Soft Photons from transport and hydrodynamics at FAIR energies

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Abstract. Direct photon spectra from uranium-uranium collisions at FAIR energies ($E_{\text{lab}}=35$ AGeV) are calculated within the hadronic Ultra-relativistic Quantum Molecular Dynamics transport model. In this microscopic model, one can optionally include a macroscopic intermediate hydrodynamical phase. The hot and dense stage of the collision is then modeled by a hydrodynamical calculation. Photon emission from transport-hydro hybrid calculations is examined for purely hadronic matter and matter that has a cross-over phase transition and a critical end point to deconfined and chirally restored matter at high temperatures. We find the photon spectra in both scenarios to be dominated by Bremsstrahlung. Comparing flow of photons in both cases suggests a way to distinguish these two scenarios.

1. Motivation
One of the major goals in high energy nuclear physics was and is the examination of a new strongly interacting deconfined phase of matter, the Quark-Gluon-Plasma (QGP) [1, 2], the state of matter which is believed to have filled the universe shortly after the Big Bang. Many hints for the existence of this phase have been found at the Relativistic Heavy Ion Collider (RHIC). The relevant observables are, e.g., jet quenching and high elliptic flow [3, 4, 5, 6]. The CERN-SPS program has also found evidence for this new state of matter. One has to mention the enhanced $K/\pi$ ratio (horn) and the step in the mean transverse mass excitation function for pions, kaons and protons [7]. More recently, LHC has confirmed these results at much higher energies [8]. The ALICE Collaboration has shown that the QGP remains a nearly ideal liquid even at much higher energies compared to RHIC [9].

One of the biggest challenges facing heavy-ion physicists is to get information from the hot and dense collision area, the so-called fireball. The small space-time volume of the fireball makes it impossible to probe it directly, so all information has to be obtained from its decay products. Single particles carry only information about their last collision, which usually happens in the cold phase at the end of the collision. Hence, the QGP can only be probed indirectly by most of the possible observables. One of the probes suggested for searching the QGP were photons and leptons. The small interaction cross-section of electromagnetic probes leads to a mean free path which is large compared to the interaction zone. Thus, most photons and electrons leave the interaction zone undisturbed and carry information of the matter present when they were created through the entire collision. Possible electromagnetic probes, which are used for measurements, are single- and dileptons and photons. One further distinguishes between direct photons that are...
created in elementary collisions, the so-called direct photons, and decay photons. This leads to the biggest challenge in measuring photons in heavy-ion collisions: Most of the photons created in the collision are decay photons from the late stages of the reaction, namely from $\pi^0$ and $\eta$ decays. The dominant process is $\pi^0 \rightarrow \gamma \gamma$. To gain direct photon data, one has to subtract the huge background of decay photons. Some experiments have measured direct photon spectra. Explicit data points at low transverse momenta have been published by the WA98 Collaboration (CERN-SPS) [10] and the PHENIX Collaboration (BNL RHIC) [11, 12]. Theoretical studies have been performed earlier, e.g., with the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model (see section 2) by Dumitru et al. [13] and Bäuchle et al. [14] and with hadron-string dynamics (HSD) by Bratkovskaya et al. [15]. Hydrodynamic approaches for direct photon calculations have been used for example in: [16, 17, 18, 19, 20, 21]. A comparison between PHENIX data [11, 12] and the model established in [14] can be found in [22].

In the present work, we investigate the composition of direct photon production and elliptic flow $v_2$ in U+U-collisions at $E_{\text{lab}} = 35$ AGeV using the model described in [14]. We compare calculations with hadronic degrees of freedom to calculations with a first order phase transition to a QGP. In Section 2 and 3, we briefly present the underlying model used for calculations and the photon sources, and in Section 4 we analyze our calculations for direct photon emission and the elliptic flow $v_2$.

2. The Model
This work is based on the microscopic Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [23, 24, 25], which is originally a hadronic transport model with hadronic and string degrees of freedom. In UrQMD, all non-charmed baryons and mesons with masses up to 2.2 GeV are included. For resonances with high masses, the widths increase and the particles overlap. Therefore, UrQMD replaces resonances with continuous string excitations for higher energies. For hard scatterings, i.e., scatterings with momentum transfer higher than $Q^2 > 1.5$ (GeV)$^2$ and a minimal center of mass energy $\sqrt{s_{\text{min}}} = 10$ GeV, PYTHIA [26] is used. The cross-sections in UrQMD are tabulated from experimental data, parametrized or, if no such data exists, extracted via detailed balance or the additive quark model (AQM). Microscopic models on the basis of an effective solution of the Boltzman equation can be used for non-equilibrium systems and provide all information about the particle trajectory at any time of the collision. On the other hand, these kinds of models are in most cases restricted to binary collisions ($2 \rightarrow n$). This implies large mean free paths of the particles, which may not be fulfilled in the high-density intermediate stage of the collision. One possible description for the hot and dense stage of the collision is ideal hydrodynamics. High elliptic flow observed at RHIC experiments seem to be consistent with ideal hydrodynamic calculations and points to the applicability of this approach [27, 28, 29]. In UrQMD version 3.3, a hybrid approach with a micro- and macroscopic description was incorporated into the UrQMD model [30, 31, 32, 33]. It is now possible to switch from the transport to the hydrodynamic description and back. At the beginning, the particles are propagated on straight trajectories in the so-called cascade mode without potentials. After the first collisions have taken place, fluidization happens and the intermediate hydrodynamic stage starts. The time for this is chosen to be when the nuclei have passed through each other, i.e., $t = 2R\sqrt{2m_N/E_{\text{lab}}}$ with $R$ being the radius of the nucleus, $m_N$ the nucleon mass and $E_{\text{lab}}$ the kinetic beam energy. Spectators are not fluidized. The particlization, i.e., the transition from the fluid-based to the particle-based description, starts when the energy density falls below a certain value in all propagated cells at the same longitudinal position. Particles are created using the Cooper-Frye formula [34]. All further scatterings and decays are again performed in the microscopic UrQMD model. For the hydrodynamic calculations, different equations of state (EoS) with different degrees of freedom are used. The Hadron Gas EoS (HG-EoS) [35] with only hadronic degrees of freedom can be applied for baseline calculations to compare with cascade
calculations. The Deconfinement EoS (DE-EoS) \cite{36} includes a first-order phase-transition to a chirally restored and deconfined phase of matter at high baryo-chemical potentials, a critical end point and a cross-over at low baryo-chemical potentials and therefore can be applied for photon emission from QGP.

