Calculations of direct photon emission in Heavy Ion Collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV

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Abstract. Direct photon emission in heavy-ion collisions is calculated within a relativistic micro+macro hybrid model and compared to the microscopic transport model UrQMD. In the hybrid approach, the high-density part of the collision is calculated by an ideal 3+1-dimensional hydrodynamic calculation, while the early (pre-equilibrium-) and late (rescattering-) phase are calculated with the transport model. We study both models with $Au + Au$-collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV and compare the results to experimental data published by the PHENIX collaboration.

1. Introduction
Creating and studying high-density and -temperature nuclear matter is the major goal of heavy-ion experiments. A state of quasi-free partonic degrees of freedom, the Quark-Gluon-Plasma (QGP) [1, 2] may be formed, if the energy density reached in the reaction is high enough. Strong jet quenching, large elliptic flow and other observations made at the Relativistic Heavy Ion Collider (BNL-RHIC) suggest the successful creation of a strongly coupled QGP (sQGP) at these energies [3, 4, 5, 6], and possible evidence for the creation of this new state of matter has also been put forward by collaborations at the Super Proton Synchrotron (CERN-SPS), as for instance the step in the mean transverse mass excitation function of protons, kaons and pions and the enhanced $K^+/\pi^+$-ratio [7].

Electromagnetic probes provide a unique insight into the early stages of heavy-ion collisions, since they have the advantage of negligible rescattering cross-sections. Therefore, they leave the production region without rescattering and carry the information from this point to the detector. Besides single- and dileptons, direct photon emission can therefore be used to study the early hot and dense, possibly partonic, stages of the reaction.

Unfortunately, most photons measured in heavy-ion collisions come from hadronic decays. The experimental challenge of obtaining spectra of only direct photons has been gone through by several experiments; WA98 (CERN-SPS) [8] and PHENIX (BNL-RHIC) [9] have published explicit data points for direct photons.

On the theory side, the elementary photon production cross-sections are known since long, see e.g. Kapusta et al. [10] and Xiong et al. [11]. The major problem is the difficulty to describe the time evolution of the produced matter, for which first principle calculations from Quantum
Chromodynamics (QCD) cannot be done. Well-developed dynamical models are therefore needed to describe the space-time evolution of nuclear interactions. Among the approaches used are relativistic transport theory [12, 13, 14, 15, 16, 17, 18, 19, 20] and relativistic fluid- or hydrodynamics [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. For both models, approximations have to be made, and in both models, the restrictions imposed by these approximations can be loosened. For transport theory, the necessary approximations include the restriction of scattering processes to two incoming particles, which limits the applicability to low particle densities. For hydrodynamics, on the other hand, matter has to be in local thermal equilibrium (for ideal, non-viscous hydrodynamic calculations) or at least close to it (for viscous calculations) [37, 38, 39]. From this, it is clear where the advantages for both models are: While in transport, non-equilibrium matter, which is present in the beginning of the heavy-ion reaction, and dilute matter, which is present in the late phase, can be described, hydrodynamics may be better suited to describe the intermediate stage, which is supposed to be dense, hot and thermalized. In addition, the transition between two phases of matter, such as Quark Gluon Plasma (QGP) and Hadron Gas (HG) can be easily described in hydrodynamics, while this is not (yet) possible for transport models, since the microscopic details of this transition are not known.

2. The Model
UrQMD v2.3 (Ultra-relativistic Quantum Molecular Dynamics) is a microscopic transport model [13, 14, 40]. It includes all hadrons and resonances up to masses $m \approx 2.2$ GeV and at high energies can excite and fragment strings. The cross-sections are either parametrized, calculated via detailed balance or taken from the additive quark model (AQM), if no experimental values are available. At high parton momentum transfers, PYTHIA [41] is employed for pQCD scatterings. UrQMD differentiates between two regimes for the excitation and fragmentation of strings. Below a momentum transfer of $Q < 1.5$ GeV a maximum of two longitudinal strings are excited according to the LUND picture, at momentum transfers above $Q > 1.5$ GeV hard interactions are modelled via PYTHIA. For detailed information on the inclusion of PYTHIA, the reader is referred to Section II of [40]. In the UrQMD framework, propagation and spectral functions are calculated as in vacuum.

In the following, we compare results from this microscopic model to results obtained with a hybrid model description [42]. Here, the high-density part of the reaction is modelled using ideal 3+1-dimensional fluid-dynamics. The unequilibrated initial state and the low-density final state are described by UrQMD. In the hydrodynamic intermediate stage we use a Hadron Gas Equation of State (HG-EoS) which includes the same degrees of freedom as are present in the transport phase. This allows to explore the effects due to the change of the kinetic description.

To connect the initial transport phase with the high-density fluid phase, the baryon-number-, energy- and momentum-densities are smoothed and put into the hydrodynamic calculation after $t = 0.6$ fm. Temperature, chemical potential, pressure and other macroscopic quantities are determined from the densities by the Equation of State used in the current calculation. During this transition, the system is forced into an equilibrated state. Particles with high rapidity $y > 2$, however, are excluded from the hydrodynamic grid and propagated in the cascade without interaction to the hydrodynamic medium.

