Measuring isotropization time quark gluon plasma from direct photon at RHIC

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\textbf{ABSTRACT}

We calculate transverse momentum distribution of direct photons from various sources by taking into account the initial state momentum anisotropy of quark gluon plasma (QGP) and late stage transverse flow effects. To evaluate the photon yield from hadronic matter we include the contributions from baryon-meson reactions. The total photon yield, calculated for various combinations of initial conditions and transition temperatures, is then compared with the recent measurement of photon transverse momentum distribution by the PHENIX collaboration. It is shown that due to the initial state anisotropy the photon yield from the QGP is larger by a factor of 8-10 than the isotropic case in the intermediate $p_T$ regime. It is also demonstrated that the presence of such an anisotropy can describe the PHENIX photon data better than the isotropic case in the present model. We show that the isotropization time thus extracted lies within the range $1.5 \geq \tau_{\text{iso}} \geq 0.5$ fm/c for the initial conditions used here.

\section{Introduction}

The primary goal of relativistic heavy ion collisions is to create a new state of matter, called quark gluon plasma and to study its properties through various indirect probes. Out of all the properties of the QGP, the most difficult problem lies in the determination of isotropization and thermalization time scales ($\tau_{\text{iso}}$ and $\tau_{\text{therm}}$). Studies on elliptic flow (upto about $p_T \sim 1.5 - 2$ GeV) using ideal hydrodynamics indicate that the matter produced in such collisions becomes isotropic with $\tau_{\text{iso}} \sim 0.6$ fm/c \cite{1, 2, 3}. On the other hand, using second order transport coefficients with conformal symmetry it is found that the isotropization/thermalization time has sizable uncertainties \cite{4}. Consequently, there are uncertainties in the initial temperature as well. The other uncertain parameters are the transition temperature $T_c$, the spatial profile, and the effects of flow. Thus it is very necessary to find suitable probes which are sensitive to these parameters. Electromagnetic probes have been proposed to be one of the most promising tools to characterize the initial state of the collisions \cite{5, 6}. 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 in heavy ion collisions. By comparing the initial temperature with the transition temperature from lattice QCD, one can infer whether QGP is formed or not. However, it should be remembered that to characterize the initial phase through photons one should take into account the late stage transverse flow and early stage momentum anisotropy, if any. Therefore, photons could be a good probe for early stages of collisions, provided the observed flow effects from the late stages of the collisions can be understood and modeled properly. The observation of pronounced transverse flow in the photon transverse momentum distribution has been taken into account in model calculations of photon $p_T$ distribution at various beam energies [7, 8, 11, 12, 13].

Photons are produced at various stages of the evolution process. The initial hard scatterings (Compton and annihilation) of partons lead to photon production, which we call hard photons. If QGP is produced initially, there are QGP-photons from thermal Compton plus annihilation processes. Photons are also produced in different hadronic reactions from hadronic matter either formed initially (no QGP scenario) or realized as a result of a phase transition (assumed to be first order in the present work) from QGP. In addition to that there is a large background of photons coming from $\pi^0$ and $\eta^0$ decays. The yield of excess photons can be obtained if this decay contribution is subtracted from the total photon yield. Photons from hadronic reactions and decays cannot be calculated in a model-independent way. The hadronic matter produced in heavy ion collisions is usually considered to be a gas of the low lying mesons $\pi$, $\rho$, $\omega$, $\eta$ 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 [5, 14, 15]. We also add the contributions from reactions involving baryons as these are found [16] to be comparable to that from the meson-meson reactions.

It is to be noted that while estimating photons from QGP, it is assumed that the matter formed in the relativistic heavy ion collisions is in thermal equilibrium. The measurement of elliptic flow parameter and its theoretical explanation also support this assumption. On the contrary, perturbative estimation suggests the slower thermalization of QGP [17]. However, recent hydrodynamical studies [4] have shown that due to the poor knowledge of the initial conditions there is a sizable amount of uncertainty in the estimate of thermalization or isotropization time. It is suggested that (momentum) anisotropy driven plasma instabilities may speed up the process of isotropization [18] and in that case one is allowed to use hydrodynamics for the evolution of the matter. However, instability-driven isotropization is not yet proved at RHIC and LHC energies.

