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Effective dynamical coupling of hydrodynamics and transport for heavy-ion collisions

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Abstract. Present hydrodynamics-based simulations of heavy-ion collisions neglect the feedback from the frozen-out particles flying back into the hydrodynamical region. This causes an artefact called "negative Cooper-Frye contributions", which is negligible for high collision energies, but becomes significant for lower RHIC BES energies and for event-by-event simulations. To avoid negative Cooper-Frye contributions, while still preserving hydrodynamical behavior, we propose a pure hadronic transport approach with forced thermalization in the regions of high energy density. It is demonstrated that this approach exhibits enhancement of strangeness and mean transverse momenta compared to conventional transport – an effect typical for hydrodynamical approaches.

1. Introduction and Motivation

A major goal of heavy-ion collision experiments is the study of the QCD phase diagram and the search for its critical point. High energy heavy-ion collisions create a high-temperature and low-baryon density system, which undergoes a cross-over during cooling, but not a phase transition. A conjecture supported by many phenomenological models is that at lower collision energies, where a higher baryon density is reached, the system undergoes a first order phase transition. Testing this conjecture and finding the critical point, where the phase transition turns into a cross-over, motivates the Beam Energy Scan (BES) experiments at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven (USA), as well as the construction of the Nuclotron-based Ion Collider fAcility (NICA) in Dubna (Russia) and the Facility for Antiproton and Ion Research (FAIR) in Darmstadt (Germany). At BES the beam energy was sequentially decreased from $\sqrt{s_{NN}} = 200$ GeV per nucleon pair down to 7.7 GeV. Also a fixed-target mode operation of STAR detector at RHIC would allow going down to $\sqrt{s_{NN}} \approx 3$ GeV [1]. Planned energy ranges per nucleon pair in heavy-ion collisions at NICA and FAIR are $\sqrt{s_{NN}} = (4 - 11)$ GeV [3] and $\sqrt{s_{NN}} = (2.3 - 5.3)$ GeV and eventually $(2.3 - 9.3)$ GeV [2]. This illustrates a substantial interest of the heavy-ion community in low-energy collisions.

In these proceedings we point out that traditional assumptions behind the hydrodynamical simulations of heavy ion collisions break at low collision energies. This motivates us to suggest an approach, which allows to relax these assumptions.

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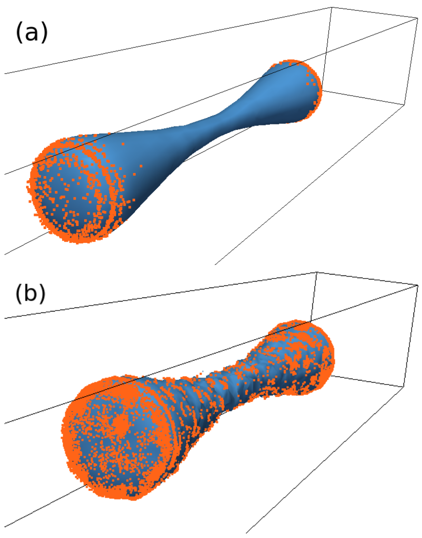

Figure 1. Demonstration of the lumpiness effect on "negative crossings". Hypersurfaces of constant Landau rest frame energy density 0.3 GeV/fm^3 for Au+Au collisions at 160 A GeV are shown at fixed time. Both are obtained from 1000 coarse-grained UrQMD events, but in (a) additional smoothing is applied (see text). Points mark particles crossing the hypersurface from outside to inside.

