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Constraining the chemical freeze-out with coarse-grained transport

Tom Reichert*
Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany
Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt, Germany
E-mail: treichert@itp.uni-frankfurt.de

Gabriele Inghirami
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany

Marcus Bleicher
Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
John von Neumann-Institut für Computing, Forschungzentrum Jülich, 52425 Jülich, Germany
Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt, Germany

We use the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model to extract the microscopic chemical freeze-out hyper-surface from a dynamical hadronic transport simulation. By coarse-graining the output, the distribution of the temperature and the baryo-chemical potential can be extracted on this hyper-surface. The energy dependence of the average chemical freeze-out temperature and the average baryo-chemical potential follows the trend seen in the statistical model and also captures the data points of the chemical freeze-out curve very well. We finally check the established chemical freeze-out criteria with our method and indeed we can confirm the constant energy per particle criterion at all investigated energies, while the entropy density criterion and the baryon density criterion are fulfilled at larger collision energies.

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*Speaker.

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1. Introduction

Heavy-ion collisions can be seen as a controlled recreation of the big bang in the laboratory, although the scales in this so called little bang are vastly different. At large collision energies the energy and baryon densities reached during such a collision are high enough that the nuclear matter switches from hadronic to quark and gluon degrees of freedom forming a Quark-Gluon Plasma (QGP). With further elapsing time the system expands into the vacuum thus cooling down and thinning out turning back to hadrons which further interact and scatter until the system decouples and the particles propagate into the detectors. At some point after initial contact and prior to measurement flavor changing reactions cease fixing the total particle abundances which is called the chemical freeze-out and subsequently also momentum changing reactions cease fixing the final state particle spectra which is called the kinetic freeze-out.

While the definition and interpretation of the kinetic decoupling is clear, i.e. the point of a particle's last interaction, the definition and meaning of the chemical decoupling are still a matter of debate. At very high energies the chemical decoupling is most often argued to be connected to the phase transition from the QGP to hadronic matter. Tremendous effort has been put into the systematic study of hadron abundances over a broad range of energies and experiments, especially at CERN/SPS [1, 2, 3, 4], BNL/AGS [5, 6, 7] and GSI/SIS [8, 9], to extract the temperature and baryo-chemical potential at chemical freeze-out with a thermal model analysis [10, 11, 12].

Following our previous studies on the chemical freeze-out [13], in this article we employ a dynamical hadronic transport approach without phase transition to extract the chemical freeze-out hyper-surface and determine the distribution of the temperature and the baryo-chemical via a coarse-graining method. We finally check established chemical freeze-out criteria, namely the constant energy per particle criterion proposed in [14], the entropy density criterion proposed in [15] and the total baryon density criterion proposed in [16] in the simulation.

2. Model setup

The present study uses the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) [17, 18] transport model in cascade mode. UrQMD is used to compute both the bulk evolution of the system and to determine the space-time coordinates of the chemical freeze-out of the hadrons. We recall that UrQMD is a hadron cascade model that simulates the dynamical evolution of heavy ion collision events by following the propagation of the individual hadrons, modeling their interactions via the excitation of color flux-tubes (strings) and by further elastic and inelastic scatterings. A transition to a deconfined stage is not explicitly included in the cascade mode employed here.

The UrQMD coarse-graining approach [19, 20, 21, 22, 23, 24, 25] consists in computing the temperature and the baryon chemical potential from the average energy-momentum tensor and net baryon current of the hadrons formed in a large set of heavy ion collision events with the same collision energy and centrality. The computation is done in the cells of a fixed spatial grid at constant intervals of time. In the present study, the cells are four-cubes with spatial sides of length $\Delta x = \Delta y = \Delta z = 1$ fm and $\Delta t = 0.25$ fm length in time direction. First, we evaluate the net-baryon four current j^{μ}_{B} and the energy momentum tensor $T^{\mu\nu}$ in each cell. We adopt the Eckart's frame definition [26] to obtain the fluid four velocity u^{μ} by normalizing j^{μ}_{B}. Via a Lorentz transformation

of the net-baryon current and of the energy momentum tensor into the Local Rest Frame (LRF) of the fluid, we compute the baryon density $\rho_B = j^0_{B,LRF}$ and the energy density $\varepsilon = T^{00}_{LRF}$.

