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STRANGENESS PRODUCTION AND LOCAL THERMALIZATION IN AN INTEGRATED BOLTZMANN + HYDRODYNAMICS APPROACH*

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We present results on strangeness production from a coupled Boltzmann and hydrodynamics approach to relativistic heavy ion reactions. This approach is based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport model with an intermediate hydrodynamical evolution for the hot and dense stage of the collision. Final particle yields are discussed, putting special attention on the production of multistrange hyperons. We find that the yields for (multi)strange particles are strongly enhanced, due to the inferred local thermal equilibrium in the hydrodynamic evolution, leading to an improved description of experimental yields for these particles.

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1. Introduction

One of the main motivations to study high energy heavy ion collisions is the creation of a new deconfined phase of strongly interacting matter, the so called Quark–Gluon Plasma (QGP) [1,2]. Since the direct detection of free quarks and gluons is impossible due to the confining nature of QCD, it is important to model the dynamical evolution of heavy ion reactions to draw conclusions from the final state particle distributions. Hadrons containing strange quarks are a very interesting topic to study, since they have to be newly created and their production mechanism is different comparing for

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example the QGP to a hadron gas. Whether a QGP phase is necessary to reproduce the experimentally measured yields, is not yet clear [3, 4]. Microscopic plus macroscopic hybrid approaches are a promising tool to simulate heavy ion collisions, employing hydrodynamics as well as transport for the hot and dense stage [5–11].

2. Model description

The Ultra-relativistic Quantum Molecular Dynamics Model is used to calculate the initial state of a heavy ion collision for the hydrodynamical evolution [8]. This is necessary to account for the non-equilibrium nature of the very early stage of the collision. Event-by-event fluctuations of the initial state are naturally included by this set-up. The coupling between the UrQMD initial state and the hydrodynamical evolution takes place when the two Lorentz-contracted nuclei have passed through each other. The hydrodynamic code transforms all the given quantities from the computational frame to the local rest frame of the energy momentum tensor, forcing the system to local thermal equilibrium. The full $(3 + 1)$ dimensional hydrodynamic evolution is performed using the SHASTA algorithm [22, 23].

An equation of state is needed as additional input, having an important influence on the evolution. For the results presented here an equation of state for a free hadron gas without any phase transition is used [24]. In this EoS local strangeness conservation is achieved, adjusting the strange chemical potential $\mu_{\rm S}$. The hydrodynamic evolution is stopped, if the energy density in all cells drops below five times the nuclear ground state energy density (*i.e.* ~ 730 MeV/fm^3). The hydrodynamic fields are mapped to hadrons according to the Cooper–Frye equation [25] on an isochronous hypersurface. Hadronic rescatterings and resonance decays are taken into account, using UrQMD. This approach [26] allows us to fix the initial conditions as well as the description of the final state and explore the effects of changes in the dynamics — hydro *versus* transport — without altering the active degrees of freedom.

3. Results

In the following, multiplicities and particle spectra are compared in the two frameworks (transport calculation UrQMD 2.3 and hybrid approach). In Fig. 1 the excitation functions of the total multiplicities of strange baryons are shown for central Au + Au/Pb + Pb collisions for $E_{\rm lab} = 2$–160 $A\,$GeV. Within the hybrid model calculation the production of strange particles is enhanced, due to the establishment of local thermal equilibrium. To further investigate the effects of thermalization, the time evolution of different quantities is analyzed.