Earlier works [7, 8, 19] on photon production assume isotropy from the very beginning, i.e. $\tau_{\text{iso}} = \tau_i$ (QGP formation time). In view of the absence of a theoretical proof behind the rapid thermalization and the uncertainties in the hydrodynamical fits of experimental data, such an assumption may not be justified. Hence in stead of equating the thermalization/isotropization time to the QGP formation time, in this work, we will introduce an intermediate time scale (isotropization time, $\tau_{\text{iso}}$) to study the effects of early time momentum-space anisotropy on the total photon yield and compare it with the PHENIX photon data [20, 21, 22]. In the present model the space-time evolution, during the interval $\tau_i < \tau < \tau_{\text{iso}}$, is modeled as in Ref. [23]. For the evolution from $\tau_{\text{iso}}$ to $\tau_F$ (freeze-out time) we use $(1+2)d$ ideal hydrodynamics.
Recently, it has been shown in Ref. [23] that for fixed initial conditions, the introduction of a pre-equilibrium momentum-space anisotropy enhances high energy dileptons by an order of magnitude. In case of photon transverse momentum distribution similar results have been reported for various evolution scenarios [24]. The model in Ref. [23] assumes two time scales: the QGP formation time, $\tau_i$, and the isotropization time, $\tau_{iso}$, which is the time when the system becomes isotropic in momentum space. Immediately after the formation of QGP at $T_i$ and $\tau_i$, the system can be assumed to be isotropic [25]. Subsequent rapid expansion of the matter along the beam direction causes faster cooling in the longitudinal direction than in the transverse direction [17]. As a result, the system becomes anisotropic with $\langle p_L^2 \rangle \ll \langle p_T^2 \rangle$ in the local rest frame. At some later time when the effect of parton interaction rate overcomes the plasma expansion rate, the system returns to the isotropic state again (at $\tau_{iso}$) and remains isotropic for the rest of the period.

The plan of the paper is the following. In the next section we will discuss the mechanisms of photon production from various possible sources and the space-time evolution of the matter very briefly. Section 3 is devoted to describe the results for various initial conditions and we summarize in section 4.

2 Formalism

2.1 Photon rate: Anisotropic QGP

The lowest order processes for photon emission from QGP are the Compton ($q(\bar{q}) g \rightarrow q(\bar{q}) \gamma$) and the annihilation ($q \bar{q} \rightarrow g \gamma$) processes. The rate of photon production from anisotropic plasma due to Compton and annihilation processes has been calculated in Ref. [26]. The soft contribution is calculated by evaluating the photon polarization tensor for an oblate momentum-space anisotropy of the system where the cut-off scale is fixed at $k_c \sim \sqrt{g p_{hard}}$. Here $p_{hard}$ is a hard-momentum scale that appears in the distribution functions.

The differential photon production rate for $1 + 2 \rightarrow 3 + \gamma$ processes in an anisotropic medium is given by [26]:

$$
E \frac{dN}{d^4x d^3p} = \frac{N}{2(2\pi)^3} \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} f_1(p_1, p_{hard}, \xi) f_2(p_2, p_{hard}, \xi) f_3(p_3, p_{hard}, \xi)
$$

$$
\times (2\pi)^4 \delta(p_1 + p_2 - p_3 - p) |\mathcal{M}|^2 [1 \pm f_3(p_3, p_{hard}, \xi)]
$$

(1)

where, $|\mathcal{M}|^2$ represents the spin averaged matrix element squared for one of those processes which contributes to the photon rate and $N$ is the degeneracy factor of the corresponding process. $\xi$ is a parameter controlling the strength of the anisotropy with $\xi > -1$. $f_1$, $f_2$ and $f_3$ are the anisotropic distribution functions of the medium partons and will be discussed in the following. Here it is assumed that the infrared singularities can be shielded by the thermal masses for the participating partons. This is a good approximation at short times compared to the time scale when plasma instabilities start to play an important role.

The anisotropic distribution function can be obtained [27] by squeezing or stretching an arbitrary isotropic distribution function along the preferred direction in momentum space,

$$
f_i(k, \xi, p_{hard}) = f_i^{iso}(\sqrt{k^2 + \xi(k.n)^2}, p_{hard})
$$

(2)
where \( n \) is the direction of anisotropy. It is important to notice that \( \xi > 0 \) corresponds to a contraction of the distribution function in the direction of anisotropy and \(-1 < \xi < 0\) corresponds to a stretching in the direction of anisotropy. In the context of relativistic heavy ion collisions, one can identify the direction of anisotropy with the beam axis along which the system expands initially. The hard momentum scale \( p_{\text{hard}} \) is directly related to the average momentum of the partons. In the case of an isotropic QGP, \( p_{\text{hard}} \) can be identified with the plasma temperature \( T \).

