(Anti-)strangeness in heavy-ion collisions

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Abstract. We study the production of hadrons in nucleus-nucleus collisions within the Parton-Hadron-String Dynamics (PHSD) transport approach that is extended to incorporate essentials aspects of chiral symmetry restoration (CSR) in the hadronic sector (via the Schwinger mechanism) on top of the deconfinement phase transition as implemented in PHSD before. The essential impact of CSR is found in the Schwinger mechanism (for string decay) which fixes the ratio of strange to light quark production in the hadronic medium. Our studies suggest a microscopic explanation for the maximum in the $K^{+}/\pi^{+}$ and $(\Lambda + \Sigma^{0})/\pi^{-}$ ratios at about 30 A GeV which only shows up if in addition to CSR a deconfinement transition to partonic degrees-of-freedom is incorporated in the reaction dynamics.

1. Introduction
In this contribution we summarize the ideas and results from the study in Ref. \cite{1} that investigates chiral symmetry restoration in heavy-ion reactions and addresses phenomena such as strangeness enhancement \cite{2, 3} or the ‘horn’ in the $K^{+}/\pi^{+}$ ratio \cite{4, 5}. Both phenomena have been attributed to a deconfinement transition before. Indeed, the actual experimental observation could not be described within conventional hadronic transport theory \cite{6, 7, 8} and remained a major challenge for microscopic approaches.

2. Extensions in PHSD3.3
Our studies are performed within the PHSD transport approach that has been described in Refs. \cite{9, 10}. The PHSD incorporates explicit partonic degrees-of-freedom in terms of strongly interacting quasiparticles (quarks and gluons) in line with an equation-of-state from lattice QCD (lQCD) as well as dynamical hadronization and hadronic elastic and inelastic collisions in the final reaction phase. For a recent review we refer the reader to Ref. \cite{11}.

2.1. Strings in (P)HSD
We recall that in the PHSD/HSD, the high energy inelastic hadron-hadron collisions in the hadronic phase are described by the FRITIOF model \cite{12}, where two incoming nucleons emerge the reaction as two excited color singlet states, i.e. ‘strings’. The production probability $P$ of
massive $s\bar{s}$ or $q\bar{q}q\bar{q}$ pairs is suppressed in comparison to light flavor production ($u\bar{u}$, $d\bar{d}$) according to the Schwinger-like formula [13], i.e.

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp\left(-\frac{\pi m_s^2 - m_u^2}{2\kappa}\right),$$

with $\kappa \approx 0.176$ GeV$^2$ denoting the string tension and $m_s, m_q = m_u = m_d$ the appropriate (dressed) strange and light quark masses. Inserting the constituent (dressed) quark masses $m_u \approx 0.33$ GeV and $m_s \approx 0.5$ GeV in the vacuum a value of $\gamma_s \approx 0.3$ is obtained from Eq.(1). This ratio is expected to be different in a nuclear medium and actually should depend on the in-medium scalar quark condensate $<\bar{q}q>$.

### 2.2. The scalar quark condensate

The well known scalar quark condensate $<\bar{q}q>$ is viewed as an order parameter for the restoration of chiral symmetry at high baryon density and temperature. A reasonable estimate for the quark scalar condensate in dynamical calculations has been suggested by Friman et al. [14],

$$\frac{<\bar{q}q>}{<\bar{q}q>_{\text{vac}}} = 1 - \frac{\Sigma_\pi}{f^2_\pi m^2_\pi} \rho_S - \sum_h \frac{\sigma_h \rho^h_S}{f^2_h m^2_h},$$

where $\sigma_h$ denotes the $\sigma$-commutator of the relevant mesons $h$ and $\rho^h_S$ the scalar density of meson $h$ [1]. Furthermore, $<\bar{q}q>_{\text{vac}}$ denotes the vacuum condensate, $\Sigma_\pi \approx 45$ MeV is the pion-nucleon $\Sigma$-term, $f_\pi$ and $m_\pi$ the pion decay constant and pion mass, respectively. The last (and essential) quantity in the relation (2), that still has to be determined for an evaluation of the quark condensate, is the nucleon scalar density $\rho_S$. The latter quantity can be calculated in relativistic mean-field theory by replacing the mass and momentum by the effective quantities

