CHIRAL SYMMETRY RESTORATION IN HEAVY-ION COLLISIONS AT HIGH BARYON DENSITY*

E.L. Bratkovskaya[a,b], W. Cassing[c], A. Palmese[c], P. Moreau[b]

[a]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[b]Institut für Theoretische Physik, Johann Wolfgang Goethe Universität
Frankfurt am Main, Germany
[c]Institut für Theoretische Physik, Universität Giessen, Germany

(Received February 16, 2017)

We study the effect of the chiral symmetry restoration (CSR) in heavy-ion collisions from $\sqrt{s_{NN}} = 3$–$20\,\mathrm{GeV}$ within the Parton–Hadron String Dynamics (PHSD) transport approach. The PHSD includes the deconfinement phase transition as well as essential aspects of CSR in the dense and hot hadronic medium, which are incorporated in the Schwinger mechanism for the hadronic particle production. Our systematic studies show that chiral symmetry restoration plays a crucial role in the description of heavy-ion collisions giving an increase of the hadronic particle production in the strangeness sector with respect to the non-strange one. We identify particle abundances and rapidity spectra to be suitable probes in order to extract information about CSR, while transverse mass spectra are less sensitive. Furthermore, the appearance/disappearance of the 'horn' structure in the K^+/π^+ ratio is investigated as a function of the system size in central $A+A$ collisions.

DOI:10.5506/APhysPolBSupp.10.507

1. Introduction

The strange particle production in relativistic heavy-ion collisions has always been suggested as one of the most sensitive observables that could spot out the creation of a Quark–Gluon Plasma (QGP) during the early stages. The earliest suggested signature is the strangeness enhancement in $A+A$ collisions with respect to elementary $p+p$ collisions [1, 2]. Later on, Gaździcki and Gorenstein [3] proposed that a sharp rise and drop in the excitation function of the K^+/π^+ ratio (so-called 'horn') should show up due to

* Presented at the "Critical Point and Onset of Deconfinement" Conference, Wrocław, Poland, May 30–June 4, 2016.

the appearance of a QGP phase at a center-of-mass energy $\sqrt{s_{NN}} \sim 7\,\mathrm{GeV}$. Several statistical models [4, 5] have succeeded in reproducing the trend of the experimental observation of the K^+/π^+ ratio and other strange-to-non-strange particle ratios, but they can provide only a statistical description of the heavy-ion collision process. On the other hand, there was no conclusive interpretation of the 'horn' from dynamical approaches for HIC, like microscopic transport models [6–8]. Only recently, the Parton–Hadron String Dynamics (PHSD), a transport approach describing HIC on the basis of partonic, hadronic and string degrees-of-freedom, obtained a striking improvement on this issue when including chiral symmetry restoration (CSR) in the string decay for hadronic particle production [9].

In this contribution, we report on new results from the PHSD with respect to the sensitivity of particle ratios to the nuclear equation of state (EoS) and the appearance of the 'horn' in the K^+/π^+ ratio as a function of the system size [10].

2. Short reminder of the PHSD

The Parton–Hadron String Dynamics (PHSD) is a microscopic covariant dynamical approach for strongly interacting systems in and out of equilibrium [11, 12]. It is a transport approach which goes beyond the quasi-particle approximation, since it is based on the Kadanoff–Baym equations for the Green functions in phase-space representation in first-order gradient expansion [13]. Including both a hadronic and a partonic phase as well as a transition between the effective degrees-of-freedom, PHSD is capable to describe the full time evolution of a relativistic heavy-ion collision. The theoretical description of the partonic degrees-of-freedom (quarks and gluons) is realized in line with the Dynamical Quasi Particle Model (DQPM) [13] which reproduces lQCD results in thermodynamical equilibrium and provides the properties of the partons, *i.e.* masses and widths in their spectral functions. In equilibrium, the PHSD reproduces the partonic transport coefficients such as shear and bulk viscosities or the electric conductivity from lQCD calculations as well [14].

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 [15], 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 [16], *i.e.*

$$\frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P\left(d\bar{d}\right)} = \gamma_s = \exp\left(-\pi\frac{m_s^2 - m_q^2}{2\kappa}\right), \tag{2.1}$$

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. (2.1). 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.* [17]

$$\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2}\rho_{\rm S} - \sum_h \frac{\sigma_h \rho_{\rm S}^h}{f_\pi^2 m_\pi^2}, \tag{2.2}$$

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 — 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 (2.2),

$$m_s^* = m_s^0 + \left(m_s^v - m_s^0\right)\left(\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}}\right), \qquad m_q^* = m_q^0 + \left(m_q^v - m_q^0\right)\left(\frac{\langle\bar{q}q\rangle}{\langle\bar{q}q\rangle_{\rm V}}\right), \tag{2.3}$$

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 (2.3) into probability (2.1), 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 (l.h.s.) as a function of the invariant energy $\sqrt{s_{NN}}$ in comparison to the experimental data available. The solid (red on-line) lines show the results from PHSD (including CSR), while the dashed (blue on-line) lines reflect the

PHSD results without CSR. It is clearly seen from Fig. 1 (l.h.s.) that the results in the conventional scenario (without incorporating the CSR) clearly underestimate the ratios at low $\sqrt{s_{NN}}$ — as found earlier in Ref. [7] — 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'. The sensitivity to the nuclear EoS (NL1 *versus* NL3) is rather moderate. Note that the 'horn' is predicted to vanish with decreasing size (*cf.* Fig. 1 (r.h.s.)).

