussing photons from QGP.

a. Photons from Hadronic Matter

First we shall consider photon emission from reactions of the type $M M \rightarrow M \gamma$, where $M$ generically denotes the low lying mesons. As mentioned earlier these type of reactions are thought to be the only sources of hadronic photons and a substantial amount of work has been done earlier\cite{3}. Recently Turbide et al.\cite{12} has claimed that $\omega$-meson exchange $t$-channel exchange diagram in $\pi \rho \rightarrow \pi \gamma$ reaction is the single most dominant process of photon production for $E_\gamma > 2$ GeV. We have made a detail study of this process considering all possible diagrams involving $\pi$, $\rho$, $\omega$, $\phi$ and $a_1$ in the intermediate state. For this purpose we have used different effective Lagrangians to obtain the relevant vertices. These include: (i) SU(2)$_L \times$SU(2)$_R$ Linear Sigma Model (LSM) by Kim et al.\cite{13}, (ii) A purely phenomenological approach by Xiong et al.\cite{14}, (iii) U(2)$_L \times$U(2)$_R$ chiral theory of mesons by B. A. Li\cite{15}, and (iv) SU(3)$_L \times$SU(3)$_R$ Non-linear Linear Sigma Model by Song et al.\cite{5}.

The emission rates of photons from the reaction $\pi \rho \rightarrow a_1 \rightarrow \pi \gamma$ for various phenomenological interactions mentioned above have been evaluated and the results are shown in fig. (1). We observe that the emission rates are different for these Lagrangians. This is primarily because these Lagrangians predict different values of the decay width ($\Gamma_{a_1 \rightarrow \pi \gamma}$) for the process $a_1 \rightarrow \pi \gamma$. The experimental value of $\Gamma_{a_1 \rightarrow \pi \gamma} = 640 \pm 246$ Kev. The $a_1 \pi \gamma$ interaction of\cite{13} predicts $\Gamma_{a_1 \rightarrow \pi \gamma} = 670$ Kev. The interaction Lagrangians of Refs.\cite{14, 15} predict the above decay width as 252 keV, 1420 keV respectively. These differences are clearly manifested in the photon emission rates shown in fig. (1).

Therefore, in our calculation we use the model of Kim et al.\cite{13}. Individual contribution from different exchanges in the concerned reaction is shown in fig (2). It is seen that within our model the $a_1$ exchange contribution still remains dominant\cite{16}.

In fig (3) we compare the existing calculation with our new result. We find that the results are not interestingly different.
Figure 1. Photon production rate from $\pi \rho \rightarrow a_1 \rightarrow \pi \gamma$ for various effective Lagrangians

Figure 2. Individual contribution from different exchanges in the $\pi \rho \rightarrow \pi \gamma$

Figure 3. Comparison between old and new results of photon yield from $\pi \rho \rightarrow \pi \gamma$
The other important observation in this work is the photon production from reactions of the type \cite{17} \( P N(\bar{N}) \rightarrow \gamma N(\bar{N}), \ N \bar{N} \rightarrow \gamma P, \ V N(\bar{N}) \rightarrow \gamma N(\bar{N}), \ N \bar{N} \rightarrow \gamma V, \ A N(\bar{N}) \rightarrow \gamma N(\bar{N}), \ N \bar{N} \rightarrow \gamma A \), where \( P, A, V \) and \( N \) denote pseudo-scalar, axial vector, vector and nucleons respectively. As mentioned in the introduction that \textit{a priori} there is no reason for not considering these type of reactions. We use a phenomenological Lagrangian to evaluate the photon yield from the above mentioned reactions.

\[
\mathcal{L}_{VNN} = g_{\rho NN} \left[ \bar{N} \gamma^{\mu} \tau N \cdot \rho_{\mu} \right] - \frac{\kappa}{2m_N} \bar{N} \sigma^{\mu\nu} \tau N \cdot \partial_{\nu} \rho_{\mu} - g_{\omega NN} \bar{N} \gamma^{\mu} N \omega_{\mu}
\]

\[
\mathcal{L}_{ANN} = \frac{g_{\pi NN}}{m_{\pi}} m_{\pi} \bar{N} \gamma^5 \gamma^{\mu} \tau N \cdot a_{1\mu}
\]