2.2 Photon rate: Isotropic case

As mentioned earlier the QGP evolves hydrodynamically from \( \tau_{\text{iso}} \) onwards. In such case the distribution functions become Fermi-Dirac or Bose-Einstein distributions. The photon emission rate, in isotropic case, from Compton \((q(q) g \rightarrow q(q) \gamma)\) 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. \[14\] in the 1-loop approximation. However, it has been shown by Auranche et al. \[28\] 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. \[29\] and the rate is given by

\[
\frac{dN}{d^4x d^3p} = \frac{1}{(2\pi)^3} A(E, T) \left( \ln[T/m_q(T)] + \frac{1}{2} \ln(2E/T) + C_{\text{tot}}(E/T) \right),
\]

where \( E = p \) and \( m_q^2(T) = 4\pi\alpha_sT^2/3 \) and \( A \) is the leading log coefficient given by

\[
A(E, T) = 2\alpha N_c \sum_i q_i^2 m_q^2(T) E f_D(E)
\]

and

\[
C_{\text{tot}} = C_{2 \rightarrow 2}(E/T) + C_{\text{brems}}(E/T) + C_{\text{aws}}(E/T)
\]

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

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

\[
C_{\text{brems}} + C_{\text{aws}} = \sqrt{1 + \frac{1}{6} N_f} \left( \frac{0.548 \ln[12.28 + T/E]}{(E/T)^{3/2}} \right.

+ \frac{0.133E/T}{\sqrt{1 + (E/T)/16.27}} \right)
\]

2.3 Photon production rate from hot 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 photons from hadronic matter and already a substantial amount of work has been done \[5, 14, 15, 30, 31, 32\] along this line.
We follow the calculations done in Ref. [32] where convenient parameterizations have been given for the reactions considered. These parameterizations will be used while doing the space-time evolution to calculate the photon yield from meson-meson reactions. The photon emission rate (static) from reactions of the type $B M \rightarrow B \gamma$ ($B$ denotes baryon) has been calculated in Ref. [16]. It is shown that this contribution is not negligible compared to that meson-meson reactions. To evaluate photon rate due to nucleon (and antimucleon) scattering from $\pi$, $\rho$, $\omega$, $\eta$ and $a_1$ mesons in the thermal bath we use the phenomenological interactions described in Ref. [16].

2.4 Hard Photons

Besides the thermal photons from QGP and hadronic matter we also calculate photons from initial hard scattering from the reaction of the type $h_A h_B \rightarrow \gamma X$ using perturbative QCD. We include the transverse momentum broadening in the initial state partons [33, 34]. The cross-section for this process can then be written in terms of elementary parton-parton cross-section multiplied by the partonic flux which depends on the parton distribution functions (PDF) for which we take CTEQ parameterization [35]. A phenomenological factor $K$ is used to take into account the higher order effects.

2.5 Space time evolution

For any quantitative prediction of the expected total thermal photon yield the static photon rate, discussed in the previous section, has to be convoluted with the space-time evolution of the fireball. For the evolution scenario we propose the following. The system evolves anisotropically from $\tau_i$ to $\tau_{iso}$ where one needs to know the time dependence of $p_{T,hard}$ and $\xi$. We shall follow the work of Ref. [23] to evaluate the $p_T$ distribution of photons from the
Figure 2: (Color online) Photon transverse momentum distribution with (a) Set I, (b) Set II and (c) Set III. The transition temperature is taken to be 192 MeV. Different lines show the yields for various values of $\tau_{\text{iso}}$. The data points are taken from [20, 21].
first few Fermi of the plasma evolution. As the effect of transverse flow is pronounced in the late stages of the collisions we shall neglect this effect in the early stage. For \( \tau > \tau_{\text{iso}} \), the system is described by ideal relativistic hydrodynamics in \((1+2)d\) with longitudinal boost invariance \([37]\) and cylindrical symmetry. As the system becomes isotropic at \( \tau = \tau_{\text{iso}} \), \( p_{\text{hard}}(\tau_{\text{iso}}) \) and \( \tau_{\text{iso}} \) can be identified as the initial conditions, i.e., initial temperature and initial time for the hydrodynamic evolution. The time dependences of the anisotropy parameter \( \xi \) and the hard scale \( p_{\text{hard}} \) are taken from Ref. \([23]\). The initial conditions for ideal hydrodynamics is obtained by the conditions,

\[
\begin{align*}
T_{i}^{\text{hydro}} &= p_{\text{hard}}(\tau_{\text{iso}}) \\
\tau_{i}^{\text{hydro}} &= \tau_{\text{iso}}
\end{align*}
\]

