Explore QCD Phase Transition with Thermal Photons (Postprint)

Authors: Fuming Liu

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Abstract

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Full Text

Preamble

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Explore QCD Phase Transition with Thermal Photons

LIU Fuming*

Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), College of Physical Science & Technology, Central China Normal University, Wuhan 430079, China

Abstract

This pilot study assesses the high-temperature and zero baryon density region of the quantum chromodynamics (QCD) phase diagram through thermal photon emission, where the nature of the QCD phase transition remains ambiguous. Based on a (3+1)-D ideal hydrodynamical model to macroscopically describe the collision system, we investigate thermal photons emitted from Pb+Pb collisions at 2.76 TeV. Our results reveal that photons from heavy ion collisions at high energy and centrality can distinguish the structure of hot dense matter, whether in the QGP phase or hadronic phase, thus providing an approach to explore the nature of this finite-temperature QCD transition (that is, first-order, second-order, or analytic crossover).

Key words: Phase diagram, Hydrodynamical model, Photon emission rate

Introduction

Quantum chromodynamics (QCD) is the theory of the strong interaction, explaining (for example) the binding of three almost massless quarks into much heavier protons or neutrons. The standard model of particle physics predicts a QCD-related transition. At low temperatures, the dominant degrees of freedom are colorless bound states of hadrons (such as protons and pions). Because of asymptotic freedom, at high energies or temperatures, hadrons break up into quark degrees of freedom. Despite enormous theoretical efforts, the nature of this finite-temperature QCD transition (that is, first-order, second-order, or analytic crossover) remains ambiguous. Here we explore the nature of the QCD transition with thermal photon emission in heavy ion collisions.

Photon emission rates from two phases at temperatures ranging from 200 MeV to much higher temperatures (i.e., 700 MeV) have been investigated. On one hand, it is hard to accept the existence of hadron gas at temperatures higher than Tc. On the other hand, according to the most popular lattice results showing a crossover phase transition, the matter situation is not a pure QGP phase. Therefore, we still consider the part other than QGP matter as hadronic matter and take the photon emission rate from hadronic gas to estimate the unknown emission rate.

The temperature-dependent photon emission rate study reveals that at very high temperature, the photon emission rates from different phases differ by several orders of magnitude. This makes clear identification of the nature of this finite-temperature QCD transition possible.

According to Kapusta's pioneering investigation [1,2], photon emission rates from the two different phases are comparable at temperatures around 200 MeV. However, in the QCD phase diagram, the temperature involving the finite-temperature QCD transition has a quite wide range, from Tc ~170 MeV to a few times Tc. However, one needs real measurement based on a certain experiment to distinguish the different options of this finite-temperature QCD transition. Therefore, a high-temperature matter should be created, and the photon emission should be measured. The best choice is Pb+Pb collisions at 2.76 TeV, which makes the existence of high-temperature matter possible. Then, based on a (3+1)-D ideal hydrodynamical model to macroscopically describe the collision system, we investigate thermal photons emitted from Pb+Pb collisions at LHC energy 2.76 TeV with two options for phase transitions.

2 Approach and Results

In this section we introduce our approach in detail. Several segments of this study are needed, which we introduce one by one in the following.

2.1 Thermal Photon Emission Rates

Thermal photon production is obtained by integrating the photon emission rate R (number of reactions per unit time per unit volume which produce a photon) over the space-time history of the expanding hot and dense matter. In this section we study the photon emission rates from different phases of the hot dense matter.

The spectral photon emissivity directly reflects the dynamics of real photon production reactions in thermalized matter. Commonly employed formalisms are finite-temperature field theory and kinetic theory. As systematically studied by Kapusta et al. [1,2], the thermal emission rate of photons with energy E and momentum p from a small system (compared to the photon's mean free path) is

$$R = \frac{1}{(2\pi)^3}\frac{1}{2E}\mathrm{Im}\Pi^{\mu}_{\mu}(E,p)$$

where Π^{μ}_{μ} is the retarded photon self-energy at finite temperature T. This formula has been derived both perturbatively and nonperturbatively. It is valid to all orders in the strong interaction. If the photon self-energy is approximated by carrying out a loop expansion to some finite order, then the formulation of Eq.(1) is equivalent to relativistic kinetic theory, where the emission rate of photons with energy E and momentum p from a process of type $1+2 \to 3+\gamma$ reads as