\[
\mathcal{L}_{PNN} = \frac{g_{\pi NN}}{m_{\pi}} \bar{N} \gamma^5 \gamma^{\mu} \tau N \cdot \partial_{\mu} \pi + \frac{g_{\eta NN}}{m_{\eta}} \bar{N} \gamma^5 \gamma^{\mu} N \partial_{\mu} \eta
\]

\[
\mathcal{L}_{em} = e A^{\mu} \left[ \bar{N} \gamma^{\mu} N - (\pi \times \partial_{\mu} \pi)_{3} \right]
\]

\[
- [\rho^{\nu} \times (\partial_{\nu} \rho_{\mu} - \partial_{\mu} \rho_{\nu})]_{3} + \frac{e}{2} F^{\mu\nu}(\rho_{\mu} \times \rho_{\nu})_{3}
\]

\[
+ \frac{eg_{\rho N f_{\pi}}}{m_{\rho}^{2}} F^{\mu\nu} [(\partial_{\mu} \bar{a}_{\nu} - \partial_{\nu} \bar{a}_{\mu}) \times \vec{\pi}]_{3}
\]

(1)

A monopole form factor of the type \((A^{2} - M^{2})/(A^{2} - X^{2})\), where \(A\) and \(M\) stand for the cutoff and the mass of the exchanged particle in the \(X(=t/u)\) channels, respectively. The values and the coupling constants are taken from Ref. \cite{18, 13}. It is to be noted here that the number of Feynman diagrams involved here is quite large and it requires too large a space to be presented here.

\textbf{b. Photons from QGP}

The photon emission rate from Compton \((q(\bar{q}) \rightarrow q(\bar{q}) \gamma)\) and annihilation \((q \bar{q} \rightarrow g \gamma)\) processes has been calculated from the imaginary part of the photon self-energy by Kapusta et al. \cite{4} in the 1-loop approximation. However, it has been shown by Auranche et al. \cite{6} that the two loop contribution is of the same order as the one loop due to the shielding of infra-red singularities. The complete calculation upto two loop was done by Arnold et al. \cite{8} and the rate is given by

\[
\frac{dN}{d^{4}k} = \frac{1}{(2\pi)^{3}} A \left( \ln[T/m_{\gamma}(T)] + \frac{1}{2} \ln(2E_{\gamma}/T) + C_{\text{tot}}(E_{\gamma}/T) \right),
\]

(2)

where \(E_{\gamma} = k\) and \(m_{\gamma}^{2}(T) = 4\pi \alpha_{s}T^{2}/3\) and \(A\) is the leading log coefficient given by

\[
A = 2 \alpha N_{c} \sum_{i} q_{i}^{2} \frac{m_{\gamma}^{2}(T)}{E_{\gamma}} f_{D}(E_{\gamma})
\]

(3)

and

\[
C_{\text{tot}} = C_{2-2}(E_{\gamma}/T) + C_{\text{brems}}(E_{\gamma}/T) + C_{\text{aws}}(E_{\gamma}/T)
\]

(4)

containing the dependence of the specific photon production processes. These are parametrized as follows:

\[
C_{2-2} = 0.04(E_{\gamma}/T)^{-1} - 0.3615 + 1.01 \exp(-1.35E_{\gamma}/T)
\]

\[
C_{\text{brems}} + C_{\text{aws}} = \sqrt{1 + \frac{N_{f}}{6} \left( \frac{0.548 \ln[12.28 + T/E_{\gamma}]}{(E_{\gamma}/T)^{3/2}} \right)}
\]
In fig. (4) we compare the photon production rates from QGP and hadronic matter at a fixed temperature. In the hadronic yield we include all the possible sources of photon production from hadronic matter (except the hadronic decays). It is seen that the hadronic matter shines more brightly than the quark matter. However, in the hadronic sector we do not include the form factors in the strong vertices. Inclusion of the form factors may deplete the hadronic yield by 10 - 15 \% \cite{3, 4}. But as shall see in the next section the inclusion of hadronic in-medium modifications enhances the rate by a factor \approx 2-3. Thus, with the incorporations of form factors and in-medium properties, the hadronic matter may still remain brighter.

III. In-medium properties of hadrons

The properties of hadrons are modified in a hot and/or dense medium. As mentioned earlier, there are enough experimental hints for this. For example, experimental data at KEK \cite{9} indicate significant shape changes in $e^+e^-$ invariant mass spectrum from $p+C$ to $P+Cu$ which means the spectral broadening of the decaying vector mesons. The Chaos Collaboration \cite{19} also indicated lighter sigma meson in $\pi^+A \rightarrow \pi^+\pi^\pm A'$ reactions. The dilepton measurement by CERES Collaboration in $Pb+Au$ collisions at CERN-SPS shows that there is enhancement in the yield below the rho meson mass. This observation could only be explained by assuming spectral modifications of hadrons in the medium (see fig. (5)) \cite{11}.