$$m^*_N(x) = m_N^v - g_s \sigma(x)$$

with $m_N^v$ denoting the nucleon mass in vacuum. In Eq. (3) the scalar field $\sigma(x)$ mediates the scalar interaction with the surrounding medium while $g_s$ is a coupling. When including self-interactions of the $\sigma$-field up to 4th order [15] the scalar field is determined locally by the nonlinear gap equation [15, 16]

$$m^2_\sigma \sigma(x) + B \sigma^2(x) + C \sigma^3(x) = g_s \rho_S = g_s d \int \frac{d^3p}{(2\pi)^3} \frac{m^*_N(x)}{\sqrt{p^2 + m^2_N}} f_N(x, p)$$

with $d = 4$ in case of isospin symmetric nuclear matter. The parameters $g_s, m_N, B, C$ are fixed in the non-linear $\sigma - \omega$ model for nuclear matter [16] and are displayed in Table I of Ref. [1]. We will use the well-known NL3 parameter set in the following with a compressibility $K = 380$ MeV and effective mass $m^*/m = 0.7$ at normal nuclear matter density. We recall that in the non-linear $\sigma - \omega$ model the energy density for symmetric nuclear matter is given by [16]

$$\epsilon = U(\sigma) + \frac{g^2_\omega}{2m^2_\omega} \rho^2_N + d \int \frac{d^3p}{(2\pi)^3} E^*(p) (N_c(p) + N_d(p)),$$

with

$$E^*(p) = \sqrt{p^2 + m^2_B} ; \quad U(\sigma) = \frac{m^2_\omega}{2} \sigma^2 + \frac{B}{3} \sigma^3 + \frac{C}{4} \sigma^4,$$

while $\rho_N$ denotes the baryon density and $N_c(p)$ and $N_d(p)$ the particle/antiparticle numbers at fixed momentum $p$. 


2.3. The string decay in a hot and dense medium

The basic assumption now is that the strange and light quark masses in the hadronic medium drop both in line with the ratio (2),

\[
\begin{align*}
  m_s^* &= m_s^0 + (m_s^0 - m_s^0) \frac{\langle q\bar{q} \rangle}{\langle q\bar{q}\rangle^V}, \\
  m_q^* &= m_q^0 + (m_q^0 - m_q^0) \frac{\langle q\bar{q} \rangle}{\langle q\bar{q}\rangle^V},
\end{align*}
\]

using \(m_s^0 \approx 100\) MeV and \(m_q^0 \approx 7\) MeV for the bare quark masses while the vacuum (dressed) masses are \(m_s^V \approx 500\) MeV and \(m_q^V \approx 330\) MeV, respectively.

In order to illustrate our main conjecture we show in Fig. 1 the ratio \(s/u\) as a function of the energy density \(\epsilon\) at temperature \(T=0\) as evaluated by Eq. (5). In this case only nucleons contribute to the scalar density in Eq. (2) and the hadronic energy density which is (apart from slight corrections due to the interaction energy) roughly given by \(\epsilon \approx m_N \rho_N\), where \(m_N\) is the vacuum nucleon mass and \(\rho_N\) the nuclear density. It is seen that the ratio \(s/u\) rises with energy density up to the limiting values given by bare masses \(m_s = m_s^0\) and \(m_q = m_q^0\) in Eq. (1). In fact, this illustration corresponds to the case of HSD; in PHSD the ratio \(s/u\) increases in the same way up to \(\epsilon_c \approx 0.5\) GeV/fm\(^3\) but then drops down to a value of \(\sim 1/3\) in the deconfined phase. Accordingly, the approach to CSR occurs in the hadronic phase and should be seen experimentally for local energy densities below \(\epsilon_c \approx 0.5\) GeV/fm\(^3\) since there is no more any 'string decay' in the partonic phase above \(\epsilon_c\) due to the direct conversion of energy and momentum to the massive quasiparticles of the QGP.

