A theory overview on the Compressed Baryonic Matter Experiment at FAIR

Marlene Nahrgang

Department of Physics, Duke University, Durham, North Carolina 27708-0305, USA
Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany

E-mail: marlene.nahrgang@phy.duke.edu

Abstract. The Compressed Baryonic Matter (CBM) experiment at FAIR offers for the first time in heavy-ion physics the opportunity to investigate extremely baryon-dense strongly interacting matter with large data samples as a basis for high precision measurements. This will allow us to put theories at test, answer questions about the structure of the phase diagram of QCD and the transport properties of the medium. In this overview I will highlight some recent advances on several key questions, which will be addressed by the CBM experiment.

1. Introduction

The latest generation of heavy-ion collision experiments are conducted at the LHC, CERN, and RHIC, BNL, in a center-of-mass beam energy range of $\sqrt{s_{\rm NN}} = 0.2 - 5.1$ TeV [1, 2, 3, 4, 5]. In the years 2010 and 2011 during the beam energy scan at RHIC [6] data at lower energies ($\sqrt{s_{\rm NN}} = 11.5 - 200$ GeV) were taken, although energies below the injection energy remain challenging for the RHIC accelerator.

The new Facility for Antiproton and Ion Research (FAIR) will further extend our understanding of strongly interating matter by reaching highest net-baryon densities both during the expansion [7] and at hadronic freeze-out [8]. It will thus become possible to explore new regions in the QCD phase diagram. In addition the FAIR accelerator will provide highest beam intensities, which will largely increase the data sample and will allow us to investigate observables which require high accuracy and to measure rare probes with the CBM detector [9].

In this overview, I will first discuss theoretical challenges concerning the investigation of the phase structure of QCD in section 2 and then discuss open charm physics at FAIR energies in section 3 as an example for the various opportunities of studying rare probes at CBM.

2. The phase structure of dense baryonic matter

Our current understanding of the QCD phase diagram with the parameters temperature T and baryochemical potential μ_B is based on combining different approaches. Due to the nonperturbative character of QCD at the scale $\Lambda_{\rm QCD}$, perturbative QCD calculations are reliable only at very high energies. The most promising first-principle approach to QCD are lattice QCD calculations. At vanishing μ_B the liberation of color degrees of freedom above a transition temperture T_c is seen in thermodynamic quantities [10, 11, 12]. For various quantities, e. g. the energy density, the chiral susceptibility, quark number susceptibilities or the Polyakov-loop, it

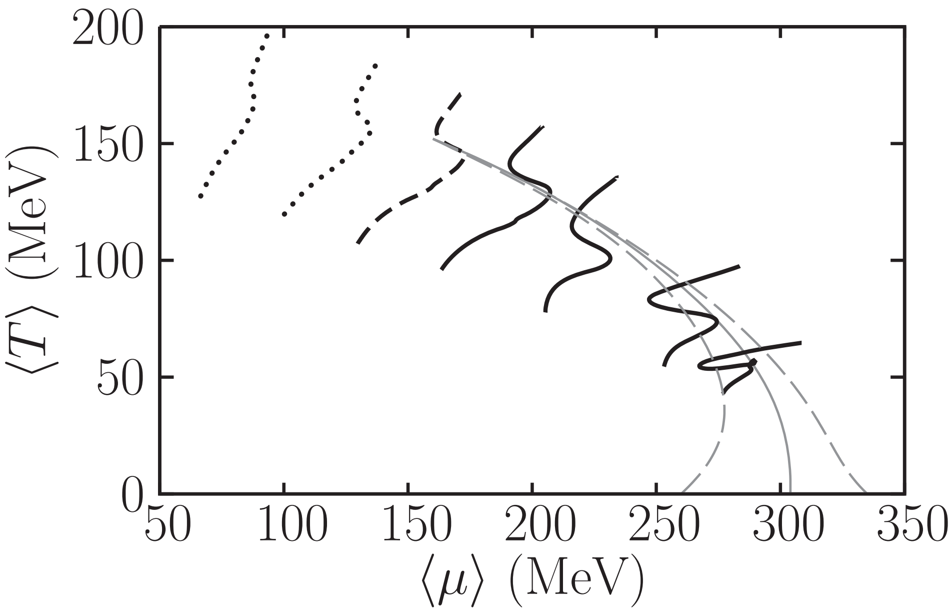

Figure 1. Averaged trajectories calculated from nonequilibrium chiral fluid dynamics. The order parameters of the phase transition are propagated explicitly and stochastically. In the region of the first-order phase transition, here shown in gray including the spinodal region limited by the gray dashed lines, one observes a back-bending of the trajectories. The system spends a significant amount of time in the spinodal region. The underlying model is the PQM model. Figure from [39].

