HADRON PRODUCTION WITHIN PHSD*

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We study the production of hadrons in nucleus–nucleus collisions within the Parton–Hadron-String Dynamics (PHSD) transport approach that is extended to incorporate essential 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. 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 provide a microscopic explanation for the maximum in the K^+/π^+ ratio at about $30\,A\,\mathrm{GeV}$ which only shows up if, in addition to CSR, a deconfinement transition to partonic degrees of freedom is incorporated in the reaction dynamics.

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1. Introduction

In this contribution, we summarize the results from our study in Ref. [1] that investigates the strangeness enhancement in nucleus–nucleus collisions [2, 3] or the 'horn' in the K^+/π^+ ratio [4, 5]. Previously, both phenomena have been addressed to a deconfinement transition. Indeed, the actual experimental observation could not be described within conventional hadronic transport theory [6–8] 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. [9, 10]. PHSD incorporates explicit partonic degrees of freedom in terms of strongly interacting quasi-particles (quarks

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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.

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 [11], 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 $qq\bar{q}\bar{q}$ pairs is suppressed in comparison to light flavor production ($u\bar{u}$, $d\bar{d}$) according to the Schwinger-like formula [12], *i.e.*

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P\left(d\bar{d}\right)} = \gamma_s = \exp\left(-\pi\frac{m_s^2 - m_q^2}{2\kappa}\right) , \tag{1}$$

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 quark condensate $\langle\bar{q}q\rangle$.

2.2. The scalar quark condensate

As it is well-known, the scalar quark condensate $\langle\bar{q}q\rangle$ 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.* [13]

$$\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_{\rm S} - \sum_h \frac{\sigma_h \rho_{\rm S}^h}{f_\pi^2 m_\pi^2} , \tag{2}$$

where σ_h denotes the σ-commutator of the relevant mesons h and $\rho_{\rm S}$ the scalar nucleon density. Furthermore, $\langle\bar{q}q\rangle_{\rm V}$ denotes the vacuum condensate, $\Sigma_\pi \approx 45$ MeV is the pion–nucleon Σ-term, f_π and m_π are the pion decay constant and pion mass, respectively.

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

$$m_s^* = m_s^0 + \left(m_s^v - m_s^0\right)\left|\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}}\right| , \qquad m_q^* = m_q^0 + \left(m_q^v - m_q^0\right)\left|\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}}\right| , \tag{3}$$

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.

3. Comparison of PHSD3.3 results to $A+A$ data

Incorporating the effective masses (3) 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^+/π^+ and $(\Lambda+\Sigma^0)/\pi^-$ at midrapidity from 5% central $A+A$ collisions in Fig. 1 as a function of the invariant energy $\sqrt{s_{NN}}$ in comparison to the experimental data available [14]. The solid (red) lines show the results from PHSD (including CSR), while the dashed (red) line reflects the PHSD results without CSR. It is clearly seen from Fig. 1 that the results in the conventional scenario (without incorporating the CSR) clearly underestimate the ratios at low $\sqrt{s_{NN}}$ — 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^+/π^+ ratio at low invariant energy follows closely the experimental excitation function when incorporating 'chiral symmetry restoration'.

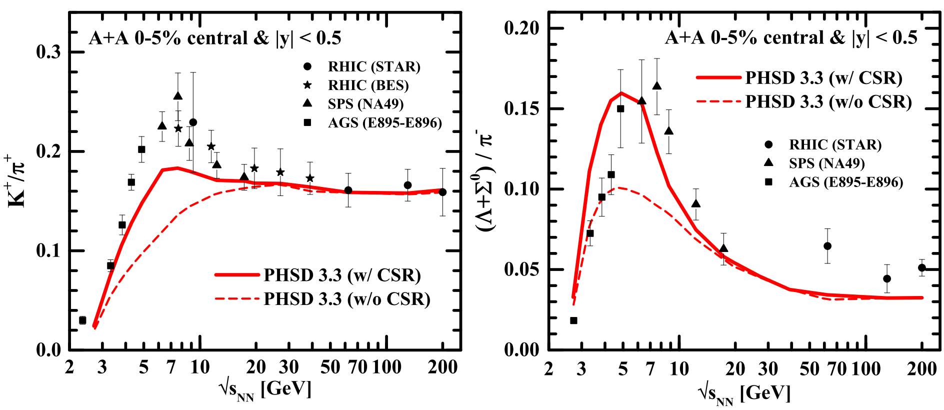

Fig. 1. (Color online) The ratios K^+/π^+ and $(\Lambda+\Sigma^0)/\pi^-$ at midrapidity from 5% central $A+A$ collisions as a function of the invariant energy $\sqrt{s_{NN}}$ in comparison to the experimental data from Ref. [14]. The results from PHSD3.3 (with CSR) are displayed in terms of the solid lines, while the dashed lines show the results without CSR.

4. Conclusions

When comparing the results from the extended PHSD approach for the ratios K^+/π^+ and $(\Lambda+\Sigma^0)/\pi^-$ from the different scenarios, we see in Fig. 1 that the results from PHSD fail to describe the data in the conventional scenario [15] without incorporating the CSR. Especially, the rise of the K^+/π^+

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^+/π^+ ratio.

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