3. Photon emission sources

Photons are not implemented natively in the UrQMD model. Within our model, photons are calculated perturbatively without changing the underlying evolution of the fireball. This treatment is justified, since the electromagnetic cross-section, responsible for photon production, is negligibly small compared to the strong cross-sections dealing with the evolution of the medium.

For the emission of photons from the hydrodynamic stage of the evolution the parametrization by Turbide et al. \cite{18} is used. The cross-sections for the emission from the transport evolution description are from Kapusta et al. \cite{37}. The two channels implemented in both descriptions and yielding most of the photons are namely $\pi\pi \to \gamma\rho$ and $\pi\rho \to \gamma\pi$. The $\pi\rho \to \gamma\pi$ rate from \cite{18} also includes an $a_1$-meson as an intermediate stage. Emission from QGP and Bremsstrahlung processes ($\pi\pi \to \pi\pi\gamma$) \cite{38} are only taken into account in the hydrodynamic description. A comprehensive discussion of other hadronic channels can be found in \cite{14}. Photons from primordial pQCD scatterings can be neglected at FAIR energies.

4. Results

![Figure 1](image1.png)

**Figure 1.** (Color online.) Photon emission from HG-EoS hybrid calculations of central U+U-collisions at $E_{\text{lab}} = 35$ AGeV. We show the total spectra (black solid line), emission from Bremsstrahlung processes (red dotted line) and other hadronic channels (blue dashed line).

![Figure 2](image2.png)

**Figure 2.** (Color online.) Photon emission from DE-EoS hybrid calculations of central U+U-collisions at $E_{\text{lab}} = 35$ AGeV. We show the total spectra (black solid line), emission from Bremsstrahlung processes (red dotted line), other hadronic channels (blue dashed line) and emission from QGP (magenta dash-dotted line).

Figures 1 and 2 show the yield of direct photons from transport and hydrodynamic calculations with the Hadron Gas EoS (HG-EoS) and the Deconfinement EoS (DE-EoS), respectively. We show the spectra for photons from Bremsstrahlung (red dotted lines), QGP (magenta dash-dotted line, only Figure 2), all other channels (blue dashed lines) and the sum of all channels (black solid lines). Emission from Bremsstrahlung is the largest contribution to the total spectra in both cases. In calculations with a phase transition to deconfined matter (see
Figure 2), the amount of photons from Bremsstrahlung is reduced, since a sizeable portion of the system is in the deconfined state and therefore does not emit photons from hadronic processes. Emission from the QGP, however, makes up for the loss almost exactly, so that the total direct photon spectra from both calculations are very similar.

In Figures 3 and 4, we show results for direct photon elliptic flow HG-EoS and DE-EoS hybrid calculations, respectively. We show the elliptic flow $v_2$ for photons from Bremsstrahlung (red dotted lines), QGP (magenta dash-dotted line, only Figure 2), all other channels (blue dashed lines) and the sum of all channels (black solid lines). The elliptic flow from other hadronic channels is large compared to the flow from Bremsstrahlung and QGP in both scenarios. In both scenarios, elliptic flow is dominated by the largest contributions. The magnitude of flow from these contributions shows the space of time in which emission from these channels happens: QGP emission (DE-EoS calculations only) happens in the early stages of the collision, in which the underlying hadronic medium has not yet built up strong elliptic flow. Thus, photons emitted from this stage carry only little elliptic flow themselves.

Photons from processes that dominate in the late part of the fireball evolution, however, have a large hadronic flow present at their emission time imprinted in their elliptic flow pattern. Comparing flow results from both scenarios, we can re-assess the conclusion we drew for direct photon spectra in Figures 1 and 2. There, we concluded that QGP emission in the Deconfinement EoS calculations basically substitutes Bremsstrahlung emission from Hadron Gas calculations in the early stages. Indeed, we see a larger elliptic flow from Bremsstrahlung in the Deconfinement EoS calculations than in the Hadron Gas EoS calculations, pointing to a later average emission time.

Unlike in the case of the spectra, the remaining difference between both calculations remains quite sizeable, with direct photon elliptic flow peaking about 20% higher where a phase transition is present.
5. Summary
We have shown calculations for direct photon emission from central Uranium+Uranium-collisions at $E_{lab} = 35$ AGeV and compared the emission patterns from matter with a first order phase transition to chirally restored and deconfined matter and critical end point (DE-EoS) to that of purely hadronic matter without phase transition. We find the direct photon spectra to be essentially unchanged, while we predict direct photon elliptic flow to be sensitive to the choice of matter. High-quality experiments, as they are being built at the FAIR facility, will be able to distinguish both scenarios.

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