Often the chemical freeze-out occurs in cells with an anisotropy between the pressure in the parallel ($P_\parallel$) and in the transverse direction ($P_\perp$), with respect to the beam axis. To take into account this condition, we employ the anisotropic correction from Florkowski and Ryblewski [27, 28].

The final step in the coarse graining procedure consists in associating to each cell of the coarse grained grid the temperature $T(\varepsilon_{corr}, \rho_B)$ and the baryon chemical potential $\mu_B(\varepsilon_{corr}, \rho_B)$ through the interpolation of a tabulated Hadron Resonance Gas EoS [29].

2.1 Chemical freeze-out in the UrQMD model

To test this novel way of tracking down the chemical freeze-out coordinates in a full transport simulation we focus on pions. The reason for this is twofold: a) pions are very abundant hadrons in the investigated energy regime and b) pions are stable particles under strong interactions, both facts simplify the reconstruction of the chemical freeze-out coordinates with high accuracy. One should note that it is discussed in the literature whether there is a separation in the chemical freeze-out (or phase transition) temperature between light flavors and strangeness [30, 31, 32, 33, 34]. However, we aim to focus on the bulk of the system which is effectively modeled by pions and postpone the investigation of flavor hierarchy. When does a π freeze-out chemically? Typically, pions are either produced directly in a string decay (dominant at higher energies) or via $N + N \to N + \Delta$, and subsequently $\Delta \to N + \pi$ reactions. Of course the Δ can be replaced by other resonances. In addition cascades like $\Delta \to N + \rho$, and subsequently $\rho \to \pi\pi$ are possible. Not all pions produced initially make it to the final state due to absorption processes, e.g. $\pi + N \to N^* \to K + \Lambda$. To extract the space-time point of the production of a finally observed π, we follow all observed pions backwards through the evolution until we reach their point of production. This defines the chemical freeze-out coordinates $(t, \vec{r})$ for each individual pion.

3. Results

All results are obtained by simulating central ($b \leq 3.4$ fm) Au+Au collisions with the UrQMD model [17, 18] in cascade mode. We only consider pions that finally decouple in the central volume with $|z| \leq 5$ fm.

Let us start with the investigation of the distribution of the temperature and the baryo-chemical potential obtained on the chemical freeze-out hyper-surface. Fig. 1 shows the respective normalized distributions (see legend for color identification). The first observation is that all distributions show a peaked structure indicating that indeed the definition and extraction of the chemical freeze-out from a dynamical transport simulation is valid. We further observe that the average temperature seems to saturate around 150 MeV with FWHM of 50 MeV while the average baryo-chemical potential further decreases with increasing energy which is expected.

To better investigate the energy dependence we average the inspected distributions and show the results in Fig. 2. Also shown is an established statistical hadronization model parametrization of the freeze-out curve [12]. An overall great agreement between the established trend and our simulation results can be observed for both the temperature and the baryo-chemical potential.