In non-central collisions, the spectators are propagated in the cascade. After the local rest frame energy density has dropped below a threshold value of $\epsilon_{\text{crit}} \approx 5\epsilon_0$, particles are created on a hyper-surface from the densities by means of the Cooper-Frye formula and propagation is continued in UrQMD.

The transition from hydrodynamic to cascade description used in the calculations presented here is gradual. I.e. each transverse slice (constant $z$) is transferred to the cascade at the same time, when the condition is met throughout that slice. This represents a pseudo-eigentime
condition.

Photon emission is calculated perturbatively in both models, hydrodynamics and transport, because the evolution of the underlying event is not altered by the emission of photons due to their very small emission probability. The channels considered for photon emission may differ between the hybrid approach and the binary scattering model. Emission from a Quark-Gluon-Plasma can only happen in the hydrodynamic phase, and only if the equation of state used has partonic or chirally restored degrees of freedom. Photons from baryonic interactions are neglected in the present calculation.

For emission from the transport part of the model, we use the well-established cross-sections from Kapusta et al. [10], and for emission from the hydrodynamic phase, we use the parametrizations by Turbide, Rapp and Gale and Arnold et al. [43] (the latter for QGP-emission). For detailed information on the emission process, the reader is referred to Bäuchle and Bleicher [44].

3. Results
Photon emission has been calculated for minimum bias (0-92 %) and central (0-10 %) Au + Au-collisions at $\sqrt{s_{NN}} = 200$ GeV with both the pure cascade and the cascade-hydrodynamic hybrid models. We note that the high-$p_T$ data obtained by PHENIX [9] can be described very well with pQCD-calculations by Gordon and Vogelsang [45], therefore we investigate the contributions of our model to low-$p_T$ photons only.

In Figure 1, we show the direct photons emitted by the cascade- and hybrid models and compare them to the aforementioned pQCD-calculations and data from the PHENIX-collaboration.

While our hadronic model fails to predict the amount of direct photons emitted at intermediate transverse momentum, the disagreement is smaller at low $p_T$. The spectra obtained with an intermediate hydrodynamic part are significantly higher than those with pure cascade calculations. In any case, the spectra are negligible compared to the pQCD contributions predicted by Gordon and Vogelsang, therefore, an enhancement with respect to those data cannot be explained by hadronic sources.

In Figure 2, we explore the contribution of the different stages to the hybrid model spectra. The contribution of the intermediate hydro phase turns out to be dominant at low transverse momenta $p_T < 3$ GeV. The contributions of the initial and final stages are lower than the complete spectrum from the cascade calculations, so that we can assume the intermediate stage in the cascade calculation to be on the order of the final stage contribution in the hybrid model calculations.

The difference between the hydrodynamic and transport descriptions of the intermediate stage has not been observed for collisions with lower energies $E_{\text{lab}} = 158$ AGeV (see [44]) and $E_{\text{lab}} = 45$ AGeV (see [46]).

4. Summary
In this article, we have applied UrQMD and the UrQMD+Hydro hybrid model to calculate photon spectra from central and minimum bias Au+Au-collisions at $\sqrt{s_{NN}} = 200$ GeV. The comparison of the (hadronic) calculations to data from the PHENIX collaboration suggest that a significant contribution to the measured spectra comes from non-hadronic sources. The low-$p_T$-excess over pQCD-predictions seen by the PHENIX-collaboration [47] cannot be explained by hadronic sources; partonic sources such as a Quark-Gluon-Plasma are therefore very likely to be responsible for this excess.

The comparison of transport and hybrid calculations show that the conclusion drawn at lower energy, which suggested that there is no difference between the spectra obtained with or without intermediate hydrodynamic stage, is not valid at these high energies. The excess of the hybrid
model calculations over the transport calculations are visible in both central and minimum bias collision samples, and the magnitude of this excess is similar in both models. This suggests that the excess depends only on the collision energy, not on the system size.

5. Outlook
The results shown here suggest the need for further studies. Calculations of direct photon spectra have to be done with the current model for other centrality selections, and with different Equations of State such as a Bag Model EoS and an EoS with a chirally restored phase. In order to investigate the difference between the hybrid model and the cascade model, an energy dependent investigation of the excess is advisable.

Different systems measured at the RHIC-facility, such as Cu+Cu-collisions and collisions at smaller center-of-mass energy, will also be calculated.

The parameters of the model – the conditions for switching to and from the hydrodynamic description and the scenario for the latter transition – will be investigated in the future.

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Figure 2. Comparison of the contribution of the different stages (initial stage, green dash-dotted lines; intermediate stage, blue dotted lines, final stage, red dashed lines) to the overall spectrum from the hybrid model (black solid line) and the overall spectrum from pure cascade calculations (red crosses) for minimum bias and central Au+Au-collisions at $\sqrt{s_{NN}} = 200$ GeV.

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