Signals of the QGP phase transition - a view from microscopic transport models

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Abstract

In this contribution the results from various transport models on different observables - considered as possible signals of the phase transition from hadronic matter to the quark-gluon plasma (QGP) - are briefly reviewed.

1 Introduction

The phase transition from partonic degrees of freedom (quarks and gluons) to interacting hadrons is a central topic of modern high-energy physics. In order to understand the dynamics and relevant scales of this transition laboratory experiments under controlled conditions are presently performed with ultra-relativistic nucleus-nucleus collisions. Hadronic spectra and relative hadron abundancies from these experiments reflect important aspects of the dynamics in the hot and dense zone formed in the early phase of the reaction.

Estimates based on the Bjorken formula [1] for the energy density achieved in central Au+Au collisions suggest that the critical energy density for the formation of a quark-gluon plasma (QGP) is by far exceeded during a few fm/c in the initial phase of Au+Au collisions at Relativistic Heavy-Ion Collider (RHIC) energies, but sufficient energy densities (∼ 0.7-1 GeV/fm³ [2]) might already be achieved at Alternating Gradient Synchrotron (AGS) energies of ∼ 10 A·GeV [3]. More recently, lattice QCD calculations at finite temperature and quark chemical potential $\mu_q$ [4] show a rapid increase of the thermodynamic pressure $P$ with temperature above the critical temperature $T_c$ for a phase transition to the QGP. The crucial question is, however, at what bombarding energies the conditions for the phase transition are fulfilled. Thus, it is very important to perform an 'energy scan' of different observables in order to find an 'anomalous' behavior that might be attributed to a phase transition.

In addition to the strong interactions in the initial stage of the reaction - attributed to the QGP - there are also strong (pre-)hadronic interactions after/during the hadronization phase. Thus it becomes very important to know the impact of such (pre-) hadronic interactions on the final observables. The relevant information on this issue can be provided by microscopic transport models based on a nonequilibrium description of the nuclear dynamics [5].

In this contribution I present the compilation of HSD results on two of the possible signals of the phase transition: strangeness and charm. The HSD (Hadron-String-Dynamics)
Figure 1: Excitation function of the $K^+/\pi^+$ ratio (l.h.s.) and inverse slope parameter for $K^+$ (r.h.s.) from central Au+Au (AGS and RHIC) or Pb+Pb (SPS) collisions. The solid lines with open squares show the results from HSD whereas the dashed lines with open triangles indicate the UrQMD calculations. The solid lines with stars correspond to HSD calculations including ‘Cronin’ initial state enhancement.

transport approach \[6, 7\] employs hadronic and string degrees of freedom and takes into account the formation and multiple rescattering of hadrons; it thus dynamically describes the generation of pressure in the early phase - dominated by strings - and the hadronic expansion phase. The HSD transport approach is matched to reproduce the nucleon-nucleon, meson-nucleon and meson-meson cross section data in a wide kinematic range. It also provides a good description of particle production in p+A reactions \[8\] as well electroproduction of hadrons off nuclei \[9\]. In order to obtain a model independent conclusion, we also address the results from the UrQMD model \[10, 11\] which has similar underlying concepts as HSD but differs in the actual realizations.

2 Strangeness signals of the QGP

As has been proposed in 1982 by Rafelski and Müller \[12\] the strangeness degree of freedom might play an important role in distinguishing hadronic and partonic dynamics. In 1999 Gaździcki and Gorenstein \[13\] - within the statistical model - have predicted experimental observables which should show an anomalous behaviour at the phase transition: the 'kink' – an enhancement of pion production in central Au+Au (Pb+Pb) collisions relative to scaled pp collisions; the 'horn' – a sharp maximum in the $K^+ / \pi^+$ ratio at 20 to 30 A·GeV; the 'step' – an approximately constant slope of $K^\pm$ spectra starting from 20 to 30 A·GeV. Indeed, such ”anomalies” have been observed experimentally by the NA49 Collaboration \[14, 15\].

