Thermal photon production
in heavy ion collisions

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Abstract

Using a three-dimensional hydrodynamic simulation of the collision and an equation of state containing a first order phase transition to the quark-gluon plasma, we study thermal photon production for \textit{Au + Au} collisions at $E_{\text{lab}} = 11.5$ AGeV and for \textit{Pb + Pb} collisions at 160 AGeV. We obtain surprisingly high rates of thermal photons even at the lower energy, suggesting that, contrary to what was expected so far, photon production may be an interesting topic for experimental search also at the Alternating Gradient Synchrotron. When applied to the reaction \textit{S + Au} at 200 AGeV, our model can reproduce preliminary data obtained by the WA80 Collaboration without having to postulate the existence of an extremely long-lived mixed phase as was recently proposed.

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In ultrarelativistic heavy-ion collisions one of the most challenging goals is to study a possible phase transition between nuclear matter and the quark-gluon-plasma (QGP), consisting of deconfined quarks and gluons. This expectation is supported by lattice gauge calculations and phenomenological models. Photons are a very promising probe in the experimental search for the QGP which is expected to exist for a brief period of a few fm/c before the majority of the final state hadrons is emitted. Particles which interact only electromagnetically may be regarded as free particles, carrying information on the early stage of the collision. In order to describe the space-time development of a nucleus-nucleus collision, very often hydrodynamical models are used, which are based on the concept of local thermal equilibrium. For heavy ion collisions at the Brookhaven Alternating Gradient Synchrotron (AGS) and at the CERN Super Proton Synchrotron (SPS) this condition may be fulfilled because of the high degree of stopping. Thus, high compression of nuclear matter has to be considered and energy densities near the critical value for the deconfinement phase transition may be reached.

In the present paper, we study thermal photon production in a realistic hydrodynamical framework and make predictions for measurements at AGS and SPS energies. We focus on the reactions \( \text{Au} + \text{Au} \) at \( E_{\text{lab}} = 11.5 \text{ AGeV} \) and \( \text{Pb} + \text{Pb} \) at 160 AGeV. We also apply our model to \( S + \text{Au} \) collisions at 200 AGeV and compare our results to preliminary data on photon production obtained by the WA80 Collaboration [1].

At the SPS, lead beams will be available at the end of 1994 and direct photon production measurements will be performed by the WA98 Collaboration [2]. Furthermore, it is intended [3] to test the PHENIX-detector [4], which is designed to detect photons with high accuracy and resolution, at the AGS in 1996. This means that our predictions for \( \text{Pb} + \text{Pb} \) at 160 AGeV and for \( \text{Au} + \text{Au} \) at 11.5 AGeV can be checked in the near future.

The photon production rates in thermalized matter have been calculated both for a QGP and for a hadron gas. In a QGP of temperature \( T \), the rates for a baryochemical
potential $\mu = 0$ can be expressed as [3]:

$$E_\gamma \frac{dN}{d^3kd^4x} = \frac{5}{18\pi} \alpha\alpha_s T^2 e^{-E_\gamma/T} \ln \left( \frac{0.2317E_\gamma}{\alpha T} \right),$$

(1)

where $E_\gamma$ and $\vec{k}$ are the energy and three-momentum of the photon, and where $\alpha = 1/137$ and $\alpha_s$ are the electromagnetic and the temperature dependent strong coupling constant, respectively. From lattice results $\alpha_s(T)$ can be parametrized as [4]:

$$\alpha_s(T) = \frac{6\pi}{(33 - 2n_f) \ln(8T/T_c)}.$$

(2)

where $T_c$ is the critical temperature and $n_f$ is the number of flavors (below, we take $n_f = 2$).

For a hadronic resonance gas at temperature $T$ and baryochemical potential $\mu = 0$, the thermal photon rates were calculated in [7]. The authors of [7] parametrized their results in the form

$$E_\gamma \frac{dN}{d^3kd^4x} = 2.4 \, T^{2.15} \exp \left[ -1 \left( \frac{1.35TE_\gamma}{0.75} - \frac{E_\gamma}{T} \right) \right] \text{[GeV}^{-2}\text{fm}^{-4}],$$

(3)

where $E_\gamma$ and $T$ are measured in units of GeV. Eq. (3) contains the contributions from $A_1$-resonances which were shown to be important in [7] and which had not been taken into account in earlier calculations of the rates [8].

In the mixed phase the rates read

$$E_\gamma \frac{dN}{d^3kd^4x} \bigg|_{\text{mix}} = w(\varepsilon) E_\gamma \frac{dN}{d^3kd^4x} \bigg|_{\text{QGP}} + (1 - w(\varepsilon)) E_\gamma \frac{dN}{d^3kd^4x} \bigg|_{\text{had}},$$

(4)

where $w(\varepsilon)$ is the fraction of QGP at the energy density $\varepsilon$.