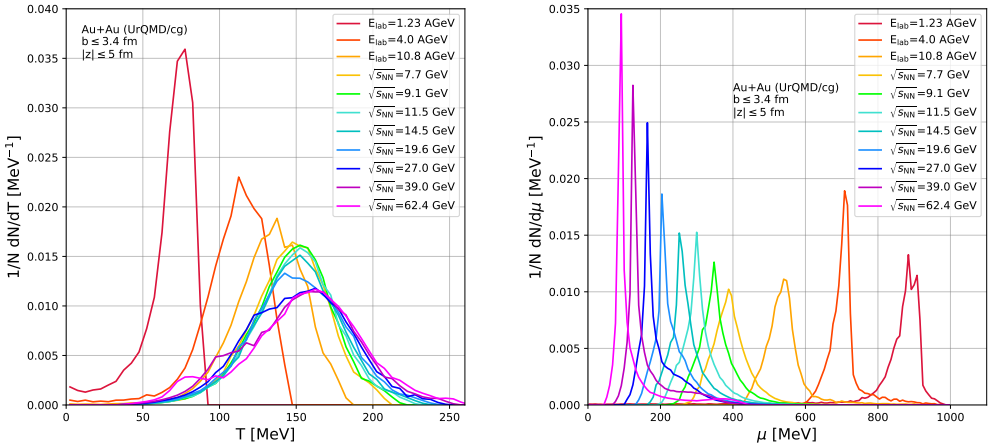

Figure 1: [Color online] Distribution of the temperature (left) and baryo-chemical potential (right) extracted on the chemical freeze-out hyper-surface from central Au+Au collisions from UrQMD.

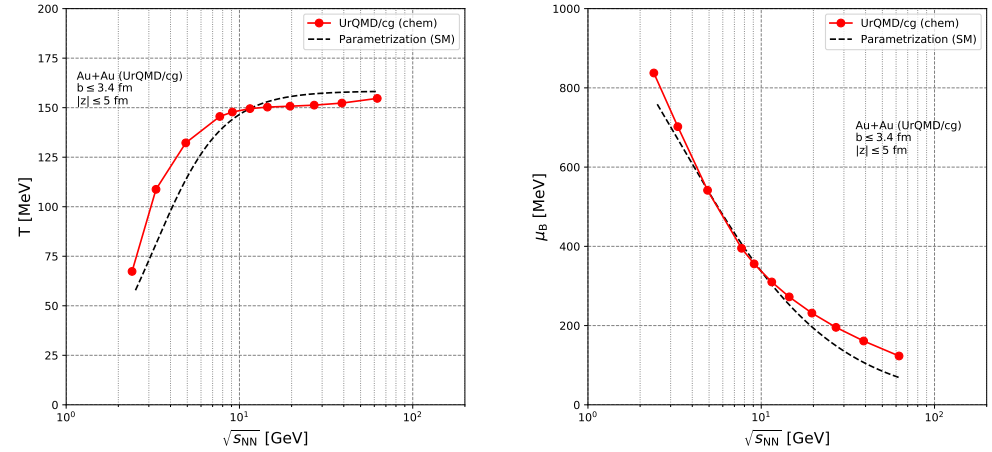

Figure 2: [Color online] Energy dependence of the average chemical decoupling temperature (left) and the baryo-chemical potential (right) from central Au+Au collisions from UrQMD.

Finally, we are in the position to relate our calculations to the data forming the freeze-out curve in the phase diagram of strongly interacting matter. In Fig. 3 we show the average temperature and average baryo-chemical potential evaluated on the chemical freeze-out hyper-surface as well as the established data [1, 2, 3, 4, 5, 6, 7, 8, 9] in the phase-diagram. The calculations capture the trend of the data points with unexpected high accuracy although UrQMD neither involves explicit quark and gluon degrees of freedom nor a phase transition.

Lastly, we can check the established chemical freeze-out criteria. In Fig. 4 we show as functions of the collision energy the average energy per particle (left) which is proposed to be 1 GeV/*particle* [14], the entropy per temperature cubed (middle) which is proposed to be 7 [15] and the total baryon and anti-baryon density (right) which is proposed to be 0.12 fm^{-3} [16]. We can