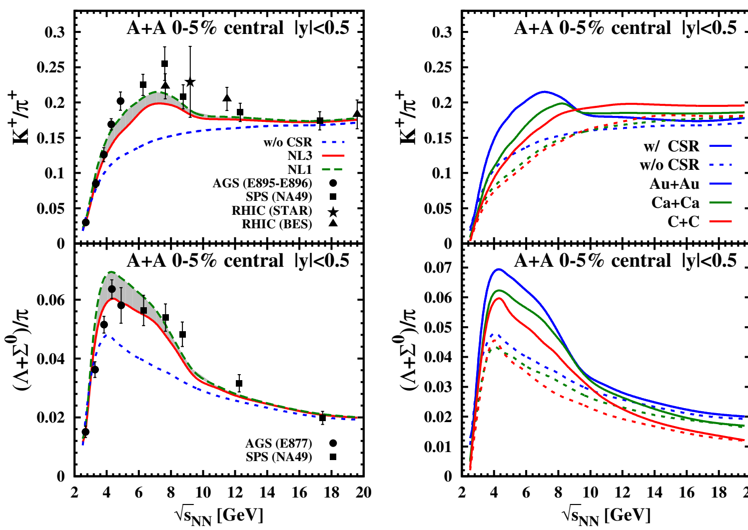

Fig. 1. (l.h.s.) The ratios K^+/π^+ and $(\Lambda+\Sigma^0)/\pi$ at midrapidity from 5% central Au+Au collisions as a function of the invariant energy $\sqrt{s_{NN}}$ up to the top SPS energy in comparison to the experimental data (taken from Ref. [10]). The grey shaded area represents the results from PHSD including CSR taking into account the uncertainty from the parameters of the σ–ω model for the nuclear EoS. (r.h.s.) The ratios K^+/π^+ and $(\Lambda+\Sigma^0)/\pi$ at midrapidity from 5% central symmetric $A+A$ collisions as a function of the invariant energy $\sqrt{s_{NN}}$. The solid lines show the results from PHSD including CSR with NL1 parameters, the dashed lines show the result from PHSD 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 (l.h.s.) that the results from PHSD fail to describe the data in the conventional scenario 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. The PHSD calculations predict that the 'horn' disappears for light systems such as C+C (*cf.* Fig. 1 (r.h.s.)).

The authors acknowledge the support by BMBF, HIC for FAIR and the HGS-HIRe for FAIR. The computational resources were provided by the LOEWE-CSC.

REFERENCES

[1] J. Rafelski, B. Müller, *Phys. Rev. Lett.* **48**, 1066 (1982); **56**, 2334 (1986).

[2] R. Stock, *J. Phys. G* **28**, 1517 (2002).

[3] M. Gaździcki, M.I. Gorenstein, *Acta Phys. Pol. B* **30**, 2705 (1999).

[4] J. Cleymans *et al.* [NA49 Collaboration], *Phys. Lett. B* **615**, 50 (2005).

[5] A. Andronic *et al.*, *Nucl. Phys. A* **772**, 167 (2006); *Phys. Lett. B* **673**, 142 (2009).

[6] J. Geiss, W. Cassing, C. Greiner, *Nucl. Phys. A* **644**, 107 (1998).

[7] E.L. Bratkovskaya *et al.*, *Phys. Rev. C* **69**, 054907 (2004).

[8] E.L. Bratkovskaya *et al.*, *Phys. Rev. Lett.* **92**, 032302 (2004).

[9] W. Cassing *et al.*, *Phys. Rev. C* **93**, 014902 (2016).

[10] A. Palmese *et al.*, *Phys. Rev. C* **94**, 044912 (2016).

[11] W. Cassing, E.L. Bratkovskaya, *Nucl. Phys. A* **831**, 215 (2009).

[12] E.L. Bratkovskaya *et al.*, *Nucl. Phys. A* **856**, 162 (2011).

[13] W. Cassing, *Eur. Phys. J. ST* **168**, 3 (2009); *Nucl. Phys. A* **795**, 70 (2007).

[14] O. Linnyk *et al.*, *Prog. Part. Nucl. Phys.* **87**, 50 (2016).

[15] B. Nilsson-Almqvist, E. Stenlund, *Comput. Phys. Commun.* **43**, 387 (1987); B. Andersson, G. Gustafson, H. Pi, *Z. Phys. C* **57**, 485 (1993).

[16] J. Schwinger, *Phys. Rev.* **83**, 664 (1951).

[17] B. Friman, W. Nörenberg, V.D. Toneev, *Eur. Phys. J. A* **3**, 165 (1998).