$$R = \frac{1}{2(2\pi)^8 E}\int \frac{d^{3p}_1}{2E_1}\frac{d^{3p}_2}{2E_2}\frac{d^{3p}_3}{2E_3} f_1 f_2 (1 \pm f_3)|M|^2 \delta^4(p_1+p_2-p_3-p)$$

where f's are the Fermi-Dirac or Bose-Einstein distribution functions as appropriate. Eq.(2) is convenient if the scattering amplitude M is evaluated in a perturbative expansion. Non-perturbative (model) calculations at low and intermediate energies, on the other hand, are more amenable to the correlator formulation, Eq.(1). In the hadronic medium, e.g., $\mathrm{Im}\Pi$ can be directly related to vector meson spectral functions within the vector dominance model (VDM).

Instructive investigation on photon emission rates from both QGP and HG phases can be found in Refs. [1,2].

The thermal rate from a quark-gluon plasma is computed using the kinetic theory formalism for the simplest two-to-two scattering diagrams such as the QCD Compton process $qg \to \gamma q$ and annihilation $q\bar{q} \to \gamma g$ [1,2]. As noted in Ref. [3], this does not yet comprise the full result to leading order in the strong coupling constant α_s. Due to collinear singularities, bremsstrahlung as well as pair annihilation graphs contribute at the same order as the resumed $2 \to 2$ processes. The full result, which also necessitates the incorporation of Landau-Pomeranchuk-Migdal (LPM) interference effects, has been computed in Ref. [4,5] as

$$R_{\mathrm{QGP}} = \frac{\alpha\alpha_s}{2\pi^2} T^2 e^{-E/T} \left[\ln\left(\frac{2.912}{g^2}\right) + C_{\mathrm{brems}}(E/T) + C_{\mathrm{annih}}(E/T) + C_{\mathrm{comp}}(E/T) \right]$$

with convenient parameterizations of three functions C. The corresponding results at different temperatures are illustrated in Fig. 1 as solid lines.

Photons can also be produced in a hadronic phase from several elementary interactions. The dominant contribution [1,2] comes from the reactions $\pi\pi \to \rho\gamma$ and $\pi\rho \to \pi\gamma$. The decay $\rho \to \pi^+\pi^-\gamma$ also contributes significantly. Interactions involving strange mesons or baryons can also produce photons, but these contributions are relatively small because of phase-space suppression due to their large masses.

The situation of thermal photon radiation rates from a hadronic gas is uncertain due to difficulties related to the strong coupling and the masses of hadrons. The study is usually carried out within effective Lagrangians. Constraints on the interaction vertices can, to a certain extent, be imposed by symmetry principles (e.g., electromagnetic gauge and chiral invariance). Coupling constants are estimated by adjusting to measured decay branchings in the vacuum. Thus, for the temperature ranges relevant to practical applications, the predicted emission rates are inevitably beset with significant uncertainties, and therefore a careful judgment of the latter becomes mandatory. We will use the results of the MYM calculation [6] and plot the corresponding parameterized rates in Fig. 1 as dotted lines.

We can see that at temperatures below 500 MeV, the emission rates from the two different phases are comparable. But when the temperature reaches 600 MeV or even higher, the emission rate from hadronic gas is several orders of magnitude higher than the rate from QGP phase. This makes possible identification of what matter exists at the relevant region of the QCD phase diagram, thus enabling determination of the order of phase transition.

2.2 Evolution of a Heavy Ion Collision System

The expanding local-thermalized matter created in heavy-ion collisions is treated by employing three-dimensional hydrodynamics [7], via the flow velocity u^μ, the energy density ε, pressure P, the entropy density s, and the baryon number density n_B as functions of the space-time position (η, τ, r, ϕ), with η being the space-time rapidity, and r, ϕ being the transverse coordinates. Those quantities are governed by the hydrodynamical equation:

$$\partial_\mu T^{\mu\nu} = 0$$

where the energy-momentum tensor can be decomposed in ideal hydrodynamics as $T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$. This hydrodynamical equation describes the collective motion of the collision system from an initial time until a freeze-out condition.

