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Direct photon emission in Heavy Ion Collisions from Microscopic Transport Theory and Fluid Dynamics

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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. Different scenarios of the transition from the macroscopic description to the transport model description and their effects are studied. The calculations are compared to measurements by the WA98-collaboration and predictions for the future CBM-experiment are made.

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1. Introduction

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) [1] and PHENIX (BNL-RHIC) [2] 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.* [3] and Xiong *et al.* [4]. 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 [5, 6] and relativisitc fluid- or hydrodynamics [7, 8]. 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).

From these deliberations, 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 [6, 9]. 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. 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 [10]. 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. Thus, those stages have only hadronic and string degrees of freedom.

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 the incoming nuclei have passed through each other. 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.

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 $\varepsilon_{\text{crit}} \approx 5\varepsilon_0$, 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 scenario used in the calculations presented here can be either isochronous, i.e. all particles are created at the same time, or "gradual". In the latter scenario, particles are created at the same time for every slice in the longitudinal direction. This represents a pseudo-eigentime condition.

For these investigations, we use three different Equations of State for the hydrodynamic phase. The base line calculations are done with a Hadron Gas Equation of State (HG-EoS), which includes the same degrees of freedom as present in the transport phase. This allows to explore the effects due to the change of the kinetic description. Secondly, we use a MIT-Bag Model EoS (BM-EoS) with a partonic phase and a first order phase transition [8]. We use the BM-EoS for investigations of photon emission from the QGP. The third Equation of State χ-EoS used here has a chirally restored phase with a critical end point [11].

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.* [3], and for emission from the hydrodynamic phase, we use the parametrizations by Turbide, Rapp and Gale and Arnold *et al.* [12] (the latter for QGP-emission). For detailed information on the emission process, the reader is referred to Bäuchle *et al.* [13].

3. Results

In Figure 1, we compare inclusive spectra from hybrid calculations with isochronous and gradual transition from the hydrodynamics to cascade phases. Here, we find the spectra to be very consistent with each other. But when looking at the contributions of the different stages – the early, intermediate (hydrodynamic) and late stage – in Figure 2, we find significant differences in the relative contributions of intermediate and late stage. While for the isochronous transition, both phases contribute in similar amounts, the gradual transition scenario is dominated by the hydrodynamic intermediate stage and has a greatly reduced late stage emission.

Photon emission has also been calculated for minimum bias $U+U$-collisions at $E_{\text{lab}} = 45$ AGeV, as are planned at the future FAIR-facility (see Figure 3). At these energies, the pQCD-contribution

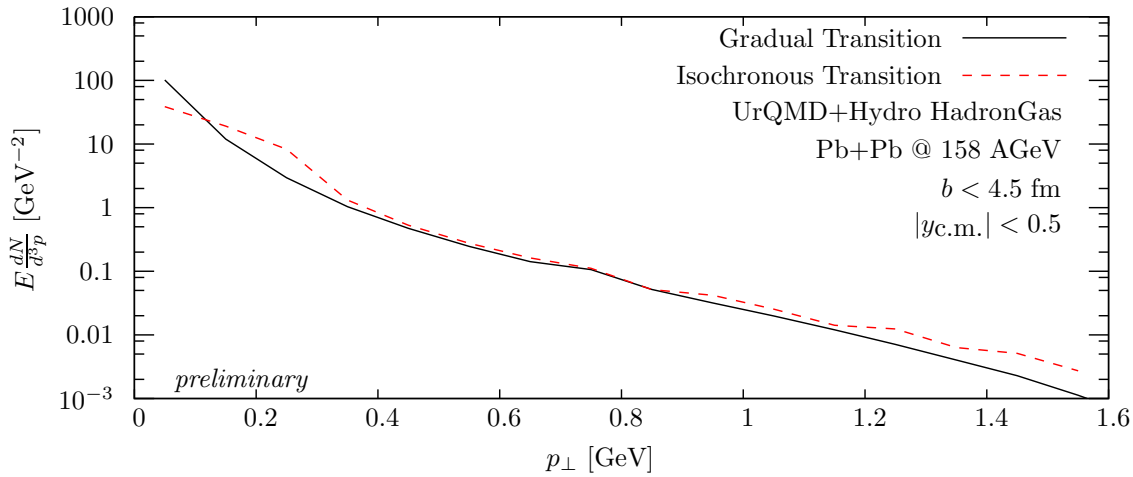

Figure 1: Direct photon spectra from hybrid-model calculations with hadron gas EoS. The calculation with isochronous transition is shown as a red dotted line, the calculation with gradual transition as black solid line.

