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# Strangeness production at SPS energies in a (3+1)dimensional Boltzmann+hydrodynamics approach

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**Abstract.** Results on strange particle production at energies from  $\sqrt{s} = 2 - 200$  A GeV from a (3+1)dimensional Boltzmann+hydrodynamics hybrid model are presented and compared to results from the Ultra-relativistic Quantum Molecular Dynamics transport approach and existing experimental data. The hybrid model with an intermediate hydrodynamical evolution for the hot and dense stage of the collision allows us to explore the centrality and system size dependence of (multi-strange) hyperon production in A+A collisions. The transition from a system which is not fully thermalized, like in C+C or Si+Si collisions, to supposedly fully thermalized systems as e.g. created in Pb+Pb reactions is investigated. The hyperon yields are enhanced in the hybrid approach due to the local equilibrium assumption and therefore in line with the experimental data. The excitation functions of strange to nonstrange particle yields (e.g.  $K^+/\pi^+$ ) calculated in the hybrid approach are able to reproduce the famous 'horn' structure at SPS energies with a purely hadronic equation of state in contrast to the pure transport approach, which failed to explain the experimental data.

## 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]. At CERN-SPS energies evidence for the creation of this new state of matter is claimed, e.g., with observations of an enhanced  $K/\pi$  ratio ('horn') and the step in the mean transverse mass excitation function for various hadron species [3]. Especially the low energy (high  $\mu_B$ ) program at SPS showed a culmination of exciting results. Therefore, the production of hadrons containing strange quarks is a very interesting topic to study in this energy regime (at the FAIR facility and at RHIC), as they have to be newly created and their production mechanism is different comparing for example the QGP to a hadron gas. Whether a QGP phase is necessary to reproduce the experimentally measured yields, is not yet clear [4, 5, 6, 7, 8].

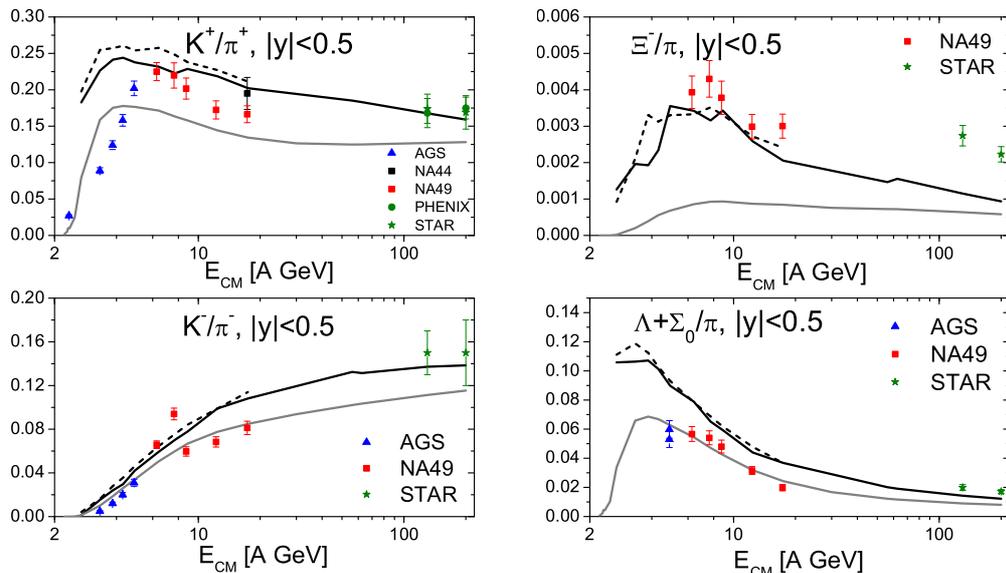
We address this question by using a relativistic transport approach, namely the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) (version 2.3) [9, 10, 11], and compare the results to a hybrid approach<sup>‡</sup> in which a hydrodynamic evolution is embedded into the intermediate stage of the model dynamics [12]. The advantage of this hybrid approach, compared to a pure hydrodynamic simulation, is that it allows for the direct comparison between non-equilibrium and locally equilibrated dynamics and accounts for a realistic decoupling of the particles with separate chemical and kinetic freeze-outs. Note that we do not aim to understand the dynamics of the strangeness equilibration process itself, but we are able to compare strangeness production in a full non-equilibrium approach with a dynamical approach involving local thermal and chemical equilibrium.

