Dynamics of strongly interacting parton-hadron matter

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Abstract

In this study we investigate the dynamics of strongly interacting parton-hadron matter by calculating the centrality dependence of direct photons produced in \( \text{Au} + \text{Au} \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV within the Parton-Hadron-String Dynamics (PHSD) transport approach. As sources for 'direct' photons, we incorporate the interactions of quarks and gluons as well as hadronic interactions (\( \pi + \pi \rightarrow \rho + \gamma, \rho + \pi \rightarrow \pi + \gamma \), meson-meson bremsstrahlung \( m + m \rightarrow m + m + \gamma \), meson-baryon bremsstrahlung \( m + B \rightarrow m + B + \gamma \)), the decays of \( \phi \) and \( a_1 \) mesons and the photons produced in the initial hard collisions ('pQCD'). Our calculations suggest that the channel decomposition of the observed spectrum changes with centrality with an increasing (dominant) contribution of hadronic sources for more peripheral reactions. Furthermore, the 'thermal' photon yield is found to scale roughly with the number of participant nucleons as \( N_{\text{part}}^{\alpha} \) with \( \alpha \approx 1.5 \), whereas the partonic contribution scales with an exponent \( \alpha_p \approx 1.75 \). Additionally, we provide predictions for the centrality dependence of the direct photon elliptic flow \( v_2(p_T) \). The direct photon \( v_2 \) is seen to be larger in peripheral collisions compared to the most central ones since the photons from the hot deconfined matter in the early stages of the collision carry a much smaller elliptic flow than those from the final hadronic interactions.

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1. Introduction

The 'direct photons' from relativistic heavy-ion collisions are expected to be a valuable probe of the collision dynamics at early times and to provide information on the characteristics of the initially created parton-hadron matter once the final state hadronic decay photons are subtracted from the experimental spectra [1,2]. In the last years, the PHENIX Collaboration [3,4] has measured the spectra of the photons produced in minimal bias \( \text{Au} + \text{Au} \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV and found a strong elliptic flow \( v_2(p_T) \) of 'direct photons', which is comparable to that of the produced pions. Since direct photons were expected to be essentially produced in the initial hot medium before the collective flow has developed, this observation was in contrast to the theoretical expectations and predictions [5]. Also more recent studies employing event-by-event hydrodynamical calculations [6,7] severely have underestimated the elliptic flow of direct photons and alternative sources of direct photons from the conformal anomaly have been suggested [8,9].

On the other hand, in Refs. [10,11] we have proposed that apart from the partonic production channels the direct photon yield and primarily the strong \( v_2 \) might be due to hadronic sources (such as meson-meson Bremsstrahlung or hadronic interactions as \( \pi + \pi \rightarrow \rho + \gamma, \rho + \pi \rightarrow \pi + \gamma \) etc.). Indeed, the interacting hadrons carry a large \( v_2 \) and contribute by more than 50% to the measured 'direct photons' in minimum bias collisions at RHIC according
to the PHSD calculations in Ref. [10] (cf. also the hydrodynamics calculations in Ref. [12]). For a quantitative understanding of the direct photon production it is important to verify the decomposition of the total photon yield according to the production sources: the late hadron decays (the cocktail), hadronic interactions beyond the cocktail (during the collision phase) and the partonic interactions in the quark-gluon plasma (QGP). Since previous transport studies have indicated that the duration of the partonic phase substantially decreases with increasing impact parameter [13] we will study here explicitly the centrality dependence of the direct photon yield together with the essential understanding of the direct photon production it is important to verify the decomposition of the total photon yield to the PHSD calculations in Ref. [10] (cf. also the hydrodynamics calculations in Ref. [12]). For a quantitative (during the collision phase) and the partonic interactions in the quark-gluon plasma (QGP). Since previous transport investigations for the case of minimum bias collisions (see also [11]). We recall that the PHSD approach has provided a consistent description of the bulk properties of heavy-ion collisions – rapidity spectra, transverse mass distributions, azimuthal asymmetries of various particle species – from low Super-Proton-Synchrotron (SPS) to top Relativistic-Heavy-Ion-Collider (RHIC) energies [13] and was successfully used also for the analysis of dilepton production from hadronic and partonic sources at SPS, RHIC and Large-Hadron-Collider (LHC) energies [14]. It is therefore of interest to calculate also the photon production in relativistic heavy-ion collisions from hadronic and partonic interactions within the PHSD transport approach, since its microscopic and non-equilibrium evolution of the nucleus-nucleus collision is independently controlled by a multitude of other hadronic and electromagnetic observables in a wide energy range [14,15].

2. Photons within PHSD

For the details on the PHSD approach we refer the reader to Refs. [15,16] and the implementation of the photon production to Refs. [10,17] (and references therein). Let us recall that the dynamical calculations within the PHSD for dileptons agree with the dilepton rate emitted by the thermalized QCD medium as calculated in lattice QCD (lQCD) [14]. We note, additionally, that the electric conductivity of the QGP from the PHSD, which controls the photon emission rate in equilibrium, is rather well in line with available lQCD results [18].

As sources of photon production - on top of the general dynamical evolution - we consider hadronic [17,19] as well as partonic [20] interactions. In the present study we extend the calculations in Ref. [10] by adding an additional source of photons, i.e. the bremsstrahlung in elastic meson+baryon collisions \( m + B \rightarrow m + B + \gamma \). This process is calculated within the soft photon approximation for charged hadrons in analogy to the treatment of photon production by the meson+meson bremsstrahlung in Refs. [10,11,17,19].

