Chiral symmetry restoration versus deconfinement in relativistic heavy-ion reactions

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for the PHSD group

Erice
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From AGS to LHC, passing FAIR/NICA and RHIC...

- Explore the QCD phase diagram and properties of hadrons at high temperature or high baryon density
- Phase transition from hadronic to partonic matter
- **Goal:** Study the properties of strongly interacting matter under extreme conditions from a microscopic point of view
- **Realization:** covariant off-shell transport approach

- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase

**Parton-Hadron-String-Dynamics (PHSD)**


September 2016
Au-Au at top RHIC energies

- At high energies, particles and antiparticles are produced in quasi-equal quantities at midrapidity whatever the centrality of the collision.
- Anti-baryon absorption at low pT is visible.

Au+Au – top RHIC

p_T spectra:

production at midrapidity dN/dy:
At low energies, a clear difference appears between the production of particles and antiparticles, and also between positively and negatively charged mesons.

p_T spectra:

production at midrapidity dN/dy:
Partonic energy fraction in central A+A

- At top RHIC energies, the QGP phase at midrapidity contains roughly 90% of the energy.
- At AGS, only a small part of the initial energy is converted into the QGP phase.

Time evolution of the partonic energy fraction for different energies:

- central Pb+Pb
Even when considering the creation of a QGP phase, the strangeness enhancement seen experimentally at FAIR/NICA energies remains unexplained. ‘Horn’ not traced back to deconfinement

There is a problem for microscopic transport!
Information from lattice QCD

Chiral symmetry restoration with increasing temperature + Deconfinement phase transition with increasing temperature

Crossover: both transitions occur at about the same temperature $T_c$ for low chemical potentials.
The string decays by pair creation of quarks+antiquarks from the vacuum: The mass of the virtual fermions is generated by the coupling to the scalar quark vacuum condensate.

The decay probability is given by the Schwinger mechanism.
According to the **Schwinger-formula**, the probability to form a massive $s\bar{s}$ in a string-decay is suppressed in comparison to light flavor $(u\bar{u}, d\bar{d})$

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

Considering a hot and dense medium, the above formula remains the same but **effective quark masses** should be employed. This dressing is due to a scalar coupling with the **in-medium quark condensate** $\langle q\bar{q}\rangle$ according to:

$$m_s^* = m_s^0 + (m_s^v - m_s^0) \frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$  \quad m_q^* = m_q^0 + (m_q^v - m_q^0) \frac{\langle q\bar{q}\rangle}{\langle q\bar{q}\rangle_V}$$

$\to$ need to evaluate the **scalar quark condensate in the medium**!
The scalar quark condensate $\langle q\bar{q} \rangle$ is viewed as an order parameter for the restoration of chiral symmetry at high baryon density and temperature. It can be expressed in line with the Hellman-Feynman theorem by:

$$\frac{\langle q\bar{q} \rangle}{\langle q\bar{q} \rangle_V} = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2 \rho_S} - \sum_h \frac{\sigma_h \rho_s^h}{f_\pi^2 m_\pi^2}$$

where $\rho_s$ is the scalar density obtained e.g. according to the non-linear $\sigma - \omega$ model, $\Sigma_\pi \approx 45$ MeV is the pion-nucleon $\Sigma$-term, and $f_\pi$ and $m_\pi$ are the pion decay constant and pion mass, given by the Gell-Mann-Oakes-Renner relation.
Chiral symmetry restoration in the hadronic phase

- **pion-nucleon Σ-term : 45 MeV**

  Yi-Bo Yang et al., arXiv 1511.09089

  \[ \langle q\bar{q}\rangle = 1 - \frac{\Sigma_\pi}{f_\pi^2 m_\pi^2} \rho_S - \sum_h \frac{\sigma_h \rho_S^h}{f_\pi^2 m_\pi^2} \]

  the leading terms are fixed within some uncertainty!

  \[ \rightarrow \text{no new 'parameters'}! \]
As a consequence of the **chiral symmetry restoration (CSR)**, the strangeness production probability increases with the energy density $\varepsilon$.

\[ \frac{P(s\bar{s})}{P(u\bar{u})} = \frac{P(s\bar{s})}{P(d\bar{d})} = \gamma_s = \exp \left( -\pi \frac{m_g^2 - m_q^2}{2\kappa} \right) \]

In the QGP phase, the string decay doesn’t occur anymore and this effect is therefore suppressed.

Some dependence on the nuclear EoS!
Sensitivity to the nuclear EoS at $T=0$

is dominantly driven by the effective mass of the nucleons
Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]
Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]

\( t = 2.71 \text{ fm/c} \)
Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]
**Pb+Pb @ 30 AGeV – 0-5% central**

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]
Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]

\(t = 7.59 \text{ fm/c}\)
Pb+Pb @ 30 AGeV – 0-5% central

Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]
Ratio of the quark scalar condensate compared to vacuum as a function of time:

\[
\frac{\langle q \bar{q} \rangle}{\langle q \bar{q} \rangle_V}
\]
Comparison to data at AGS: 10.7 A GeV

A. Palmese et al., arXiv:1607.04073
Excitation function of hadron ratios

→ low sensitivity to the nuclear EoS
Excitation function of hadron ratios

→ low sensitivity to the nuclear EoS
Conclusion

- At high energies, particles and antiparticles are produced in almost quasi-equal quantities at midrapidity in the hadronization process from the deconfined QGP phase.

- By decreasing the collisional energy, clear differences appear between the production of particles and antiparticles.

- The strangeness enhancement at AGS/FAIR/NICA energies cannot be attributed to deconfinement.

- Including essential aspects of chiral symmetry restoration in the hadronic phase, we observe a rise in the $K^+/\pi^+$ ratio at low $\sqrt{s_{NN}}$ and then a drop due to the appearance of a deconfined partonic medium $\rightarrow$ a ‘horn’ emerges.

Further tests will be presented by Alessia in the next talk!
PHSD group 2016

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Comparison to FOPI data at SIS: 1.93 A GeV

no kaon potential

Introduction          HIC          Strangeness          Conclusion

Alessia Palmese
Comparison to data from HADES at SIS

Introduction

Hadron production at SIS within PHSD
Comparison to data from HADES at SIS

Introduction

HIC

Strangeness

Conclusion

Alessia Palmese

Hadron production at SIS within PHSD

missing phis