## 2. The model

In the hydrodynamic+transport hybrid model UrQMD v3.3, we use Boltzmann dynamics with hadron-hadron interactions, string excitation and fragmentation to calculate the initial state of a heavy ion collision for the hydrodynamical evolution. Hence we account for non-equilibrium effects in the very early stage of the collision and event-by-event fluctuations are naturally included [13]. Nucleons that did not interact are propagated during the whole evolution in the hadronic cascade, whereas the other particles are mapped to the hydrodynamical grid. The full (3 + 1) dimensional hydrodynamic evolution proceeds employing the SHASTA algorithm [14, 15]. For the present comparison we restrict ourselves to a hadron gas equation of state which includes the same degrees of freedom as in the cascade part of UrQMD [16].

The transition from the hydrodynamic phase to the Boltzmann dynamics takes place when the energy density  $\epsilon$  of every cell in a transverse slice drops below 4 (or 5) times the ground state energy density  $\epsilon_0 \approx 145 \text{ MeV}/\text{fm}^3$ . This gradual transition procedure provides a reasonable approximation to an iso-eigentime criterion and has

<sup>‡</sup> This new hybrid approach is available for download at <http://urqmd.org/> as UrQMD v3.3.



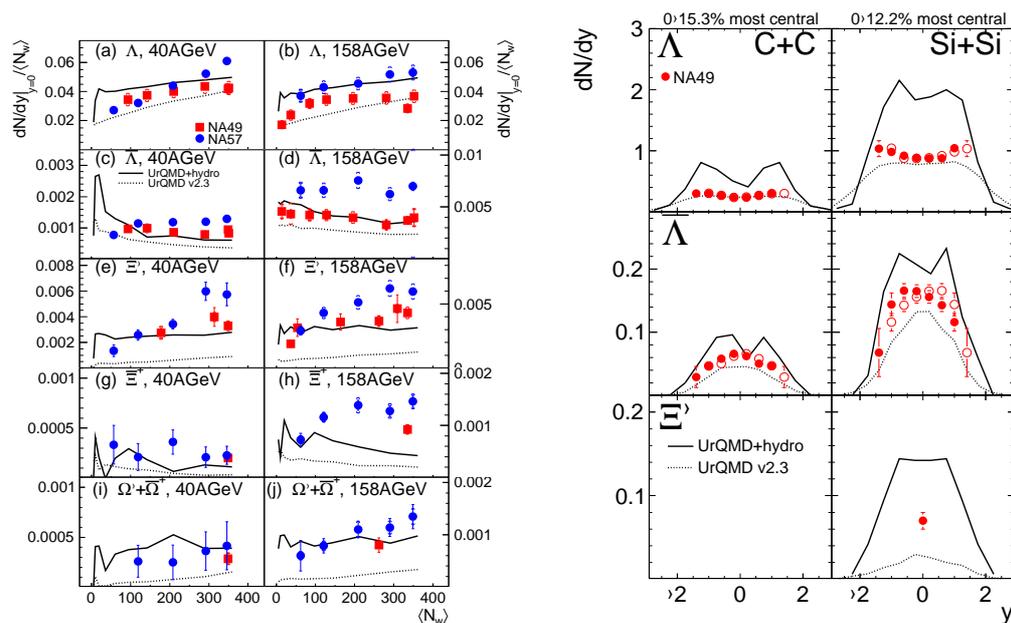
**Figure 1.** Excitation functions for kaon to pion ratios (left) and strange baryon to pion ratios (right) from most central heavy ion collisions at energies of  $E_{c.m.} = 2-200$  AGeV. Compared are two hybrid model calculations (black lines), UrQMD 2.3 (grey lines) and results from experiments [21, 22, 23, 24, 25, 26, 3, 27]. The two black lines represent results for different freeze out criteria  $4 \epsilon_0$  (solid line) and  $5 \epsilon_0$  (dashed line).

been applied successfully in Refs. [17, 18]. The hydrodynamic fields are then mapped to particle degrees of freedom via the Cooper-Frye equation on an isochronous hypersurface for each individual slice. For the production of strange baryons the corresponding chemical potentials  $\mu_B$  and  $\mu_S$  are taken into account, where  $\mu_S$  is chosen in a way that net strangeness vanishes locally. The subsequent rescatterings and final decays are calculated in the cascade part of the UrQMD model.

For a more detailed description and results of the hybrid model we refer to the references [12, 19].

