Photon production from non-equilibrium QGP in heavy ion collisions

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Abstract. We present a calculation of thermal photon production i.e. photons from secondary interactions among particles produced in heavy ion collisions at collider energies. This is done within the framework of hydrodynamics. We take into account the lack of chemical equilibrium in QGP. It turns out that main effects from chemical non-equilibrium composition of QGP, reduction of particle number and increase in temperature, nearly cancel in photon spectrum.

1. Introduction

Thermal emission of real photons is very sensitive to the initial temperature of emitting matter and their mean free path in the produced matter is so long that they escape from the fireball without further interactions. This makes thermal photons an excellent probe of the early stage of the collision. Unfortunately, even in best situations, thermal photons are only a small contribution to the total photon spectrum. At low transverse momentum $k_T$, the main contribution is from the electromagnetic decays of hadrons, mostly from $\pi^0$, and at high $k_T$ from prompt photons i.e. photons from primary interactions of the partons of the colliding nuclei. At collider energies, however, we have a possible window at intermediate $k_T \simeq 3 - 7$ GeV to detect the thermal part of the photon spectrum. Also a new contribution to the photon spectrum has been proposed recently [1, 2]. As high energy jets propagate through QGP they will induce emission of real photons. Photons from this process will mix with the thermal spectrum increasing the overall signal from QGP.

One uncertainty in thermal emission is the chemical composition of the QGP. We present here a calculation of the thermal part of the photon spectrum within the framework of hydrodynamics [3]. Supplemented with photon emission rates in thermal matter, hydrodynamics provides a closed framework to study the thermal emission in a heavy-ion collision. Within this framework it is relatively easy to take the chemical composition of the QGP into account. It turns out that the effects from chemical non-equilibrium, the decrease of quark number relative to gluons and the increase in temperature, nearly cancel in the thermal photon contribution to the spectrum.
2. Theoretical framework

Our framework to study the thermal photon emission is the following: The initial energy and particle densities are obtained from the pQCD + saturation model [4] which also gives the production time of the initial parton matter. Assuming thermal equilibrium immediately after production, the whole expansion of the matter can be treated by using hydrodynamics. This model, with the extra assumptions of longitudinal boost invariance and that the matter behaves as an ideal fluid, is in good agreement with the measured hadron spectra at RHIC [5]. Since we study the effects of particle composition on the photon emission, we relax the assumption of chemical equilibrium. We also neglect the small net baryon number.

Chemical composition of the matter can be controlled by introducing chemical potentials which we approximate by using multiplicative fugacities for both quarks and gluons. The time evolution of fugacities is determined by rate equations and following Biro et al. [6], processes $q\bar{q} \leftrightarrow gg$ and $gg \leftrightarrow ggg$ are included. Rate equations can be solved together with the hydrodynamic equations [6, 7, 8], once the equation of state is specified. This model gives a complete space-time evolution of energy density and transverse velocity as well as temperature, fugacities and other thermodynamic quantities. Once the space-time evolution is known from hydrodynamics and the photon emission rate as a function of temperature and fugacities is specified, we can integrate the rate over the space-time history of the collision to obtain the spectrum of thermal photons. Photon emission rate in the hot hadron gas is calculated and parametrized in refs. [9, 10, 11]. In QGP in chemical equilibrium the emission rate, complete to leading order in $\alpha_{em}$ and $\alpha_s$, is calculated in [12]. Following the method of ref. [13], this calculation has been extended to the non-equilibrium case in ref. [14].

3. Equation of state

The equation of state (EoS) is specified by combining the hadron gas equation of state and the QGP bag model EoS by Maxwell construction. The hadron gas is an ideal gas of all hadronic states up to a mass 1.3 GeV and QGP is treated as an ideal gas of gluons and three flavors of massless quarks. In the approximation of multiplicative fugacities $\lambda_i$ for quarks and gluons the particle densities in the QGP are given by

$$n_i(T, \lambda_i) = \lambda_i \tilde{n}_i(T) = \lambda_i a_i T^3, \quad i = q, g$$

where $\tilde{n}_i$ is the particle density in chemical equilibrium. Within the same approximation, pressure is given by

$$p = \lambda_q \tilde{p}_q + \lambda_g \tilde{p}_g - B,$$

where $B$ is bag constant. The connection between the critical temperature $T_c$ and the bag constant $B$ is given by Gibbs phase co-existence condition

$$p_{HG}(T_c) = p_{QGP,th}(T_c, \lambda_q, \lambda_g) - B(\lambda_q, \lambda_g),$$

(3)
where $p_{QGP,th}$ is the thermal part of the pressure in QGP [2].

The use of fugacities for describing the gluon and quark densities out of chemical equilibrium leads to an ambiguity on how to choose the bag constant and the critical temperature (cf. eq. (3)). In the full kinetic and chemical equilibrium with fugacities equal to one the situation is clear since the temperature is the only independent variable (neglecting net baryon number) in both phases. With QGP out of chemical equilibrium, we do not know quantities in the hadron gas which would be uniquely defined from the quark and gluon fugacities at phase transition. Here we fix the ambiguity in matching by simply taking $T_c$ to be a constant, independent of fugacities. In other words, we assume that the QGP always hadronizes at the same temperature into the same state of hadron gas. In our calculations $T_c = 167$ MeV both in and out-of chemical equilibrium. Because the photon emission from QGP is dominated by the early, high density stage of the collision our results are not sensitive to the details of the phase transition.

4. Results

The time evolution of temperature and fugacities in the center of the fireball are shown in the Fig. 1. As can be seen from the top figure the matter is close to chemical equilibrium at the end of the QGP phase. This justifies further our choice of fixed value for $T_c$. In the lower figure we can see the time evolution of temperature compared with the full chemical equilibrium case. Same initial energy density is used both in equilibrium and in out-of-equilibrium case.

These two figures show the effect of lack of chemical equilibrium. When the energy density is kept constant, reduction of the particle number below its equilibrium value leads to an increase of temperature. Under these conditions there are less particles but they have higher average energy. These deviations from the equilibrium values have opposite effects on the photon emission rates and nearly cancel each other. This can be seen from Fig. 2, where we plot thermal photon spectrum for both cases. Only at high transverse momenta, $k_T \gtrsim 10$ GeV, the increase in temperature is becoming more important and the equilibrium spectrum starts to fall faster than the non-equilibrium one. However the experimentally accessible region is around $k_T \sim 5$ GeV, where the spectrum is practically independent of the chemical composition of QGP.

5. Discussion

We have calculated the spectrum of thermal photons, emitted during the expansion stage of heavy ion collision, in the case when the QGP is not in chemical equilibrium. The space-time evolution of the heavy ion collision is modeled by hydrodynamics together with rate equations for the time evolution of chemical composition of QGP. Thermal photon spectrum is then obtained by integrating the temperature and in the QGP the fugacity dependent photon emission rates over this space-time history. We have demonstrated that the lack of chemical equilibrium does not change much the photon emission.
spectrum as compared to the chemical equilibrium case. The reason for this is that while there are less particles in the non-equilibrium QGP, the temperature becomes higher. These have opposite effects on photon emission and nearly cancel in the region where the possibilities to detect experimentally the thermal part of the spectrum are the best. Thus in heavy ion collisions thermal photons are not measuring initial temperature alone, but the combination of temperature and particle densities.

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