

QCD Phase Diagram at NICA energies: K^+/π^+ horn effect and light clusters in THESEUS*

D. BLASCHKE^{a,b,c}, A.V. FRIESEN^a, YU. IVANOV^{a,b}, YU.L.
KALINOVSKY^a, M. KOZHEVNIKOVA^a, S. LIEBING^a, A. RADZHABOV^{d,e},
G. RÖPKE^{b,f}

^aJINR Dubna, 141980 Dubna, Russia

^bNational Research Nuclear University (MEPhI), 115409 Moscow, Russia

^cUniversity of Wrocław, 50-204 Wrocław, Poland

^dMatrosov Institute System Dynamics & Control Theory, 664003 Irkutsk, Russia

^eIrkutsk State University, 664003 Irkutsk, Russia

^fUniversity of Rostock, D-18051 Rostock, Germany

We discuss recent progress in the development of the three-fluid hydrodynamics-based program THESEUS towards an event generator suitable for applications to heavy-ion collisions at the intermediate energies of the planned NICA and FAIR experiments. We follow the strategy that modifications of particle distributions at the freeze-out surface in the QCD phase diagram may be mapped directly to the observable ones within a sudden freeze-out scheme. We report first results of these investigations for the production of light clusters (deuterons and tritons) which can be compared to experimental data from the HADES and the NA49 experiment and for the interpretation of the "horn" effect observed in the collision energy dependence of the K^+/π^+ ratio. Medium effects on light cluster production in the QCD phase diagram are negligible at the highest NICA energies but shall play a dominant role at the lowest energies. A sharp "horn"-type signal in the K^+/π^+ ratio can be obtained when the onset of Bose condensation modelled by a pion chemical potential results in an enhancement of pions at low momenta (which is seen at LHC energies) and would occur already in the NICA energy range.

PACS numbers: 12.38.Mh

1. Chemical freeze-out and light clusters in the phase diagram

In this contribution, we present recent progress in the development of the three-fluid hydro-dynamics-based program THESEUS [1] towards an event

* Presented at NICA Days and 4th MPD Collaboration Meeting, Warsaw, 21.10.2019

generator suitable for applications to heavy-ion collisions at the intermediate energies of the planned NICA and FAIR experiments for which we follow the strategy that modifications of particle distributions at the freeze-out surface in the QCD phase diagram may be mapped directly to the observable ones within a sudden freeze-out scheme. In Fig. 1 we show that the inclusion

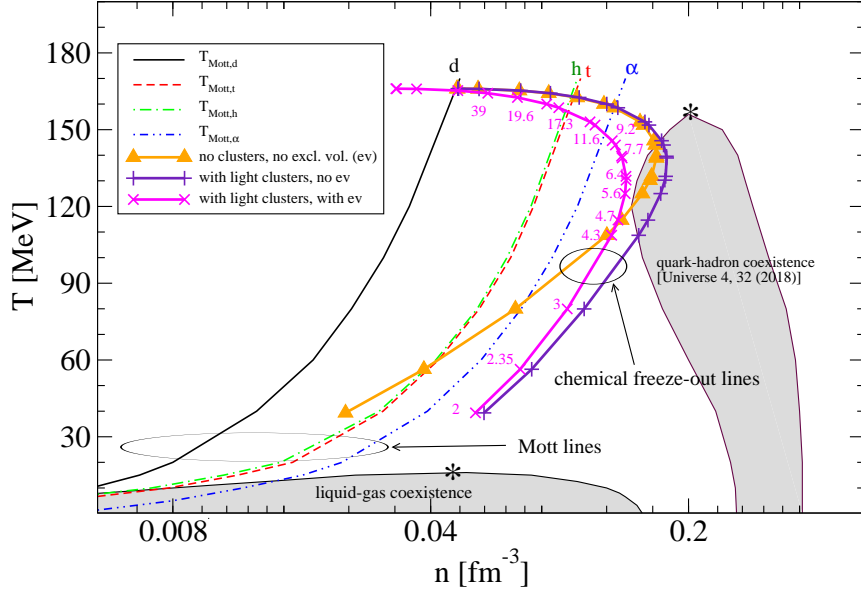


Fig. 1. Chemical freezeout lines in the temperature-density plane (phase diagram) together with Mott lines for light clusters. The coexistence regions for the nuclear gas-liquid transition and for an example of the hadron-quark matter transition [8] are shown as grey shaded regions together with their critical endpoints, see text.

of light clusters into the thermal statistical model increases the freeze-out density for lowest available collision energies by a factor of two [2], when evaluated along the freeze-out line in the $T - \mu$ plane described by the fit of [4], in comparison to the model without clusters [5]. We also show the Mott-lines for the light clusters as indicators for the region in the phase diagram where in-medium effects on cluster formation at the freeze-out have to be taken into account. In Fig. 2 we demonstrate by comparing with preliminary HADES data [6] that at lowest NICA energies of $E_{\text{lab}} = 2.0$ A GeV the description of light clusters requires the account for in-medium effects [7] while at energies above $E_{\text{lab}} \approx 20$ A GeV an acceptable description is achieved without them [2].