In Refs. \[16, 17, 18\] we have investigated the hadron production as well as transverse hadron spectra in nucleus-nucleus collisions from 2 A·GeV to 21.3 A·TeV within the independent transport approaches UrQMD and HSD. The comparison to experimental data demonstrates that both approaches agree quite well with each other and with the experimental data on hadron production. The enhancement of pion production in central Au+Au (Pb+Pb) collisions relative to scaled pp collisions (the 'kink') is well described by both approaches without involving any phase transition. However, the maximum in the $K^+ / \pi^+$ ratio at 20 to 30 A·GeV (the 'horn') is missed by $\sim 40\% \ [16, 18]$ – cf. Fig. 1 (l.h.s.).
comparison to the transverse mass spectra from \( pp \) and C+C (or Si+Si) reactions shows the reliability of the transport models for light systems [17]. For central Au+Au (Pb+Pb) collisions at bombarding energies above \( \sim 5 \text{ A-GeV} \), however, the measured \( K^\pm m_T \)-spectra have a larger inverse slope parameter than expected from the calculations. The approximately constant slope of \( K^\pm \) spectra at SPS (the 'step') is not reproduced either [17, 18] – cf. Fig. 1 (r.h.s.). The HSD calculations also demonstrate that the 'partonic' Cronin effect plays a minor role at AGS and SPS energies for the parameter \( T \). The slope parameters from \( pp \) collisions (r.h.s. in Fig. 1) are seen to increase smoothly with energy both in the experiment (full squares) and in the transport calculations (full lines with open circles) and are significantly lower than those from central Au+Au reactions for \( \sqrt{s} > 3.5 \text{ GeV} \).

Thus the pressure generated by hadronic interactions in the transport models above \( \sim 5 \text{ A-GeV} \) is lower than observed in the experimental data. This finding suggests that the additional pressure - as expected from lattice QCD calculations at finite quark chemical potential and temperature - might be generated by strong interactions in the early pre-hadronic/partonic phase of central Au+Au (Pb+Pb) collisions.

3 Charm signals of the QGP

The microscopic HSD transport calculations (employed here) provide a suitable space-time geometry of the nucleus-nucleus reaction and a rather reliable estimate for the local energy densities achieved. The energy density \( \varepsilon(r,t) \) – which is identified with the matrix element \( T^{00}(r,t) \) of the energy momentum tensor in the local rest frame at space-time \( (r,t) \) – reaches up to 30 GeV/fm\(^3\) in a central Au+Au collision at \( \sqrt{s} = 200 \text{ GeV} \) [19].

According to present knowledge the charmonium production in heavy-ion collisions, i.e. \( c\bar{c} \) pairs, occurs exclusively at the initial stage of the reaction in primary nucleon-nucleon collisions. The parametrizations of the total charmonium cross sections \( (i = \chi_c, J/\Psi, \Psi') \) from \( NN \) collisions as a function of the invariant energy \( \sqrt{s} \) used in this work are taken from [7, 20, 21, 22]. We recall that (as in Refs. [21, 22, 23, 24, 25]) the charm degrees of freedom in the HSD approach are treated perturbatively and that initial hard processes (such as \( c\bar{c} \) or Drell-Yan production from \( NN \) collisions) are 'precalculated' to achieve a scaling of the inclusive cross section with the number of projectile and target nucleons as \( A_P \times A_T \) when integrating over impact parameter. For fixed impact parameter \( b \) the \( c\bar{c} \) yield then scales with the number of binary hard collisions \( N_{\text{bin}} \) (cf. Fig. 8 in Ref. [22]).

In the QGP 'threshold scenario', e.g the geometrical Glauber model of Blaizot et al. [26] as well as the percolation model of Satz [27], the QGP suppression '(i)' sets in rather abruptly as soon as the energy density exceeds a threshold value \( \varepsilon_c \), which is a free parameter. This version of the standard approach is motivated by the idea that the charmonium dissociation rate is drastically larger in a quark-gluon-plasma (QGP) than in a hadronic medium [27].

On the other hand, the extra suppression of charmonia in the high density phase of nucleus-nucleus collisions at SPS energies [28, 29] has been attributed to inelastic comover scattering (cf. [7, 20, 24, 30, 31, 32, 33, 34, 35, 36] and Refs. therein) assuming that the corresponding \( J/\Psi \)-hadron cross sections are in the order of a few mb [37, 38, 39]. In these models 'comovers' are viewed not as asymptotic hadronic states in vacuum but rather as hadronic correlators (essentially of vector meson type) that might well survive at energy densities above 1 GeV/fm\(^3\). Additionally, alternative absorption mechanisms might play a role such as gluon scattering on color dipole states as suggested in Refs. [40, 41, 42, 43] or charmonium dissociation in the strong color fields of overlapping strings [23].
Figure 2: The $J/\Psi$ nuclear modification factor $R_{AA}$ for $Au + Au$ collisions at $\sqrt{s} = 200$ GeV as a function of the number of participants $N_{part}$ in comparison to the data from [44] for midrapidity (full circles) and forward rapidity (full triangles). HSD results for the QGP ‘threshold melting’ scenarios are displayed in terms of the lower (green solid) lines for midrapidity $J/\Psi$’s ($|y| \leq 0.35$) and in terms of the upper (orange dashed) lines for forward rapidity ($1.2 \leq y \leq 2.2$) within different recombination scenarios (see text). The error bars on the theoretical results indicate the statistical uncertainty due to the finite number of events in the HSD calculations. Predictions for the ratio $B_{\mu\mu}(\Psi^\prime)\sigma_{\Psi^\prime}/B_{\mu\mu}(J/\Psi)\sigma_{J/\Psi}$ as a function of the number of participants $N_{part}$ are shown in the lower set of plots. The figure is taken from [19].