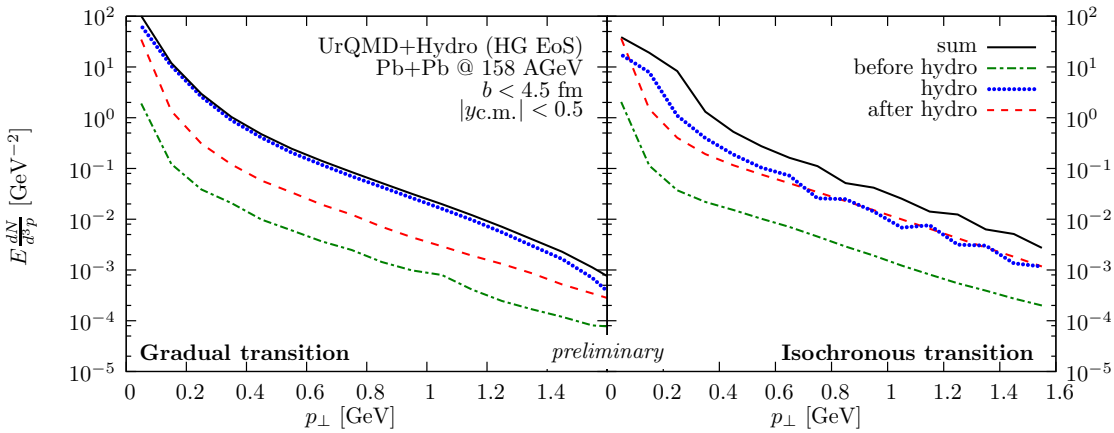

Figure 2: Contribution of the stages before (dark green dash-dotted), during (blue dotted) and after (red dashed) hydrodynamic evolution with gradual transition (left-hand side) and isochronous transition (right hand side).

from proton-proton collisions is negligible. We can confirm that the cascade-calculation and the hybrid calculation with Hadron Gas EoS yield consistent results, as was found in calculations for $E_{\mathrm{lab}} = 158$ AGeV (see [13]). The emission in Bag Model EoS calculations is greatly enhanced with respect to the hadronic base line calculations, and the results from using the Chiral EoS show a significant enhancement at large $p_\perp$. Thus, experiments at FAIR will be well-suited to distinguish the different models.

4. Summary

With UrQMD, we have explored the impact of the transition scenario from the hydrodynamic to the cascade phase on the emission of photons. The main result is that with the standard model parameters, the effect of changing this transition is negligible. A closer look at the origin of the

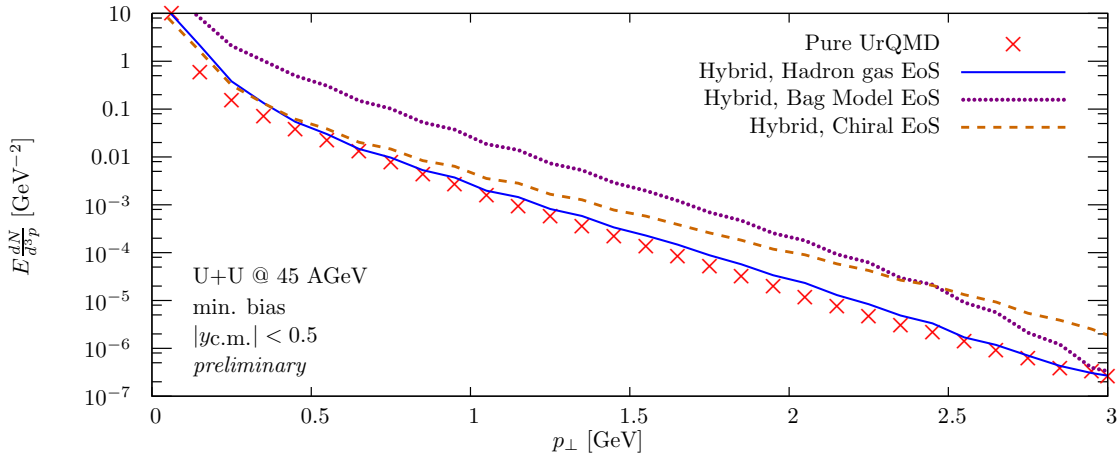

Figure 3: Comparison of the direct photon spectra with different variations of the model for FAIR-CBM-energies. The calculations are done with the "isochronous" transition scenario (see text). We show calculations without hydrodynamic state (red crosses), hadron gas EoS (blue solid), Bag model EoS (violett dotted) and chiral EoS (orange dashed line).

photons and the contribution of the different stages suggests that the comparison between gradual and isochronous transition scenarios is likely to depend on the criterium for this transition – i.e. at what energy density this transition happens.

At low beam energies, where pQCD-effects do not contribute to the overall spectra, a clearer comparison between different scenarios will be possible. Specifically, calculations with different EoS yield significant differences.

5. Outlook

The results shown here suggest the need for further studies. Especially the different contributions of the stages between the transition scenarios suggest a closer inspection of the transition parameters and its impact on photon emission. The time of the first transition from cascade to hydrodynamics should also be examined. All of these studies will be carried out for various equations of state.

The preliminary results for the FAIR-system $U+U$ at $E_{\text{lab}} = 45$ AGeV show significant differences between the various Equations of State, which will be examined in more detail in the near future.

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