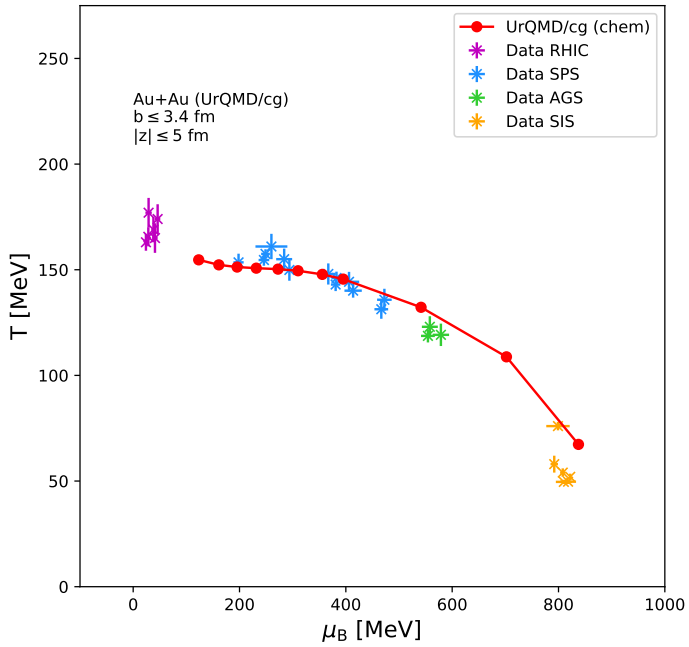

Figure 3: [Color online] Average temperature and average baryo-chemical potential evaluated on the chemical freeze-out hyper-surface from central Au+Au collisions from UrQMD. Also shown are statistical hadronization model fits to data from CERN/SPS [1, 2, 3, 4], BNL/AGS [5, 6, 7] and GSI/SIS [8, 9].

confirm that indeed the average energy per particle is roughly constant ranging from 1 - 1.2 over all investigated energies. The other two criteria are also confirmed, however starting at $\sqrt{s_{\mathrm{NN}}} = 7.7$ and 20 GeV for the entropy and baryon density criterion, respectively.

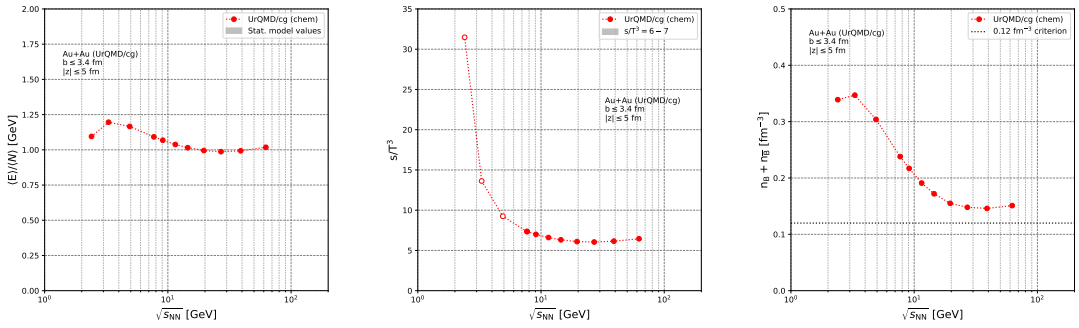

Figure 4: [Color online] The different chemical freeze-out criteria evaluated on the chemical freeze-out hyper-surface from central Au+Au collision from UrQMD. The energy-per-particle criterion [14] is shown on the left, the entropy density criterion [15] is shown in the middle and the baryon density criterion [16] is shown on the right.

4. Summary

In this article we have used the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model to extract the exact microscopic chemical freeze-out hyper-surface from a dynamical hadronic transport simulation. By coarse-graining the output we extracted the distribution of the temperature and the baryo-chemical potential on this hyper-surface. The distributions were strongly peaked indicating that one can indeed define an approximate chemical freeze-out surface in transport models. The energy dependence of the average chemical freeze-out temperature and the average baryo-chemical potential follows the trend seen in the statistical model and also captures the data points of the freeze-out curve very well. We finally checked the established chemical freeze-out criteria with our method and indeed we can confirm the constant energy per particle criterion at all investigated energies. In our simulation the entropy density criterion is fulfilled above $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV and the baryon density criterion is fulfilled above $\sqrt{s_{\mathrm{NN}}} = 20$ GeV.

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References

[1] P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B **365**, 1-6 (1996) doi:10.1016/0370-2693(95)01258-3 [arXiv:nucl-th/9508020 [nucl-th]].

[2] P. Braun-Munzinger, I. Heppe and J. Stachel, Phys. Lett. B **465**, 15-20 (1999) doi:10.1016/S0370-2693(99)01076-X [arXiv:nucl-th/9903010 [nucl-th]].