There are various theoretical models to estimate the spectral modifications of hadrons in the medium. We shall discuss Quantum Hadrodynamical Model (QHD) \cite{20} in some what detail and briefly mention the final results of the other models. Let us first consider how nucleon properties are modified in a medium. In QHD the nucleons interact with each other by the exchange of a scalar $\sigma$ and vector $\omega$ mesons (see fig. (6)).

The modified nucleon then enters in the $\rho$-self energy whose spectral function is given by

$$A_V = \frac{1}{\pi} \left[ \frac{\text{Im} \Pi}{(q^2 - m_V^2 + \text{Re} \Pi)^2 + (\text{Im} \Pi)^2} \right]$$

(6)

The self energy $\Pi$ is calculated using Walecka Model described by $\mathcal{L}_{VNN}$ in eq.(1).

The effective masses of hadrons in QHD can be parametrized as follows:
Figure 5. Dilepton spectra for \( \langle N_{ch} \rangle = 270 \).

![Diagram](image)

Figure 6. Feynman diagram for \( \rho NN \) and \( \sigma NN \) interactions. There is another diagram with \( \sigma \) replaced by \( \omega \).

![Diagram](image)

Figure 7. A typical Feynman diagram for in-medium effects in photon production

\[
\frac{M_N^*}{M_N} = 1 + \sum_{j=0,1,2,3} a_j \left( \frac{T}{T_c} \right)^{j+1} \tag{7}
\]

\( a_0 = 0.56, \ a_1 = -2.306, \ a_2 = 2.96, \ a_3 = -1.277 \) and

\[
\frac{m_{\rho}^*(\omega)}{m_{\rho}(\omega)} = 1 + \sum_{j=0,1,2,3} a_j \left( \frac{T}{T_c} \right)^{j+1} \tag{8}
\]

\( a_0 = 0.14(0.32), \ a_1 = -0.609(-1.28), \ a_2 = 0.958(1.745) \ a_3 = -0.6157(-0.827) \) for \( \rho \ (\omega) \).
Figure 8. Photon rate with and without in-medium effects from $M M \to M \gamma$ reactions.

So far as the other scenarios are concerned, in the Universal scaling scenario (USS), the effective mass of hadrons (except pseudo-scalar) is given by

$$m_H^* = m_H \left(1 - \frac{T^2}{T_c^2}\right)^\lambda$$

where, $\lambda = 1/6$ (Brown-Rho) and $\lambda = 1/2$ (Nambu)

A typical diagram of photon production where the medium effects enters is shown in fig. (7). If we include the in-medium effects in the photon production we see an enhancement by a factor of 2-3 in the yield (see fig. (8)). In the total rate from hadronic matter this enhancement will perhaps, be balanced by the decrease due to the inclusion of form factor in the hadronic vertices.

IV. Summary and Discussions

We have calculated the photon emission rate from hot and/or dense hadronic matter from all possible sources of photons. In fact, we have considered a new set of reactions (in addition to the existing sources of hadronic thermal photons) which were previously ignored. We find that the new set of reactions are equally important. The total rate from hadronic matter is then compared with that from quark matter and one finds that hadronic photons are brighter than that from QGP. This result implies that the observation of QGP photons seems to be difficult because of the large hadronic backgrounds.

The role of intermediary $a_1$ meson in the $\pi \rho \to \pi \gamma$ is re-visited. The observation of Turbide et al. [12] regarding the importance of $\omega$ meson $t$-channel diagram in the above mentioned reaction is no longer true within the ambit of the present model. In our model we find that the $a_1$ exchange diagram still constitutes the dominant contribution [16].

We have incorporated the in-medium effects in the photon producing reactions of the type $M M \to M \gamma$ and it is found that the photon yield increases by a factor of 2-3. However, we did not include the same in the new set of reactions involving nucleons. A detail study including all these effects along with space time evolution is in progress.

Acknowledgment: The author is grateful to J. Alam, S. Sarkar, A. K. Dutt-Mazumder, B. Dutta-Roy, B. Sinha, T. Hatsuda and B. Mohanty as this work was done in collaboration with them.

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