### 3. Results

First we compare particle ratios from the two frameworks i.e., the pure transport calculation (grey line) and the hybrid approach (black line). In Fig. 1 the excitation functions of different particle ratios (at mid-rapidity), including strange baryons, are shown for central Au+Au/Pb+Pb collisions for center of mass energies of  $\sqrt{s} = 2 - 200$  AGeV. We also compare two different freeze-out criteria;  $4 \epsilon_0$  (solid line) and  $5 \epsilon_0$  (dashed line). Within the hybrid model calculation the production of strange particles is enhanced, due to the establishment of local thermal equilibrium. This leads to an improved description of multi-strange particle ratios at energies above  $\sqrt{s} \approx 5$  AGeV, while at lower energies the non-equilibrium approach seems to provide a better description of the data. Especially the 'horn' structure in the  $K^+/\pi^+$  ratio is



**Figure 2.** Left: Centrality dependence of the (anti-) hyperon yields at mid rapidity ( $|y| \leq 0.5$ ) at  $E_{\text{lab}} = 40A$  GeV (left) and  $E_{\text{lab}} = 158A$  GeV (right) measured by NA49 (squares) [29, 21, 30, 31] and NA57 (circles) [32, 33, 34]. The solid line represents calculations with UrQMD+hydro and the dashed line represents calculations with UrQMD [35].

Right: The rapidity spectra of  $\Lambda$ ,  $\bar{\Lambda}$  and  $\Xi^-$  produced in central C + C and Si + Si collisions at  $E_{\text{lab}} = 158A$  GeV [29, 30]. The closed symbols indicate measured points: open points are reflected with respect to mid rapidity. The solid line represents calculations with UrQMD + hydro and the dashed line represents calculations with UrQMD [35].

reproduced without the explicit inclusion of a phase transition. As in thermal model studies we contribute it to a transition from a baryon dominated to a meson dominated regime in the phase diagram, reached at SPS energies. Note that the transport model is not able to reproduce the 'horn' structure in the  $K^+$  to  $\pi^+$  ratio. This was explained by an over-estimation of the pion yields rather than the actual  $K^+$  production rate [20].

### 3.1. Centrality dependence

As a next step we investigate the centrality dependence of strange baryon production in Pb + Pb reactions (for details see [35]). The centrality and system size dependence of hyperon production at  $E_{\text{lab}} = 40A$  and  $158A$  GeV at mid rapidity ( $|y| \leq 0.5$ ) is shown in Fig. 2 (left) and compared to data [29, 21, 30, 31, 32, 33, 34]. The dashed line represents calculations with standard UrQMD and the solid line depicts predictions from transport + hydro simulations.

The standard transport approach describes the data only in very peripheral collisions quite well. Moving to more central Pb + Pb collisions, it is evident that the production of strange hadrons, from a system in local equilibrium, is in much better agreement with

the measured data than obtained in the binary collision prescription (see also [28]). Especially for multistrange hyperons it is visible that the production via independent strings and resonance excitations is not sufficient to explain the experimentally measured yields.

Instead of varying the centrality of the collision to explore the applicability limit of the hybrid model in terms of collision volume, we can also perform calculations for smaller systems. Figure 2 (right) represents the rapidity spectra of  $\Lambda$  and  $\bar{\Lambda}$  for central C + C and Si + Si collisions at 158A GeV measured by the NA49 Collaboration [29, 30] compared to results from the hybrid model (solid line) and the standard UrQMD (dashed line). Even if the number of participants in central Si + Si collisions is similar to peripheral Pb + Pb collisions (33.5–43.5 % most central), the geometry and the starting time for the hydrodynamic evolution are different, as both depend on the radius of the nucleus:  $t_{start} = 2R\sqrt{2m_N/E_{lab}}$ .

It is evident that standard UrQMD (dashed lines) describes the data better than the transport+hydrodynamics approach (solid lines) for such small systems. The limited system size does not allow for the same degree of equilibration in C + C and Si+Si interactions as in the case of Pb + Pb collisions for all shown centralities. This indicates that up to Si + Si reactions, equilibration cannot be achieved and the system is merely a (non-)trivial convolution of elementary baryon-baryon (and in smaller parts meson-baryon) interactions.

#### 4. Conclusion

We presented results on strange hadron production in an hydrodynamic+transport hybrid approach. The assumption of local thermal equilibration of strangeness leads to an improvement of the description of strange particle ratios, at energies above  $\sqrt{s} \approx 5$  AGeV, when compared to the pure transport results. At lower energies the assumption of full local equilibration of strangeness seems questionable.

In this context, the 'horn' structure in the  $K^+/\pi^+$  ratio excitation function can be reproduced by our approach, which does not explicitly include a phase transition.

Our results on the system size and centrality dependence of strange particle production show that strangeness equilibration is only reached in Pb + Pb collision (at energies above  $\sqrt{s} \approx 5$  AGeV) at least in all shown centrality classes. Compared to Pb + Pb collisions the system seems not fully equilibrated in C + C and Si + Si collisions and therefore the Boltzmann approach provides a better description of the measured rapidity spectra. The applicability of our hybrid approach therefore is limited to energies above 5 AGeV, at least for observables concerning strange matter.