(7)

In our calculation, we assume a first-order phase transition beginning at the time \( \tau_{c}(p_{\text{hard}}(\tau_{c}) = T_{c}) \) and ending at \( \tau_{H} = r_{d}\tau_{c} \) where \( r_{d} = g_{Q}/g_{H} \) is the ratio of the degrees of freedom in the two (QGP phase and hadronic phase) phases. We shall consider two values of the transition temperature \( T_{c} = 192 \) and \( 170 \) MeV \([38]\). The freeze-out temperature is fixed at \( T_{F} = 120 \) MeV. To cover the uncertainties in the initial conditions for RHIC energy, various combinations of \( T_{i}, \tau_{i} \) consistent with the measured multiplicity \( (dN/dy) \) have been considered. We also vary \( T_{c} \) to see its effect on the isotropization of the QGP.

Therefore, the total thermal photon yield, arising from the present scenario is given by,

\[
\frac{dN}{d^{2}p_{T}dy} = \left[ \int d^{4}x E \frac{dR}{d^{3}p} \right]_{\text{aniso}} + \left[ \int d^{4}x E \frac{dR}{d^{3}p} \right]_{\text{hydro}},
\]

(8)

where the first term denotes the contribution from the anisotropic QGP phase and the second term represents the contributions evaluated in ideal hydrodynamics scenario.

### 2.6 Initial conditions and equation of state (EOS)

To cover the uncertainties in the initial conditions for a given beam energy, we consider three sets of initial conditions, (I) \( T_{i} = 440 \) MeV, \( \tau_{i} = 0.1 \) fm/c (II) \( T_{i} = 400 \) MeV, \( \tau_{i} = 0.2 \) fm/c, and (III) \( T_{i} = 350 \) MeV, \( \tau_{i} = 0.25 \) fm/c which are consistent with \( dN/dy \sim 1100 \) measured at RHIC energies. The initial energy density and radial velocity profiles are taken as:

\[
\varepsilon(\tau_{i}, r) = \frac{\varepsilon_{0}}{1 + e^{(r-R_{A})/\delta}}
\]

(9)

and

\[
v(\tau_{i}, r) = v_{0} \left[ 1 - \frac{1}{1 + e^{(r-R_{A})/\delta}} \right]
\]

(10)

We also need the EOS to solve the hydrodynamic equations. Bag model type EOS has been used for QGP. For EOS of the hadronic matter all the resonances with mass \(< 2.5 \) GeV \( /c^{2} \) have been considered \([39]\).

It is to be mentioned that in our case \( \tau_{\text{iso}} \) is always less than \( \tau_{c} \) and we switch on the transverse expansion at \( \tau_{\text{iso}} \) as the effect of transverse expansion in the very early stages is found to be negligible. Therefore, for \( \tau > \tau_{\text{iso}} \) the energy density and the other thermodynamic variables are functions of \( r \) and \( \tau \). The critical energy density corresponding to the quark-hadron phase transition is, thus, also a contour in the \((r, \tau)\) space.
3 Results

We will now discuss contributions to the total photon yield due to medium photon spectrum from anisotropic QGP with initial conditions that might be achieved at RHIC. In what follows we shall consider the free-streaming interpolating model ($\delta = 2$). The results for collisionally-broadened interpolating model ($\delta = 2/3$) are described in Ref. [24]. In Fig. (1) we present the photon yield due to Compton and annihilation processes in the mid rapidity ($\theta_\gamma = \pi/2$, $\theta_\gamma$ being the angle between the photon momentum and the anisotropy direction) as a function of photon transverse momentum. Left (right) panel corresponds to $T_i = 0.440 (0.350)$ GeV and $\tau_i = 0.1 (0.25)$ fm/c. In estimating these results, we have used $\alpha_s = 0.3$. Different lines in Fig. 1 correspond to different isotropization times, $\tau_{iso}$. We clearly observe enhancement of photon yield when $\tau_{iso} > \tau_i$. The enhancement of photon yield in the transverse directions ($y = 0$) is due to the fact that momentum-space anisotropy enhances the density of plasma partons moving at the mid rapidity [24].