[3] J. Letessier and J. Rafelski, J. Phys. G **25**, 295-309 (1999) doi:10.1088/0954-3899/25/2/018 [arXiv:hep-ph/9810332 [hep-ph]].

[4] C. Spieles, H. Stoecker and C. Greiner, Eur. Phys. J. C **2**, 351-358 (1998) doi:10.1007/s100520050145 [arXiv:nucl-th/9704008 [nucl-th]].

[5] J. Letessier, J. Rafelski and A. Tounsi, Phys. Lett. B **328**, 499-505 (1994) doi:10.1016/0370-2693(94)91510-5 [arXiv:hep-ph/9711321 [hep-ph]].

[6] F. Becattini, J. Phys. G **25**, 287-294 (1999) doi:10.1088/0954-3899/25/2/017 [arXiv:hep-ph/9810306 [hep-ph]].

[7] J. Cleymans, D. Elliott, H. Satz and R. L. Thews, Z. Phys. C **74**, 319-324 (1997) doi:10.1007/s002880050393 [arXiv:nucl-th/9603004 [nucl-th]].

[8] J. Cleymans, D. Elliott, A. Keranen and E. Suhonen, Phys. Rev. C **57**, 3319-3323 (1998) doi:10.1103/PhysRevC.57.3319 [arXiv:nucl-th/9711066 [nucl-th]].

[9] J. Cleymans, H. Oeschler and K. Redlich, J. Phys. G **25**, 281-285 (1999) doi:10.1088/0954-3899/25/2/016 [arXiv:nucl-th/9809031 [nucl-th]].

[10] E. Schnedermann, J. Sollfrank and U. W. Heinz, Phys. Rev. C **48**, 2462-2475 (1993) doi:10.1103/PhysRevC.48.2462 [arXiv:nucl-th/9307020 [nucl-th]].

[11] J. Cleymans and K. Redlich, Phys. Rev. C **60**, 054908 (1999) doi:10.1103/PhysRevC.60.054908 [arXiv:nucl-th/9903063 [nucl-th]].

[12] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature **561**, no.7723, 321-330 (2018) doi:10.1038/s41586-018-0491-6 [arXiv:1710.09425 [nucl-th]].

[13] T. Reichert, G. Inghirami and M. Bleicher, Eur. Phys. J. A **56**, no.10, 267 (2020) doi:10.1140/epja/s10050-020-00273-y [arXiv:2007.06440 [nucl-th]].

[14] J. Cleymans and K. Redlich, Phys. Rev. Lett. **81**, 5284-5286 (1998) doi:10.1103/PhysRevLett.81.5284 [arXiv:nucl-th/9808030 [nucl-th]].

[15] J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Phys. Lett. B **615**, 50-54 (2005) doi:10.1016/j.physletb.2005.03.074 [arXiv:hep-ph/0411187 [hep-ph]].

[16] P. Braun-Munzinger and J. Stachel, J. Phys. G **28**, 1971-1976 (2002) doi:10.1088/0954-3899/28/7/355 [arXiv:nucl-th/0112051 [nucl-th]].

[17] S. A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann and J. Konopka, *et al.* Prog. Part. Nucl. Phys. **41**, 255-369 (1998) doi:10.1016/S0146-6410(98)00058-1 [arXiv:nucl-th/9803035 [nucl-th]].

[18] M. Bleicher, E. Zabrodin, C. Spieles, S. A. Bass, C. Ernst, S. Soff, L. Bravina, M. Belkacem, H. Weber and H. Stoecker, *et al.* J. Phys. G **25**, 1859-1896 (1999) doi:10.1088/0954-3899/25/9/308 [arXiv:hep-ph/9909407 [hep-ph]].

[19] G. Inghirami, P. Hillmann, B. Tomášik and M. Bleicher, J. Phys. G **47**, no.2, 025104 (2020) doi:10.1088/1361-6471/ab53f4 [arXiv:1909.00643 [hep-ph]].