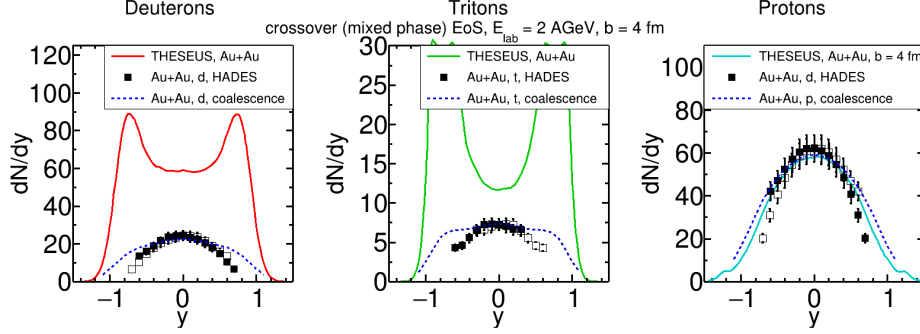


Fig. 2. Preliminary results of the HADES collaboration for the rapidity distribution of deuterons (left panel), tritons (middle panel) and protons (right panel) in Au+Au collisions at $E_{\text{lab}} = 1.23$ A GeV compared with results from the three-fluid hydrodynamics simulation (THESEUS) at $E_{\text{lab}} = 2.0$ A GeV for impact parameter $b = 4$ fm using a crossover equation of state model with the cluster abundances described using a coalescence model (dashed lines) and in a thermal statistical model without selfenergy effects (solid lines). For details see text.

2. Beth-Uhlenbeck approach to the "horn" effect

The Beth-Uhlenbeck expression for the ratio of the yields of kaons and pions is defined as ratio of their partial number densities [10]

$$\frac{n_{K^\pm}}{n_{\pi^\pm}} = \frac{\int dM \int d^3p (M/E) g_{K^\pm}(E) [1 + g_{K^\pm}(E)] \delta_{K^\pm}(M)}{\int dM \int d^3p (M/E) g_{\pi^\pm}(E) [1 + g_{\pi^\pm}(E)] \delta_{\pi^\pm}(M)}, \quad (1)$$

where $E = \sqrt{M^2 + p^2}$, $g(E) = (e^{E/T} - 1)^{-1}$ is the Bose function and $\delta_M(M)$ is meson phase shift. In order to relate the model results with the actual phenomenology of chemical freeze-out in heavy-ion collisions we use the idea to map points with a fixed value of μ/T on the line in phase diagram of our PNJL model to points on the curve fitted to statistical model analyses. For the description of experimental data the scan line is chosen as a critical line in PNJL model supplemented by a straight line at some fixed T . This ansatz is needed due to fact that the pseudocritical temperature at zero chemical potential in the PNJL model is too high when compared with lattice QCD and with the fit of the freeze-out line. A sharp "horn"-type signal in the K^+/π^+ ratio [9] can be obtained when the onset of Bose condensation modelled by a pion chemical potential results in an enhancement of pions at low momenta (which is seen at LHC energies [11]) and would occur already in the NICA energy range, see Fig. 3 and Ref. [12].

As a next step the in-medium modifications of cluster and hadron distribution functions shall be included to the particlization routine of the

THESEUS program to improve the description of light cluster formation and the "horn" effects.

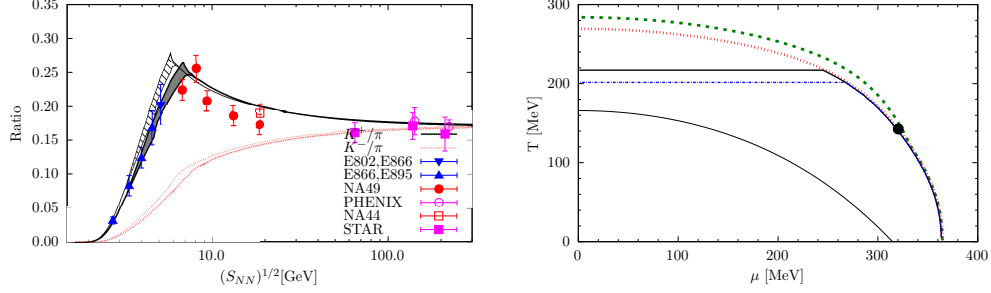


Fig. 3. Plot of the K^\pm/π^\pm ratios (left panel) compared to the experimental data for different scan lines of phase diagram (right panel). For details see Ref. [12].

Acknowledgements

The work on the light cluster production was supported by the Russian Science Foundation under grant no. 17-12-01427, and the work on the "horn" effect was supported by the Russian Fund for Basic Research under grant no. 19-02-40137.

REFERENCES

- [1] P. Batyuk *et al.*, Phys. Rev. C **94**, 044917 (2016).
- [2] D. Blaschke *et al.*, "Strangeness and light fragment production at high baryon density," arXiv:2001.02156 [nucl-th].
- [3] G. Röpke *et al.*, Phys. Part. Nucl. Lett. **15**, no. 3, 225 (2018).
- [4] J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Phys. Rev. C **73**, 034905 (2006).
- [5] J. Randrup and J. Cleymans, Eur. Phys. J. **52**, 218 (2016).
- [6] M. Szala (HADES Coll.), contribution at "Strangeness in Quark Matter", Bari (2019).
- [7] S. Typel *et al.*, Phys. Rev. C **81**, 015803 (2010).
- [8] S. Typel and D. Blaschke, Universe **4**, no. 2, 32 (2018).
- [9] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B **30**, 2705 (1999).
- [10] D. Blaschke, A. Dubinin, A. Radzhabov and A. Wergieluk, Phys. Rev. D **96**, no. 9, 094008 (2017).
- [11] V. Begun and W. Florkowski, Phys. Rev. C **91**, 054909 (2015).
- [12] D. Blaschke, A. Friesen, Y. Kalinovsky and A. Radzhabov, Particles **3**, no. 1, 169 (2020).