The explicit treatment of initial $c\bar{c}$ production by primary nucleon-nucleon collisions and the implementation of the comover model - involving a single matrix element $M_0$ fixed by the data at SPS energies - as well as the QGP threshold scenario in HSD are described in Refs. [19, 30] (see Fig. 1 of Ref. [30] for the relevant cross sections). We recall that the ‘threshold scenario’ for charmonium dissociation is implemented as follows: whenever the local energy density $\varepsilon(x)$ is above a threshold value $\varepsilon_j$ (where the index $j$ stands for $J/\Psi, \chi_c, \Psi^\prime$), the charmonium is fully dissociated to $c + \bar{c}$. The default threshold energy densities adopted are $\varepsilon_1 = 16$ GeV/fm$^3$ for $J/\Psi$, $\varepsilon_2 = 2$ GeV/fm$^3$ for $\chi_c$, and $\varepsilon_3 = 2$ GeV/fm$^3$ for $\Psi^\prime$. Two more scenarios were implemented similarly to the ‘comover suppression’ and the ‘threshold melting’ by adding the only additional assumption – that the comoving mesons (including the $D$-mesons) exist only at energy densities below some energy density $\varepsilon_{cut}$, which is a free parameter. We use $\varepsilon_{cut} = 1$ GeV/fm$^3$, i.e. of the order of the critical energy density.

In the following, we compare our calculations to the experimental data at the top RHIC energy of $\sqrt{s} = 200$ GeV. We recall that the experimentally measured nuclear modification
Figure 3: Same as Fig. 2 for the ‘comover absorption scenario’ including the charmonium reformation channels without cut in the energy density (l.h.s.) and with a cut in the energy density $\epsilon_{\text{cut}} = 1 \text{ GeV/fm}^3$ (see text for details). The figure is taken from [19].

The factor $R_{AA}$ is given by,

$$R_{AA} = \frac{dN(J/\Psi)_{AA}/dy}{N_{\text{coll}} \cdot dN(J/\Psi)_{pp}/dy},$$

where $dN(J/\Psi)_{AA}/dy$ denotes the final yield of $J/\Psi$ in $AA$ collisions, $dN(J/\Psi)_{pp}/dy$ is the yield in elementary $pp$ reactions and $N_{\text{coll}}$ is the number of binary collisions.

Due to the very high initial energy densities reached (corresponding to $T \geq 2T_c$), in the threshold melting scenario all initially created $J/\Psi$, $\Psi'$ and $\chi_c$ mesons melt. However, the PHENIX collaboration has found that at least 20% of $J/\Psi$ do survive at RHIC [44]. Thus, the importance of charmonium recreation is shown again. In HSD, we account for $J/\Psi$ recreation via the $D\bar{D}$ annihilation processes as explained in detail in [19, 30]. Note that in our approach, the cross sections of charmonium recreation in $D + \bar{D} \rightarrow J/\Psi + \text{meson}$ processes is fixed by detailed balance from the comover absorption cross section $J/\Psi + \text{meson} \rightarrow D + \bar{D}$.

But even after both these processes are added to the threshold melting mechanism, the centrality dependence of the $R_{AA}(J/\Psi)$ cannot be reproduced in the ‘threshold melting’ scenario, especially for peripheral collisions (cf. Fig. 2). This holds for both possibilities: with (r.h.s. of Fig. 2) and without (center of Fig. 2) energy-density cut $\epsilon_{\text{cut}}$, below which $D$-mesons and comovers do exist and can participate in $D + \bar{D} \leftrightarrow J/\Psi + \text{meson}$ reactions.