Next we shall consider the total photon yield from various sources. This is displayed in Fig. (2) for different initial conditions as described in the text. It is seen that the experimental data is well reproduced for all the three values of $\tau_{iso}$ considered here. This is because of the following reason. For lower values of $\tau_{iso}$ the initial state momentum anisotropy leads to lower yield as compared to higher values of $\tau_{iso}$. But the initial temperature ($p_{hard}(\tau_{iso})$), required for hydrodynamic evolution from $\tau_{iso}$ onward is higher in the former case leading to higher yield. These two competing effects are clearly revealed from the figure. To show that the presence of initial state momentum anisotropy and the importance of the contribution from baryon-meson reactions we plot the the total photon yield assuming hydrodynamic evolution from the very begining as well as with finite $\tau_{iso}$ (right panel describes the total contribution with and without the initial state momentum space anisotropy only for $\tau_{iso} = 1$ fm/c) in Fig. (3). It is clearly seen that some amount of anisotropy is needed to reproduce the data. We note that the value of $\tau_{iso}$ needed to describe the data also lies in the range
1.5 \, \text{fm/c} \geq \tau_{\text{iso}} \geq 0.5 \, \text{fm/c} \text{ for both values of the transition temperatures.}

To see the sensitivity of \( \tau_{\text{iso}} \) with the initial conditions we present the results with different initial conditions (Sets II and III) in Fig. (4) with \( T_c = 192 \) (a) and 170 MeV (b). We again see that the values of \( \tau_{\text{iso}} \) required to fit the data are in the range of 0.5 – 1.5 fm/c and is almost independent of the transition temperature for a given initial conditions.

In order to see the hydrodynamic contributions to the total photon yield we plot the second term of Eq.(8) in Fig.(5). The left (right) panel corresponds to \( T_i^{\text{hydro}} = 318(348) \) MeV for \( \tau_{\text{iso}} = 1(0.5) \, \text{fm/c} \), obtained by solving \( T_i^{\text{hydro}} = p_{\text{hard}}(\tau_{\text{iso}}) \). We also note that \( \tau_c = 2.28(1.98) \, \text{fm/c} \) for \( \tau_{\text{iso}} = 1(0.5) \, \text{fm/c} \). It is found that because of the transverse kick the low energy photons populate the intermediate regime and consequently, the contribution from hadronic matter becomes comparable with that from the hadronic matter destroying the window where the contribution from QGP is supposed to dominate.

4 Conclusions

To summarize, we have calculated total single photon transverse momentum distributions by taking into account the effects of the pre-equilibrium momentum space anisotropy of the QGP and late stage transverse expansion on photons from hadronic matter with various initial conditions. To describe space-time evolution in the very early stage we have used the phenomenological model described in Ref. [23] for the time dependence of the hard momentum scale \( (p_{\text{hard}}) \) and plasma anisotropy parameter \( (\xi) \). To calculate the hard photon contributions we include the transverse momentum broadening in the initial hard scattering. The total photon yield is then compared with the PHENIX photon data. Within the ambit of the present model it is shown that the data can be described quite well if \( \tau_{\text{iso}} \) is in the range of 0.5 - 1.5 fm/c for all the combinations of initial conditions and transition temperatures considered here. It is to be noted that the apparent hump observed in all the figures (except
Figure 5: (Color online) Contributions to total photon yield due to ideal hydrodynamics (second term of Eq.(8)) with Set II for (a) $\tau_{\text{iso}} = 0.5 \text{ fm/c}$ and (b) $\tau_{\text{iso}} = 1 \text{ fm/c}$ for $T_c = 192 \text{ MeV}$. Here QM (HM) denotes quark matter (hadronic matter).

Fig.(5)) needs to be understood and we wish to discuss it in a subsequent paper. We conclude by noting that the isotropization time extracted from the PHENIX photon data is within the limit that is required to fit the other experimental observables, such as elliptic flow at RHIC using ideal hydrodynamics [40].

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