[20] P. Huovinen, M. Belkacem, P. J. Ellis and J. I. Kapusta, Phys. Rev. C **66**, 014903 (2002) doi:10.1103/PhysRevC.66.014903 [arXiv:nucl-th/0203023 [nucl-th]].

[21] S. Endres, H. van Hees, J. Weil and M. Bleicher, Phys. Rev. C **91**, no.5, 054911 (2015) doi:10.1103/PhysRevC.91.054911 [arXiv:1412.1965 [nucl-th]].

[22] S. Endres, H. van Hees, J. Weil and M. Bleicher, Phys. Rev. C **92**, no.1, 014911 (2015) doi:10.1103/PhysRevC.92.014911 [arXiv:1505.06131 [nucl-th]].

[23] S. Endres, H. van Hees and M. Bleicher, Phys. Rev. C **93**, no.5, 054901 (2016) doi:10.1103/PhysRevC.93.054901 [arXiv:1512.06549 [nucl-th]].

[24] G. Inghirami, H. van Hees, S. Endres, J. M. Torres-Rincon and M. Bleicher, Eur. Phys. J. C **79**, no.1, 52 (2019) doi:10.1140/epjc/s10052-019-6537-6 [arXiv:1804.07751 [hep-ph]].

[25] T. Reichert, G. Inghirami and M. Bleicher, Phys. Lett. B **817**, 136285 (2021) doi:10.1016/j.physletb.2021.136285 [arXiv:2011.04546 [nucl-th]].

[26] C. Eckart, Phys. Rev. **58**, 919-924 (1940) doi:10.1103/PhysRev.58.919

[27] W. Florkowski and R. Ryblewski, Phys. Rev. C **83**, 034907 (2011) doi:10.1103/PhysRevC.83.034907 [arXiv:1007.0130 [nucl-th]].

[28] R. Ryblewski and W. Florkowski, Phys. Rev. C **85**, 064901 (2012) doi:10.1103/PhysRevC.85.064901 [arXiv:1204.2624 [nucl-th]].

[29] D. Zschiesche, S. Schramm, J. Schaffner-Bielich, H. Stoecker and W. Greiner, Phys. Lett. B **547**, 7-14 (2002) doi:10.1016/S0370-2693(02)02736-3 [arXiv:nucl-th/0209022 [nucl-th]].

[30] R. Bellwied, S. Borsanyi, Z. Fodor, S. D. Katz and C. Ratti, Phys. Rev. Lett. **111**, 202302 (2013) doi:10.1103/PhysRevLett.111.202302 [arXiv:1305.6297 [hep-lat]].

[31] P. Alba, W. Alberico, R. Bellwied, M. Bluhm, V. Mantovani Sarti, M. Nahrgang and C. Ratti, Phys. Lett. B **738**, 305-310 (2014) doi:10.1016/j.physletb.2014.09.052 [arXiv:1403.4903 [hep-ph]].

[32] M. Bluhm and M. Nahrgang, Eur. Phys. J. C **79**, no.2, 155 (2019) doi:10.1140/epjc/s10052-019-6661-3 [arXiv:1806.04499 [nucl-th]].

[33] J. M. Stafford, P. Alba, R. Bellwied, V. Mantovani-Sarti, J. Noronha-Hostler, P. Parotto, I. Portillo-Vazquez and C. Ratti, Springer Proc. Phys. **250**, 367-371 (2020) doi:10.1007/978-3-030-53448-6_58 [arXiv:1912.12968 [hep-ph]].

[34] F. A. Flor, G. Olinger and R. Bellwied, Phys. Lett. B **814**, 136098 (2021) doi:10.1016/j.physletb.2021.136098 [arXiv:2009.14781 [nucl-ex]].

[35] P. Moreau, O. Soloveva, L. Oliva, T. Song, W. Cassing and E. Bratkovskaya, Phys. Rev. C **100**, no.1, 014911 (2019) doi:10.1103/PhysRevC.100.014911 [arXiv:1903.10257 [nucl-th]].