Comover absorption scenarios give generally a correct dependence of the yield on the centrality. If an existence of $D$-mesons at energy densities above 1 GeV/fm$^3$ is assumed, the amplitude of suppression of $J/\Psi$ at mid-rapidity is also well reproduced (see the line for ‘comover without $\epsilon_{\text{cut}}$’ scenario in Fig. 3 l.h.s.). Note that this line corresponds to the prediction made in the HSD approach in [45]. On the other hand, the rapidity dependence of the comover result is wrong, both with and without $\epsilon_{\text{cut}}$. If hadronic correlators exist only at $\epsilon < \epsilon_{\text{cut}}$, comover absorption is insufficient to reproduce the $J/\Psi$ suppression even...
at mid-rapidity (Fig. 3, r.h.s.). But its contribution to the charmonium suppression is, nevertheless, substantial. The difference between the theoretical curves marked ‘comover + $\epsilon_{\text{cut}}$’ and the data shows the maximum possible suppression that can be attributed to a deconfined medium.

We mention that there are also alternative explanations of the experimental data for the anomalous $J/\Psi$ suppression in A+A collisions: e.g. formation of charmonia only at the phase boundary as advocated by Andronic et al. [49] in the statistical hadronization model.

4 Summary

Summarizing this contribution, I want to point out that strange hadron production in central Au+Au (or Pb+Pb) collisions is quite well described in the independent transport approaches HSD and UrQMD [16]. The exception are the pion rapidity spectra at the highest AGS energy and lower SPS energies, which are overestimated by both models. As a consequence the HSD and UrQMD transport approaches underestimate the experimental maximum (‘horn’) of the $K^+/\pi^+$ ratio at $\sim 20-30$ A-GeV [16]. The inverse slope parameters $T$ for $K^\pm$ mesons from the HSD and UrQMD transport models are practically independent of system size from pp up to central Pb+Pb collisions and show only a slight increase with collision energy, but no ‘step’ in the $K^\pm$ transverse momentum slopes as suggested by Gaździecki and Gorenstein [13] in 1999 and found experimentally by the NA49 Collaboration. The rapid increase of the inverse slope parameters of kaons for collisions of heavy nuclei (Au+Au) found experimentally in the AGS energy range, however, is not reproduced by both models (see Fig. 1). Since the pion transverse mass spectra – which are hardly effected by collective flow – are described sufficiently well at all bombarding energies [18], the failure has to be attributed to a lack of pressure. I have argued - based on lattice QCD calculations at finite temperature and baryon chemical potential $\mu_B$ [24] as well as the experimental systematics in the chemical freeze-out parameters [48] - that this additional pressure should be generated in the early phase of the collision, where the ‘transverse’ energy densities in the transport approaches are higher than the critical energy densities for a phase transition (or cross-over) to the QGP. The interesting finding of the analysis is, that pre-hadronic degrees of freedom might already play a substantial role in central Au+Au collisions at AGS energies above $\sim 5$ A-GeV.

The formation and suppression dynamics of $J/\Psi$, $\chi_c$ and $\Psi'$ mesons has, furthermore, been studied within the HSD transport approach for Au + Au reactions from FAIR to top RHIC energies of $\sqrt{s} = 200$ GeV. It is found that both the ‘comover absorption’ and ‘threshold melting’ concepts fail severely at RHIC energies [19] whereas both models perform quite well at SPS energies. The failure of the ‘hadronic comover absorption’ model goes in line with its underestimation of the collective flow $v_2$ of leptons from open charm decay [40]. This suggests that the dynamics of $c, \bar{c}$ quarks at RHIC energies are dominated by strong pre-hadronic/partonic interactions of charmonia with the medium in a strong QGP (sQGP), which cannot be modeled by ‘hadronic’ scattering or described appropriately by color screening alone.

The evidence for creating a ‘new state of matter’, the sQGP, in Au+Au collisions at RHIC is overwhelming and is additionally supported by the strong suppression of high $p_T$ hadrons and ‘far-side’ jets - both observations being insufficiently described by string/hadronic models [50, 51] - as well as the quark-number scaling of elliptic flow $v_2(p_T)$. The question now reads: what are the properties of the sQGP?
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References