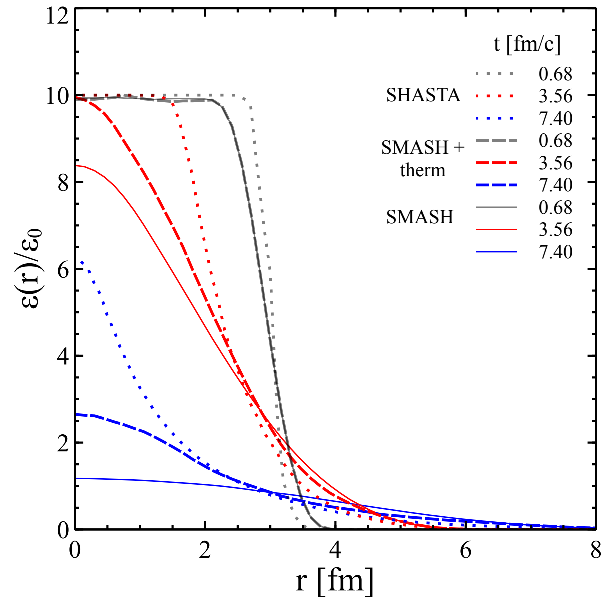

Figure 2. The time evolution of an expanding sphere is compared for ideal hydrodynamics (SHASTA, dotted lines), hadron cascade (SMASH, solid lines) and the same hadron cascade enhanced by forced thermalization where rest frame energy density exceeds 0.3 GeV/fm^3 (SMASH+therm, dashed lines).

2. Negative contributions on the freeze-out hypersurface

Relativistic hydrodynamics is very successful in the description of the dynamics of heavy-ion collisions and explains a plethora of measured particle spectra and flows (v_2, v_3, etc.) at RHIC and LHC. Due to this success of hydrodynamics it is stated that the hot and dense matter created in heavy-ion collisions at RHIC and LHC has a very small kinematic viscosity. All the current hydrodynamics-based simulations adopt the following approximations: the hydrodynamic equations are solved in the whole forward light cone, including regions where hydrodynamics is not applicable; the particlization hypersurface is chosen a posteriori from hydrodynamics; frozen-out particles flying again into the hydrodynamical region cannot cause feedback to hydrodynamics. Particle spectra produced from the hypersurface element $d\sigma_\mu$ are typically computed using the Cooper-Frye formula:

$$E\frac{d^3N}{d^3p} = f(p)\, p^\mu d\sigma_\mu \tag{1}$$

According to this formula, for space-like $d\sigma_\mu$, there exist momenta for which the number of produced particles is negative. This negative number corresponds to particles that fly back into the hydrodynamical region. In a simulation, where hydrodynamical equations for the dense region are coupled with kinetic equations for the sparse region, these negative contributions will be properly taken into account. However, currently such simulations only exist for non-relativistic hydrodynamics [4].

Are the above mentioned approximations adequate? In other words: are negative Cooper-Frye contributions negligible? A study dedicated to this question [5] found that they may be small at high collision energies, but become larger for the lower ones reaching 10-15% for pions at midrapidity at energies of FAIR, NICA and RHIC BES. Here we would like to mention one more feature that has not been discussed in detail in [5]: in event-by-event simulations, where the particlization hypersurface may be lumpy, negative contributions can be increased dramatically. This effect of a lumpy hypersurface is illustrated by Fig. 1. It shows two surfaces of constant Landau rest frame energy density, $e_c = 0.3$ GeV/fm^3, at fixed time. They were obtained from coarse-grained UrQMD simulation of Au+Au collision at 160 A GeV. Both were constructed from 1000 events, but for one simulation the energy density in the cells was smoothed using running average ($\epsilon = \frac{1}{27}\sum_{i=1}^{27}\epsilon_i$) where the sum is running over the cell neighbours. Particles crossing hypersurfaces from the outside to the inside (the "negative crossings") for all events are shown with dots. One can see that lumps increase the amount of "negative crossings" substantially. The lumpiness effect requires further investigation, because unlike in this coarse-grained transport study, in the hydrodynamic simulation the lumpy initial state may be smoothed by the hydrodynamical evolution. For viscous hydrodynamics the freeze-out hypersurface is smoother than for ideal hydrodynamics given the same initial state, so the effect is smaller. The larger the viscosity, the stronger the smoothing and the smaller the effect.

3. Forced thermalization at high density regions

To relax the approximations used by hydrodynamical approaches, but preserve their advantages, we have constructed and tested the following conceptually simple approach. In the hadronic transport calculation we have performed forced thermalization in the regions where the rest frame Landau energy density ϵ is larger than some ϵ_c. In this way we reach hydrodynamical behavior in the region where hydrodynamics is applicable. The kinetic Boltzmann equation is solved in the rest of the space, and it automatically turns out that the surface connecting both regions is found dynamically. This was implemented using the SMASH hadron cascade [6]. In the forced thermalization procedure we required the exact conservation of energy, momentum and quantum numbers. Its implementation and testing are described in detail in [7].