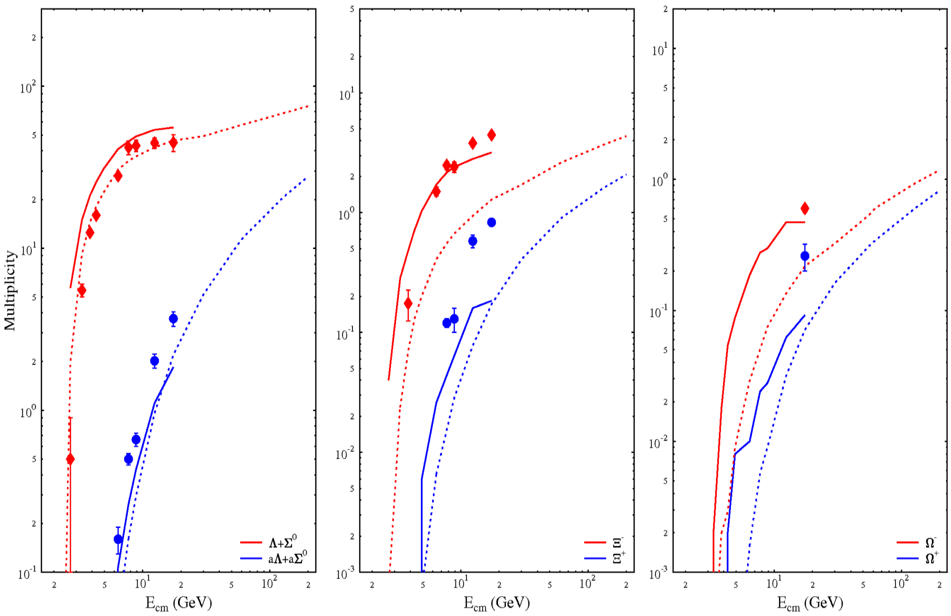

Fig. 1. (Color online) Excitation function of strange baryon multiplicities (4π) in Au + Au/Pb + Pb collisions from $E_{\rm lab} = 2\ A\,{\rm GeV}$ to $\sqrt{s_{\rm NN}} = 200$ GeV. UrQMD + Hydro (HG) calculations are depicted with full lines, while UrQMD 2.3 calculations are depicted with dotted lines. The corresponding data from different experiments [12–21] are depicted with symbols.

In Fig. 2 (left, top and middle) the time evolution of particle yields in the two different models for the most central Pb + Pb collisions at $E_{\rm lab} = 40\ A\,{\rm GeV}$ are compared. The multiplicities at different timesteps are extracted from the hydrodynamic evolution via the freeze-out procedure. Fig. 2 (left, top) depicts the total (red circles and full line) and the midrapidity (blue squares and full line) particle yields. The full lines indicate the default UrQMD calculation, while the symbols show the results of the hybrid model. The multiplicities increase rapidly in the initial 3 fm/c and then decrease a little, followed by a slower constant rise until the final multiplicity is reached. This qualitative behaviour is very similar in both approaches. The decrease of the multiplicity can be associated with the thermalization because absorption and production processes are on the same order.

Next, we explore the time evolution for two particle species in more detail. The qualitative behaviour of the temporal evolution of the pion yield (Fig. 2 (left, middle)) is similar to that discussed above for the total multiplicity. The decrease at the starting time of the hydrodynamic evolution $t \sim 3$ fm/c is much stronger than in the model without hydrodynamic phase, because of the instant thermalization at the transition time. The de-