[1] J.D. Bjorken, Phys. Rev. D 27, 140 (1983).
[2] F. Karsch et al., Nucl. Phys. B 502, 321 (2001).
[3] W. Cassing et al., Nucl. Phys. A 674, 249 (2000).
[4] Z. Fodor, S. D. Katz, and K. K. Szabo, Phys. Lett. B 568, 73 (2003).
[5] H. Stöcker and W. Greiner, Phys. Rept. 137, 277 (1986).
[6] J. Geiss et al., Nucl. Phys. A 644, 107 (1998).
[7] W. Cassing and E. L. Bratkovskaya, Phys. Rep. 308, 65 (1999).
[8] A. Sibirtsev and W. Cassing, Nucl. Phys. A 641, 476 (1998).
[9] T. Falter et al., Phys. Lett. B 594, 61 (2004); Phys. Rev. C 70, 054609 (2004).
[10] S.A. Bass et al., Prog. Part. Nucl. Phys. 42, 255 (1998).
[11] M. Bleicher et al., J. Phys. G 25, 1859 (1999).
[12] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982).
[13] M. Gażydicki and M. I. Gorenstein, Acta Phys. Polon. B 30, 2705 (1999).
[14] S. V.Afanasiev et al., NA49 Collaboration, Phys. Rev. C 66, 054902 (2002).
[15] V. Friese et al., NA49 Collaboration, J. Phys. G 30, 119 (2004).
[16] H. Weber et al., Phys. Rev. C 67, 014904 (2003).
[17] E. L. Bratkovskaya et al., Phys. Rev. Lett. 92, 032302 (2004).
[18] E. L. Bratkovskaya et al., Phys. Rev. C 69, 054907 (2004).
[19] O. Linnyk et al., Phys. Rev. C76, 041901 (2007).
[20] W. Cassing, E. L. Bratkovskaya, and S. Juchem, Nucl. Phys. A674, 249 (2000).
[21] E. L. Bratkovskaya, W. Cassing, and H. Stöcker, Phys. Rev. C67, 054905 (2003).
[22] W. Cassing, E. L. Bratkovskaya, and A. Sibirtsev, Nucl. Phys. A691, 753 (2001).
[23] J. Geiss et al., Phys. Lett. B447, 31 (1999).
[24] W. Cassing and E. L. Bratkovskaya, Nucl. Phys. A623, 570 (1997).
[25] W. Cassing and C. M. Ko, Phys. Lett. B396, 39 (1997).
[26] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. 77, 1703 (1996).
[27] H. Satz, J. Phys. G32, R25 (2006).
[28] M. C. Abreu et al., Phys. Lett. B410, 337 (1997); B477, 28 (2000); B450, 456 (1999).
[29] A. Foerster et al., NA60 Collaboration, J. Phys. G32, S51 (2006).
[30] O. Linnyk et al., Nucl. Phys. A786, 183 (2007).
[31] N. Armesto and A. Capella, Phys. Lett. B430, 23 (1998).
[32] R. Vogt, Phys. Rep. 310, 197 (1999).
[33] C. Gerschel and J. H"ufner, Ann. Rev. Nucl. Part. Sci. 49, 255 (1999).
[34] D. E. Kahana and S. H. Kahana, Prog. Part. Nucl. Phys. 42, 269 (1999).
[35] C. Spieles et al., J. Phys. G25, 2351 (1999), Phys. Rev. C60, 054901 (1999).
[36] L. Gerland et al., Nucl. Phys. A663, 1019 (2000).
[37] K. L. Haglin, Phys. Rev. C61, 031903 (2000).
[38] Z. Lin and C. M. Ko, Phys. Rev. C62, 034903 (2000); J. Phys. G27, 617 (2001).
[39] A. Sibirtsev, K. Tsushima, and A. W. Thomas, Phys. Rev. C63, 044906 (2001).
[40] B. Zhang, C. M. Ko, B.-A. Li, Z. Lin, and B.-H. Sa, Phys. Rev. C62, 054905 (2000).
[41] L. Grandchamp, R. Rapp, Phys. Lett. B523, 60 (2001), Nucl. Phys. A 709, 415 (2002).
[42] D. Blaschke, Y. Kalinovsky, and V. Yadichev, Lect. Notes Phys. 647, 366 (2004).
[43] M. Bedjidian et al., hep-ph/0311048.
[44] H. B"usching et al., PHENIX Collaboration, Nucl. Phys. A774, 103 (2006).
[45] E. L. Bratkovskaya et al., Phys. Rev. C69, 054903 (2004).
[46] E. L. Bratkovskaya, W. Cassing, H. St"ocker, and N. Xu, Phys. Rev. C71, 044901 (2005).
[47] H. Weber, E.L. Bratkovskaya and H. St"ocker, Phys. Lett. B 545, 285 (2002).
[48] J. Cleymans and K. Redlich, Phys. Rev. C 60, 054908 (1999).
[49] A. Andronic et al., Nucl. Phys. A 789, 334 (2007).
[50] W. Cassing, K. Gallmeister and C. Greiner, Nucl. Phys A 735, 277 (2004).
[51] K. Gallmeister and W. Cassing, Nucl. Phys A 748, 241 (2005).