Hadron production within PHSD *

P. Moreau¹, W. Cassing², A. Palmese², E. L. Bratkovskaya¹

¹Frankfurt Institute for Advanced Studies and Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany

²Institut für Theoretische Physik, Universität Gießen, Germany

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. 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 $K^+/\pi^+$ ratio 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.

PACS numbers: 25.75.Nq, 25.75.Ld, 25.75.-q, 24.85.+p, 12.38.Mh

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 $K^+/\pi^+$ 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 [6,7,8] and remained a major challenge for microscopic approaches.

* XI Workshop on Particle Correlations and Femtoscopy 2015, Warsaw, Poland
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 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.

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

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

(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 $<\bar{q}q>$.

2.2. The scalar quark condensate

As it is well known the 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. [13],

$$\frac{<\bar{q}q>}{<\bar{q}q>_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2} \rho_S - \sum_h \frac{\sigma_h \rho_h^h}{f_\pi^2 m_\pi^2},$$

(2)

where $\sigma_h$ denotes the $\sigma$-commutator of the relevant mesons $h$ and $\rho_S$ the scalar nucleon density. Furthermore, $<\bar{q}q>_V$ 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 basic assumption now is that the strange and light quark masses in the hadronic medium drop both in line with the ratio (2),

\[ m_s^* = m_s^0 + (m_s^0 - m_s^v) \left| \frac{<\bar{q}q>}{<\bar{q}q>_{V}} \right|, \]

\[ m_q^* = m_q^0 + (m_q^0 - m_q^v) \left| \frac{<\bar{q}q>}{<\bar{q}q>_{V}} \right|, \]

using \( m_s^0 \approx 100 \text{ MeV} \) and \( m_q^0 \approx 7 \text{ MeV} \) for the bare quark masses while the vacuum (dressed) masses are \( m_s^v \approx 500 \text{ MeV} \) and \( m_q^v \approx 330 \text{ MeV} \), 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 \( K^+/\pi^+ \) 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 \cite{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. \cite{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'.

![Fig. 1](image-url)
4. Conclusions

When comparing the results from the extended PHSD approach for the ratios $K^+/\pi^+$ and $(A+\Sigma^0)/\pi^-$ 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 $K^+/\pi^+$ 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.

Acknowledgements

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] W. Cassing et al., Phys. Rev. C 93, 014902 (2016)
[2] J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066.
[3] R. Stock, J. Phys. G 28 (2002) 1517.
[4] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B 30 (1999) 2705.
[5] M. Gazdzicki et al., Acta Phys. Polon. B 42 (2011) 307.
[6] J. Geiss, W. Cassing, and C. Greiner, Nucl. Phys. A 644 (1998) 107.
[7] E. L. Bratkovskaya et al., Phys. Rev. C 69 (2004) 054907.
[8] H. Weber et al., Phys. Rev. C 67 (2003) 014904.
[9] W. Cassing and E.L. Bratkovskaya, Nucl. Phys. A 831 (2009) 215.
[10] E. L. Bratkovskaya et al., Nucl. Phys. A 856 (2011) 162.
[11] B. Nilsson-Almqvist and E. Stenlund, Comp. Phys. Comm. 43 (1987) 387; B. Andersson, G. Gustafson, and H. Pi, Z. Phys. C 57 (1993) 485.
[12] J. Schwinger, Phys. Rev. 83 (1951) 664.
[13] B. Friman, W. Nörenberg and V. D. Toneev, Eur. Phys. J. A 3 (1998) 165.
[14] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 81 (2010) 024911; M. M. Aggarwal et al. [STAR Collaboration], Phys. Rev. C 83 (2011) 024901.
[15] P. Moreau et al., J. Phys. Conf. Ser. 668, 012072 (2016)