In order to obtain the single-inclusive spectra it is necessary to integrate the photon rates over the space-time region defined by the space-time evolution of the hot and dense matter,

$$E_\gamma \frac{dN}{d^3k} = \int d^4 x E_\gamma \frac{dN}{d^3kd^4x} (T(x), u^\mu(x)),$$

(5)

where the temperature field $T(x)$ and the four velocity field $u^\mu(x)$ are obtained from a hydrodynamic description of the expanding matter. On the rhs of eqs. (1) and (3)
the energy $E_\gamma$ has to be replaced by $k_\mu u^\mu(x)$. In the framework of hydrodynamics the ultrarelativistic heavy ion collision can be divided into three stages: (i) the collision or compression stage, (ii) the expansion stage and (iii) the freeze-out stage. The space-time development of dense and hot matter in local thermal equilibrium is described by the equations of relativistic hydrodynamics:

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu (bu^\mu) = 0,$$  \hspace{0.5cm} (6)

where $T^{\mu\nu}$ is the energy-momentum tensor, $b$ the baryon-number density and $u^\mu$ the four-velocity of the fluid element. Here we consider the case of an ideal fluid, i.e., we neglect dissipative effects. In this case, $T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - g^{\mu\nu}P$, where $\varepsilon$ is the energy density $P$ the pressure. In order to solve the equations, one needs to specify the equation of state (EOS), which may be given, e.g., in the form $P = P(\varepsilon, b)$. The equations of motion are solved exactly and fully 3-dimensionally with the numerical code HYLANDER.

Our hydrodynamical simulation describes also the initial compression (or collision) stage where the propagation of shock waves which heat up the system is calculated fully 3-dimensionally. The applicability of one-fluid hydrodynamics at this early stage is supported by the fact that in heavy ion collisions at AGS and at SPS energies the mean free paths are small compared to the size and lifetime of the system and a considerable amount of stopping is expected.

We use an EOS given by a parametrization of lattice-QCD results where the hadronic phase is treated as a resonance gas. This EOS exhibits a first order phase transition between hadronic matter and the QGP at a critical temperature $T_c = 200 \text{ MeV}$; it

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1RQMD simulations for central $Au + Au$ collisions have found complete stopping up to (and even somewhat beyond) SPS energies.

2The results in were obtained for a purely gluonic system. New results which take into account the effects of dynamical quarks yield lower values for the critical temperature, $T_c \sim 150 \text{ MeV}$ (see and refs. therein). There is no EOS published yet for this case.
corresponds to a baryochemical potential $\mu = 0$. Apart from the EOS our hydrodynamic model does not contain any free parameters.

Fig. 1 shows the first 8 fm/c of the space-time evolution of central $Au + Au$ collisions at $E_{lab} = 11.5$ AGeV (left column) and of central $Pb + Pb$ collisions at 160 AGeV, in time steps $\Delta t = 2$ fm/c. Contour plots for the energy-density calculated with HYLANDER are displayed. Four characteristic regimes are considered. The energy density $\varepsilon = 0.14$ GeV/fm$^3$ corresponds to the interface between hot and cold nuclear matter, $\varepsilon = 0.25$ GeV/fm$^3$ to the freeze out regime, the region $2.5 \leq \varepsilon \leq 5.5$ GeV/fm$^3$ to the mixed phase and $\varepsilon \geq 5.5$ GeV/fm$^3$ to the pure QGP phase, respectively. As can be seen in the figure, for both reactions a lump of pure QGP and a mixed phase with a lifetime of about 7 fm/c are produced. The total lifetimes of the thermalized matter are $\sim 12$ fm/c for $Au + Au$ at 11.5 AGeV and $\sim 16$ fm/c for $Pb + Pb$ at 160 AGeV. Figs. 2a and 2b show the thermal photon spectra for these two reactions. The rates are surprisingly large even at AGS energies. To understand the origin of these results, we have plotted separately the contributions from the pure QGP phase, the mixed phase and the purely hadronic phase. For $Au + Au$ at 11.6 AGeV the contribution of the purely hadronic phase dominates the photon production, whereas for $Pb + Pb$ at 160 AGeV it is comparable to the contribution of the pure QGP phase. The reason that the pure hadronic phase plays such an important role in photon production is twofold. Firstly, as can be seen from eqs. (1) and (3), at temperatures $T \sim 0.2$ GeV the hadron gas outshines the QGP by a factor of about two. Secondly, the hadronic space-time volume exceeds the volumes occupied by the mixed phase and by the QGP. The fact that at SPS energies the QGP contribution can compete with that of pure hadronic phase is a consequence of the high initial temperatures ($T_i \sim 300$ MeV) at these energies.