We conclude that the assumption of local equilibration alone allows us to explain a major part of the strangeness enhancement in central collisions of massive nuclei which does not necessarily invoke the formation of a QGP. For peripheral reactions or small collision systems a microscopic description with binary interactions between hadrons is favored. Furthermore, the possibility of creating an equilibrated fireball, which can

undergo a phase transition, is reduced in such small systems because the creation of a QGP would be observed in higher strangeness production.

## 5. Acknowledgments

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## 6. Bibliography

- [1] J. W. Harris and B. Muller, *Ann. Rev. Nucl. Part. Sci.* **46**, 71 (1996)
- [2] S. A. Bass, M. Gyulassy, H. Stoecker and W. Greiner, *J. Phys. G* **25**, R1 (1999)
- [3] C. Alt *et al.* [NA49 Collaboration], *Phys. Rev. C* **77**, 024903 (2008)
- [4] P. Koch, B. Muller and J. Rafelski, *Phys. Rept.* **142**, 167 (1986).
- [5] S. Soff *et al.*, *Phys. Lett. B* **471**, 89 (1999)
- [6] C. Greiner, P. Koch-Steinheimer, F. M. Liu, I. A. Shovkovy, H. Stoecker, *J. Phys. G* **31**, S725(2005)
- [7] P. Braun-Munzinger, J. Stachel and C. Wetterich, *Phys. Lett. B* **596**, 61 (2004)
- [8] J. Noronha-Hostler, H. Ahmad, J. Noronha and C. Greiner, arXiv:0906.3960 [nucl-th].
- [9] M. Bleicher *et al.*, *J. Phys. G* **25**, 1859 (1999)
- [10] S. A. Bass *et al.*, *Prog. Part. Nucl. Phys.* **41**, 255 (1998)
- [11] H. Petersen, M. Bleicher, S. A. Bass and H. Stoecker, arXiv:0805.0567 [hep-ph].
- [12] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stoecker, *Phys. Rev. C* **78**, 044901(2008)
- [13] J. Steinheimer *et al.*, *Phys. Rev. C* **77**, 034901 (2008)
- [14] D. H. Rischke, S. Bernard and J. A. Maruhn, *Nucl. Phys. A* **595**, 346 (1995)
- [15] D. H. Rischke, Y. Pursun and J. A. Maruhn, *Nucl. Phys. A* **595**, 383 (1995)
- [16] L. V. Bravina *et al.*, *J. Phys. G* **25**, 351 (1999)
- [17] Q. f. Li, J. Steinheimer, H. Petersen, M. Bleicher and H. Stoecker, *Phys. Lett. B* **674**, 111 (2009)
- [18] H. Petersen and M. Bleicher, *Phys. Rev. C* **79**, 054904 (2009)
- [19] J. Steinheimer *et al.*, arXiv:0905.3099 [hep-ph].
- [20] H. Weber, E. L. Bratkovskaya, W. Cassing and H. Stoecker, *Phys. Rev. C* **67**, 014904 (2003)
- [21] C. Alt *et al.* [NA49 Collaboration], *Phys. Rev. C* **78**, 034918 (2008)
- [22] S. V. Afanasiev *et al.* [The NA49 Collaboration], *Phys. Rev. C* **66**, 054902 (2002)
- [23] L. Ahle *et al.* [E866 Collaboration and E917 Collaboration], *Phys. Lett. B* **476**, 1 (2000)
- [24] J. Adams *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **92**, 112301 (2004)
- [25] K. Adcox *et al.* [PHENIX Collaboration], *Phys. Rev. C* **69**, 024904 (2004)
- [26] J. L. Klay *et al.* [E-0895 Collaboration], *Phys. Rev. C* **68**, 054905 (2003)
- [27] M. K. Mitrovski *et al.* [NA49 Collaboration], *J. Phys. G* **32**, S43 (2006)
- [28] E. Santini, H. Petersen and M. Bleicher, arXiv:0909.4657 [nucl-th].
- [29] T. Anticic *et al.* [NA49 Collaboration], *Phys. Rev. C* **80**, 034906 (2009)
- [30] C. Alt *et al.* [NA49 Collaboration], *Phys. Rev. Lett.* **94**, 052301 (2005)
- [31] C. Alt *et al.* [NA49 Collaboration], *Phys. Rev. Lett.* **94**, 192301 (2005)
- [32] F. Antinori *et al.* [NA57 Collaboration], *J. Phys. G* **32**, 427 (2006)
- [33] F. Antinori *et al.* [NA57 Collaboration], *Phys. Lett. B* **595**, 68 (2004)
- [34] <http://wa97.web.cern.ch/WA97/yields.html>
- [35] H. Petersen, M. Mitrovski, T. Schuster and M. Bleicher, *Phys. Rev. C* **80**, 054910 (2009)