Since a new production mechanism has been added to the hadronic production channels, we first check whether this addition does not lead to an overestimation of the data from the PHENIX Collaboration [4] in minimal bias \( Au+Au \) collisions in Fig. 1 (l.h.s.). Since the decays of mesons as ‘late’ hadronic sources are less sensitive to the creation of the hot and dense medium and to its properties, they are usually subtracted experimentally from the total photon yield to access the ‘direct’ photon spectrum. In our calculations of the direct photon spectrum in Fig. 1 (l.h.s.) the following sources are taken into account: the decays of \( \omega, \eta' \), \( \phi \) and \( a_1 \) mesons; the reactions \( \pi + \rho \rightarrow \pi + \gamma \), \( \pi + \pi \rightarrow \rho + \gamma \); the photon bremsstrahlung in meson-meson and meson-baryon collisions \( m + m \rightarrow m + m + \gamma \), \( m + B \rightarrow m + B + \gamma \); photon production in the QGP in the processes \( q + g \rightarrow g + \gamma \), and \( q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma \) as well as the photon production in the initial hard collisions ("pQCD"), which is given by the hard photon yield in \( p+p \) collisions scaled with the number of binary collisions \( N_{\text{coll}} \). We find that our PHSD calculations are in a reasonable agreement with the PHENIX data [4] and show a clear dominance of the hadronic production channels over the partonic channels for transverse momenta below about 0.7 GeV/c. In particular, the bremsstrahlung contributions are responsible for the 'banana shape' spectrum and the strong increase for low \( p_T \). Accordingly, especially experimental data well below 1 GeV/c in \( p_T \) will be helpful in disentangling the various sources.

We have, furthermore, calculated the produced photons as a function of the number of participants \( N_{\text{part}} \). Integrating the thermal photon spectra - defined by the partonic radiation channels and the hadronic non-decay contributions - over the transverse momentum \( p_T \) in the interval \( 0.4 \leq p_T \leq 5 \) GeV/c, we obtain the number of 'thermal photons' as a function of centrality, which is plotted in Fig. 1 (r.h.s.) (full squares) as a function of \( N_{\text{part}} \) calculated in the Monte-Carlo Glauber model described in Ref. [21]. Since only binary collision channels contribute to the production of thermal photons in our approach, their yield rises faster than \( N_{\text{part}} \). A power-law fit to our results gives approximately a scaling \( \sim N_{\text{part}}^\alpha \) with \( \alpha \approx 1.5 \). In addition we display in Fig. 1 (r.h.s.) the scaling with \( N_{\text{part}} \) for the partonic
(full dots) and hadronic bremsstrahlung channels (full triangles) separately, which give exponents of \( \approx 1.75 \) and \( \approx 1.5 \), respectively.

As one might have expected the contribution of the photons from the QGP is larger in central collisions in PHSD while the hadronic sources contribute more dominantly in peripheral collisions. We quantify the relative contributions by plotting in Fig. 2 (l.h.s.) the ratio of the number of photons produced in the QGP to the number of all direct photons while the hadronic sources contribute more dominantly in peripheral collisions. We quantify the relative contributions hadronic channels that come along with a large hadronic elliptic flow and is below 10% in the most peripheral centrality bin. Accordingly, minimal bias collisions are dominated by the bin. On the other hand, the ratio of QGP photons to the total direct photons falls rapidly with decreasing centrality the hot deconfined matter in the early stages of the collision relative to the collisions as compared to the most central reactions. This is due to the much smaller elliptic flow of the photons from (full dots) and hadronic bremsstrahlung channels (full triangles) separately.

In Fig. 2 (r.h.s.) we provide predictions for the centrality dependence of the direct photon elliptic flow \( v_2(p_T) \) within the PHSD approach. The direct photon \( v_2 \) is seen to be larger in the peripheral collisions compared to the most central ones. This result can be readily understood when keeping in mind the ratios presented in Fig. 2 (l.h.s.) and the roughly linear increase of the hadron \( v_2 \) with impact parameter [13]. As has been described in detail in Ref. [10], the PHSD approach predicts a very small \( v_2 \) of photons produced in the initial hot deconfined phase by partonic channels of the order of 2%.

3. Summary

The spectra of direct and thermal photons - as produced in Au-Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) - have been calculated differentially in collision centrality within the PHSD transport approach, which has been previously tested in comparison to the measured spectra and flow of photons in minimal bias collisions at the same energy [10]. We have found that the channel decomposition of the photon spectra changes with centrality providing a larger contribution of the hadronic sources in more peripheral collisions. As a consequence, the direct photon \( v_2 \) is larger in peripheral collisions as compared to the most central reactions. This is due to the much smaller elliptic flow of the photons from the hot deconfined matter in the early stages of the collision relative to the \( v_2 \) from final hadrons within our approach.
The increase of the direct photon $v_2$ with decreasing centrality for the two most central bins has been also indicated in hydrodynamics calculations in Refs. [7], although with slightly lower absolute values of $v_2$. Future measurements of the photon spectra and elliptic flow as a function of the collision centrality will be mandatory for a clarification of the 'photon $v_2$ puzzle' from the experimental side and to estimate the contribution from unconventional sources [8, 9]. Furthermore, since only collisional channels contribute to the production of thermal photons in PHSD, their yield rises faster than the number of participating nucleons $N_{\text{part}}$ as expected also from qualitative considerations. A power-law fit to our results gives approximately a scaling $= N_{\text{part}}^{\alpha}$ with $\alpha \approx 1.5$, whereas the partonic and hadronic channels separately scale with exponents of $\approx 1.75$ and $\approx 1.5$, respectively.

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