In order to implement this scenario of 'chiral symmetry restoration' in the PHSD code we solve the gap equation (4) for each cell in space-time in order to determine the scalar nucleon density \(\rho_S\), the scalar quark condensate by Eq. (2) and the strangeness ratio by Eq. (1) which drives the string decay in each local cell. Since in the case of HSD (without any deconfined partonic phase) the ratio \(s/u\) increases further with energy density \(\epsilon\) as in Fig. 1, one has to expect an overestimation of strangeness production in the HSD when implementing CSR via (1) at high bombarding energies where the scalar quark condensate is vanishing in the overlap zone of the reaction.

![Figure 1](image_url). The ratios of strange to light quarks \((s/u)\) according to Eq. (1) and the various ratios for diquarks as a function of the nuclear energy density \(\epsilon\) for \(T=0\).
3. Comparison of PHSD3.3 results to A+A data

For an illustration we present here the ratio (2) in Fig. 2 as a function of $x$ and $z$ (for $y = 0$) at different times $t$ for a central Au+Au collisions at 30 A GeV. Whereas in the approach phase the ratio drops to about $2/3$ inside the impinging nuclei (cf. Fig. 2) the scalar quark condensate practically vanishes in the full overlap phase from about 3 to 7 fm/c and regains the vacuum value only in the late expansion phase as noted before. However, for all times from contact ($\sim 2.5$ fm/c) to about 8 fm/c the ratio of the scalar quark condensate remains far below unity, which implies that the decay of strings in the hadronic environment is modified substantially in the hot and dense medium.

The white borderlines in Fig. 2 separate the space-time regions of deconfined matter to hadronic matter. It is clearly seen that although the chiral symmetry is approximately restored in the full overlap phase from 2.8 to 6 fm/c some region is occupied by deconfined partons in the PHSD. In these regions, however, an enhanced production of strangeness should not occur since the Schwinger mechanism (1) no longer applies due to a vanishing string tension and a transformation of energy and momentum to massive partonic degrees-of-freedom.

Figure 2. The ratio (2) for the scalar quark condensate as a function of $x$ and $z$ (for $y = 0$) at different times $t$ for central Au+Au collisions at 30 A GeV. The white borderline separates the space-time regions of deconfined matter and hadronic matter.

Incorporating the effective masses (6) into the probability (1), we can determine the effects of CSR in the production of hadrons by string fragmentation. In order to illustrate our findings we show the ratios $K^+/\pi^+$ and $(\Lambda + \Sigma^0)/\pi^−$ at midrapidity from 5% central A+A collisions in Fig. 3 as a function of the invariant energy $\sqrt{s_{NN}}$ in comparison to the experimental data available [17]. It is clearly seen from Fig. 3 that the results in the conventional scenario (without incorporating the CSR) clearly underestimate the ratios at low $\sqrt{s_{NN}}$ for both HSD and PHSD – as found earlier in Refs. [7, 8] – while the inclusion of CSR leads to results significantly closer to the data. Especially, the rise of the $K^+/\pi^+$ ratio at low invariant energy follows closely the experimental excitation function when incorporating ‘chiral symmetry restoration’. Then a drop is observed in the PHSD case due to the appearance of a deconfined medium at higher bombarding energies contrary to the HSD case where an overestimation was expected.

4. Conclusions

When comparing the results from the extended PHSD approach for the ratios $K^+/\pi^+$ and $(\Lambda + \Sigma^0)/\pi^−$ from the different scenarios we see in Fig. 3 that the results from PHSD fail to
Figure 3. The ratios $K^+/\pi^+$ and $(\Lambda + \Sigma^0)/\pi^-$ at midrapidity from 5% central A+A collisions as a function of the invariant energy $\sqrt{s_{NN}}$ in comparison to the experimental data from [17]. The results from PHSD3.3 and HSD3.3 (with CSR) are displayed in terms of the full lines while the dashed lines show the default results without CSR.

describe the data in the conventional scenario [18] without incorporating the CSR. Especially, the rise of the $K^+/\pi^+$ ratio at low invariant energies follows closely the experimental excitation function when including ‘chiral symmetry restoration’ in the string decay. Nevertheless, the drop in this ratio again is due to ‘deconfinement’ since there is no longer any hadronic string decay in a partonic medium at higher energies. Accordingly, the experimental ‘horn’ in the excitation function is caused by chiral symmetry restoration but also deconfinement is essential to observe a maximum in the $K^+/\pi^+$ ratio.

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