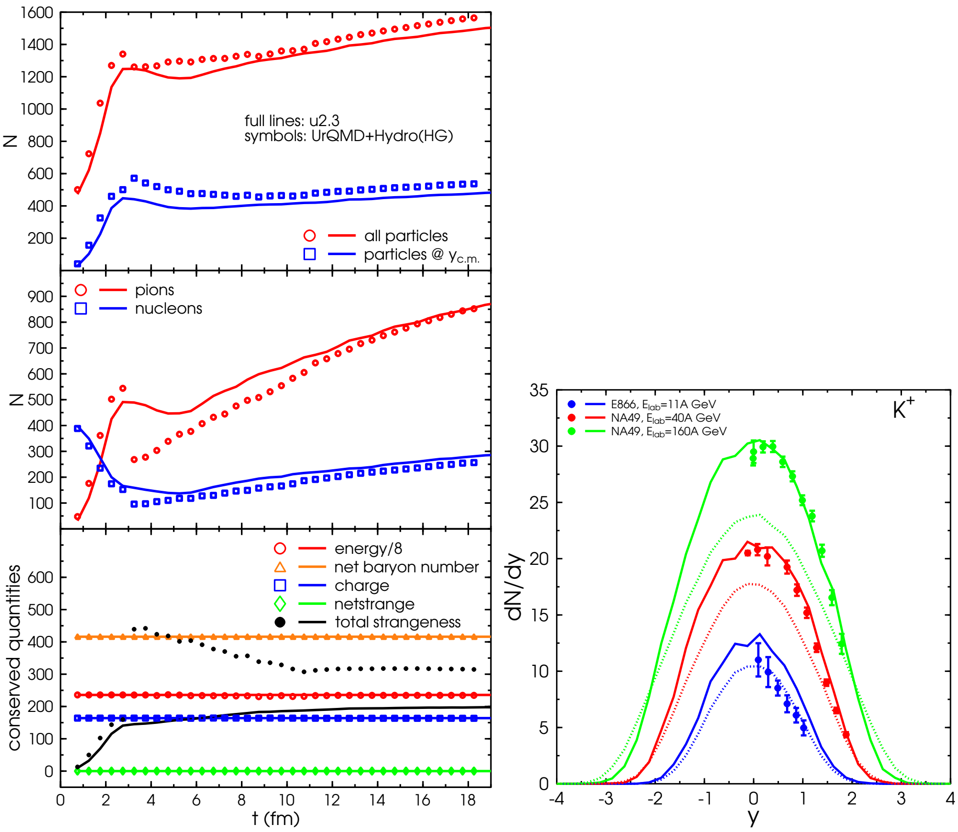

Fig. 2. (Color online) (left) Time evolution of the total particle number and the midrapidity ($|y| < 0.5$) yield (upper panel), of the total number of pions and nucleons (middle panel) and of the conserved quantities (lower panel) for central ($b = 0$ fm) Pb + Pb collisions at $E_{\rm lab} = 40$ A GeV. (right) Rapidity spectra of K^+ for central ($b < 3.4$ fm) Au + Au/Pb + Pb collisions for $E_{\rm lab} = 11$, 40 and 160 A GeV. UrQMD + Hydro (HG) calculations are depicted with full lines, while UrQMD 2.3 calculations are depicted with dotted lines. The corresponding data from different experiments [15, 27] are depicted with symbols.

fault UrQMD transport calculation results in a similar, but much smoother, shape of the curve. This similarity hints to the fact that the microscopic calculation also equilibrates the hot and dense matter to a rather large degree. The number of nucleons decreases in the beginning due to the production of resonances and string excitations. At the thermalization the minimum is reached and the number of nucleons increases slowly until the final value is reached. In this case, not only the qualitative behaviour is independent of the underlying dynamics but also the absolute values are very close to each other. The net baryon number (triangles), the charge (squares) and the net strangeness (diamonds) are exactly conserved in both approaches (Fig. 2 (left, bottom)). The total energy (circles) is only on average over several events conserved in the hybrid model calculation due to the freeze-out prescription. Note however, that the total strangeness in the system ($s+\bar{s}-$ quarks) is very different in both approaches. In the default transport calculation (black line) the total strangeness increases in the early stage of the collision and remains constant. Within this approach, strange particles are produced by resonance excitations and string decays. This is contrasted by the hybrid calculation (dots). Due to the local thermal equilibration and the thermal production of strange particles in the hybrid calculation the yield of strange quarks jumps to a higher value at the switching time ($t_{\rm start}$). The total strangeness then decreases as the system cools down, but the final value remains 50% higher than in the default transport calculation. Fig. 2 (right) shows the K^+ rapidity distributions for three different beam energies. Except for the AGS energy the hybrid model calculation provides an almost perfect description of experimental data. The previously discussed strangeness enhancement is again visible. This hints to the fact that a locally thermalized system is produced. The question of a phase transition being present, remains for further investigations.

4. Summary

We have presented results on strangeness production from an integrated Boltzmann + hydrodynamics approach to relativistic heavy ion reactions. This hybrid approach is based on the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport approach with an intermediate hydrodynamical evolution for the hot and dense stage of the collision. The present implementation allows to compare pure microscopic transport calculations with hydrodynamic calculations using exactly the same initial conditions and freeze-out procedure. The yields for strange particles are strongly enhanced, due to the local equilibrium implied for the hydrodynamic evolution, fitting very nicely to the experimental data at SPS energies, supporting the assumption of (strangeness) equilibration at these energies. A phase transition to the QGP is not needed to reach the yields.

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