In Fig. 2 we show the comparison of our approach, pure SMASH transport and SHASTA ideal hydrodynamics [8] within a simple setup: a sphere of radius $R_0 = 3$ fm is initialized with constant energy density $10\epsilon_0$, where ϵ_0 is a nuclear ground state energy density, and allowed to evolve. Fig. 2 demonstrates that our approach exhibits intermediate behavior between hydrodynamics and transport. The difference between our approach and hydrodynamics emerges due to the fact that at the boundary of the hydrodynamical region hydrodynamics assumes a small Knudsen number, but in our approach in the vicinity of the boundary particles may simply fly out.

Finally, we apply our approach to Au+Au collision at $\sqrt{s_{NN}} = 3$ GeV and observe several expected effects characteristic for hydrodynamics. The main results are shown in Fig. 3. Firstly, we find that multiplicities of strange particles are larger in our approach than in a pure SMASH transport and tend to be close to the multiplicities from the UrQMD hybrid approach [9] initialized and treated in the same way. This is the effect of the forced thermalization: in pure transport the amount of strange particles is below the equilibrium values. Secondly, we observe that the average transverse momentum in our approach is larger for different particles species than in transport. This is happening due to the isotropization: more momentum is transferred from the collision axis to the midrapidity region. The increase of $\langle p_t \rangle$ seems to be independent on the time between thermalizations Δt_{th}. Also, the effect is especially pronounced for K^-, which are produced only in the secondary strangeness exchange reactions.

To sum up, we have performed the first tests of a new approach, where in a pure hadronic transport forced thermalization is applied in the dense regions. This approach interpolates between transport and hydrodynamics, avoiding the traditional problem of negative Cooper-Frye contributions. The plan for the future besides additional tests is to understand bulk observables at low and intermediate collision energies.

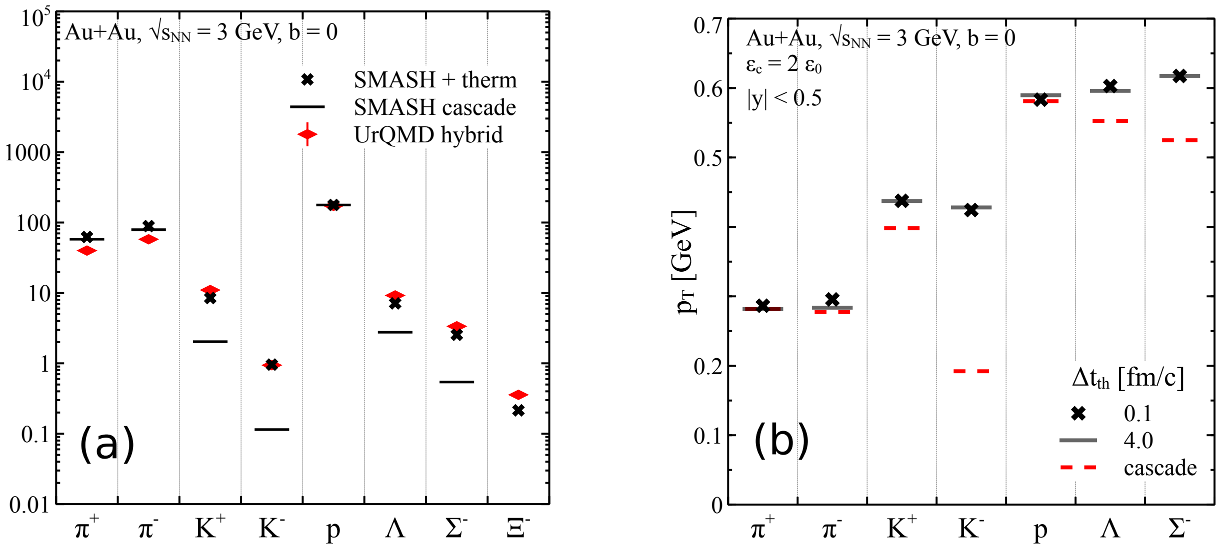

Figure 3. Central Au+Au collision at $\sqrt{s} = 3$ GeV. Panel (a): Final multiplicities are compared for SMASH, SMASH with thermalization, and UrQMD hybrid. Panel (b): Mean transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$ at midrapidity for the calculation with forced thermalization is compared to the cascade.

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