An event generator EPOS has been used to construct the initial condition. Additionally, a dynamical equation, i.e., the relation between energy density and pressure, is needed to close the hydrodynamical equation. The equation of state used is from Ref. [8]. For more details of the solution of the hydro equation, one can read Ref. [7]. In Fig. 2, the resulting energy density at the initial time $\tau_0 = 0.35$ fm/c from Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at centrality 0%–40% (Fig. 2a) and 40%–80% (Fig. 2b) are shown.

In this model, centrality is defined with impact parameter b and constrained with experimental data such as rapidity distribution of produced hadrons and multiplicity distribution function. It is equivalent to the definition based on the Glauber model. Here the impact parameter is $b \in [0, 9.85)$ fm for 0%–40% and $b \in [9.85, 13.93)$ fm for 40%–80%, respectively. One can see that more energy has been deposited in the midrapidity region to form the hot dense matter in more central collisions.

To calculate particle production, another equation of state, i.e., the relation between energy density and temperature, is needed. For hadron production, this relation is only used at the freeze-out condition. But for thermal photon emission, this relation is used throughout the whole hydrodynamical evolution. The relation between energy density and temperature is obtained based on the structure of the hot dense matter, i.e., a QGP or a hadronic gas, or anything in between. In this work, we still take the relation between energy density and temperature from lattice calculation [9]. The obtained temperature for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the initial time $\tau_0 = 0.35$ fm/c is shown in Fig. 3 for centrality 0%–40% and 40%–80% respectively. We can see that temperatures as high as 900 MeV have been reached in 0%–40% centrality, however, only in a small volume and for a short time interval. At most space-time points, the temperature will be lower than this peak value.

2.3 Thermal Photon Production

Thermal photon production is obtained by integrating the photon emission rate R (number of reactions per unit time per unit volume which produce a photon) over the space-time history of the expanding hot and dense matter:

$$E\frac{dN}{d^{3p}} = \int d^{4x}\, R(p \cdot u, T)$$

where p^μ is the four-momentum of the produced photon. The flow velocity u^μ and the temperature T are based on the above calculation. The photon emission rate covers emission from both QGP phase and hadronic gas, where at a given space-time point:

$$R = f_{\mathrm{QGP}} R_{\mathrm{QGP}} + (1 - f_{\mathrm{QGP}}) R_{\mathrm{HG}}$$

f_{QGP} is the fraction of QGP phase.

There are two options for f_{QGP}. Option one (opt1) is consistent with the dynamical equation of state from lattice QCD [8], where pressure is calculated [9] as $P = T\frac{\partial \ln Z}{\partial V}$. From this one obtains the temperature-dependent f_{QGP}. This makes hadronic gas appear at very high temperature with very small fraction, i.e., about 4% at 700 MeV.

Option two (opt2) of f_{QGP} is defined according to first-order phase transition, which was widely used in Ref. [9], where no fraction of hadronic gas appears at temperature higher than 200 MeV.

With these two options of f_{QGP}, the transverse momentum spectra of thermal photons at midrapidity from Pb+Pb collisions at 2.76 TeV are plotted in Fig. 4 for centrality 0%–40% (Fig. 4a) and 40%–80% (Fig. 4b). Dotted lines are results based on option one of f_{QGP}. Solid lines are based on option two.

At later times, the system temperature gets colder and the emission from the two options is expected to be comparable due to the emission rates from the two different phases. Thus photons emitted at times later than $\tau_0 = 0.35$ fm/c are counted as a comparison, i.e., from 0.75 fm/c, 1.15 fm/c, and 1.55 fm/c, plotted as different dots and colors of lines.

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3 Conclusion

The comparison of the transverse spectrum of thermal photons from Pb+Pb collisions at 2.76 TeV reveals that high collision energy and centrality are needed to create high-temperature matter. The early evolution is the most sensitive stage to distinguish the structure of the hot dense matter, whether in QGP phase or hadronic phase, thus providing an approach to explore the nature of this finite-temperature QCD transition (that is, first-order, second-order, or analytic crossover).

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