Preliminary data on photon production for $S + Au$ collisions at SPS energies were

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3 At present there exist no reliable lattice data concerning the EOS at $\mu \neq 0$. 
recently presented by the WA80 Collaboration [1]. The fact that the measured direct photon rates are surprisingly high has led to speculations concerning the existence of an extremely long-lived mixed phase with lifetimes of about $30-40 \text{ fm/c}$ [13]. We have applied our hydrodynamic collision simulation to this reaction and plotted the resultant thermal photon rates in Fig. 2c. We find a remarkably good agreement with the WA80 data [1], without having to adjust any parameters or having to assume an extremely long-lived mixed phase as in Ref. [13]. In particular, it turns out that the hadronic rather than the mixed phase dominates photon emission. The space-time evolution for $S + Au$ collisions is illustrated in Fig. 3. Due to the asymmetry of the collision, the central rapidity region is shifted, which is of importance for the calculation of the photon spectra.

So far we have not discussed the effects of baryon stopping on thermal photon production. At AGS and SPS energies, one expects nonvanishing values of the baryochemical potential due to the high baryon number densities in the central rapidity region. In Ref. [17], photon emission rates from a QGP of temperature $T$ and baryochemical potential $\mu$ were calculated by means of the Braaten-Pisarski technique. The authors give the expression

$$E_\gamma \frac{dN}{d^3k d^4x} = \frac{5}{18\pi^2} \alpha_s T^2 \left(1 + \frac{\mu^2}{\pi^2 T^2}\right) e^{-E_\gamma/T} \ln \frac{0.2317 E_\gamma}{\alpha_s T}. \quad (7)$$

At fixed baryon number density and energy density, we have used a bag model EOS with $T_c(\mu = 0) = 0.2 \text{ GeV}$ to estimate the decrease in temperature and the resultant decrease in the photon rates [18, 17] near the critical curve of the deconfinement phase transition. Using eqs. (7) and (3) we obtain reduction factors of about 2 both for the QGP and for [14] for the system $S + Au$ one expects a smaller degree of stopping than for $Pb + Pb$ or $Au + Au$. On the other hand, fits to rapidity and transverse momentum spectra of hadrons produced in $S + S$ at 200 AGeV already indicate a considerable amount of stopping [14] which should be even more pronounced for $S + Au$. This suggests that our hydrodynamic collision simulation is also applicable for the latter reaction. Note, however, that recently the WA80 data have also been described [15, 16] under the assumption of Bjorken initial conditions.
the hadronic component.

From the above considerations we conclude that the main result of this letter – namely, that there are experimentally observable rates of thermal photons to be expected both at the AGS and at the SPS – remains unaffected if one takes into account a finite baryochemical potential.

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5 A reduction by a factor of $\sim 2$ for $S + Au$ at 200 AGeV would imply that we underestimate the WA80 data. There are three possible effects which would lead to an increase of the photon rates and thus may explain the missing factor. An additional contribution is also expected from the hadronic processes $A_1 \rightarrow \pi \gamma$, $b_1 \rightarrow \pi^{0} \gamma$, and $K_1 \rightarrow K \gamma$ [19]. Furthermore at nonzero baryochemical potential the presence of baryons may open additional channels for thermal photon production. Thirdly, one expects a decrease of the rho meson mass as the temperature approaches the critical temperature of the chiral phase transition [20].
Figure Captions

Fig. 1 Energy density contour plots in the \((x, r)\) plane, for \(Au + Au\) collisions at \(E_{lab} = 11.5\) AGeV (left column) and \(Pb + Pb\) collisions at \(E_{lab} = 160\) AGeV (right column). \(x\) is the coordinate in longitudinal direction, \(r\) the radial coordinate in the transverse plane. The plots were obtained in the equal velocity frame by applying the hydrodynamic collision simulation.

Fig. 2 Single-inclusive photon spectra as a function of the transverse momentum \(k_\perp\) for mid-rapidity photons, (a) for \(Au + Au\) collisions at \(E_{lab} = 11.5\) AGeV, (b) for \(Pb + Pb\) at 160 AGeV and (c) for \(S + Au\) at 200 AGeV. The contributions from the pure QGP phase, the mixed phase and the pure hadronic phase are shown separately. The data points are from ref. [1].

Fig. 3 Energy density contour plots as in Fig.1 for \(S + Au\) collisions at \(E_{lab} = 200\) AGeV.
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Fig. 1

Au+Au / AGS

| t= 0 fm/c | energy density [GeV/fm³] |
|----------|--------------------------|
|          | 0.14                     |
|          | 0.25                     |
|          | 2.5                      |
|          | 5.5                      |

Pb+Pb / SPS

| t= 0 fm/c | energy density [GeV/fm³] |
|-----------|--------------------------|
|           | 0.14                     |
|           | 0.25                     |
|           | 2.5                      |
|           | 5.5                      |

-4 -2 0 2 4 6 8
x [fm]

0 2 4 6 8
r [fm]
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Fig. 3

S+Au / SPS

energy density [GeV/fm³]

- t = 0 fm/c
  - 0.14
  - 0.25
  - 2.5
  - 5.5

- t = 2 fm/c

- t = 4 fm/c

- t = 6 fm/c

- t = 8 fm/c

- x [fm]
  - 0
  - 2
  - 4
  - 6

- r [fm]
  - 0
  - 2
  - 4
  - 6
  - 8
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