has been found that the transition is an analytic crossover with T_c between $145 - 165$ MeV. Due to the fermionic sign problem lattice QCD calculations at finite μ_B are hardly feasible numerically and although a couple of approaches exist [13, 14, 15, 16, 17] there are no conclusive results about the phase structure of QCD at finite μ_B yet. Besides lattice QCD there are other analytical approaches to calculate the phase structure of QCD, e. g. within a Dyson-Schwinger approach [18], which suggest the existence of a critical point at larger μ_B and a first-order phase transition line beyond it. Here, the quantitative results still depend on various approximations, which need to be made.

In low-energy effective models of QCD, e. g. Quark-Meson (QM) models or Nambu-Jona-Lasino (NJL) models, one tries to capture essential features like chiral symmetry and to mimic confinement via the inclusion of an effective Polyakov-loop field (PQM or PNJL models). The model-dependent results strongly differ according to the particular parameters, ingredients and approaches to solve the thermodynamic quantities, if in mean-field or beyond. Toward higher net-baryon densities most of these models find a critical point and a first-order phase transition line [19, 20, 21, 22, 23, 24].

Experimentally, there are a lot of indications for the formation of a color-deconfined plasma, the quark-gluon plasma (QGP) at high collision energies [1, 2, 3, 4, 5]. Going to lower energies the question of the existence and the location of the conjectured critical point, as well as the onset of deconfinement, is of highest priority for the CBM experiment. There are two strategies for a discovery of the critical point, either via directly seeing unambiguous signals of a critical point, or by evidence for a first-order phase transition starting at the location of the critical point and growing stronger toward lower beam energies.

For the search of the critical point a nonmonotonic behavior of fluctuations in multiplicities of conserved quantities as a function of beam energy is the most advocated signal [25, 26]. It is based on the divergence of the correlation length ξ of fluctuations in the order parameter in a thermodynamical system. The moments of these fluctuations are proportional to powers of ξ: the variance $\langle(\delta N)^2\rangle \propto \xi^2$, the skewness $\langle(\delta N)^3\rangle \propto \xi^{4.5}$ and the kurtosis $\langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 \propto \xi^7$ [27].

A system created in a heavy-ion collision is, however, inhomogenous, finite in space and time and highly dynamical. These conditions will weaken the growth of the correlation length and thus the critical phenomena are reduced. Most limiting might be the effect of critical slowing down: at a critical point not only the correlation diverges but so does the relaxation time. This means, that any system evolving through a critical point in a finite amount of time, will necessarily be driven out of equilibrium even if it was equilibrated at higher temperatures. In a phenomenological approach [28] including the dynamical critical exponents [29] it was demonstrated that the correlation length at best grows to ~ 2 fm. For a first order phase transition, however, the situation is opposite: a strong nonequilibrium situation is necessary to see fluctuations coming from the instability of slow modes in the spinodal region [30, 31, 32, 33]. Including this spinodal region means that one has to avoid equilibrium equation of states, which consist of a high-temperature part and low-temperature part joined together by a Maxwell construction. If instead one uses an equation of state that allows unstable phases it was demonstrated, that initial density irregularities are enhanced during the phase transition [34].

In order to understand the phase transition dynamics in the CBM energy regime, it is extremely important to develop realistic dynamical simulations of the critical point and the first-order phase transition. Models of nonequilibrium chiral fluid dynamics [35, 36, 37, 38, 39] have recently addressed this challenge by coupling the stochastic dynamics of the order parameter of the phase transition to a fluid dynamical expansion of the bulk matter. It showed an increase of irregularities in the net-baryon density developing dynamically at the phase transition. These results have been obtained within a PQM model and studies need to be improved by applying a more realistic equation of state, which reproduces the baryon-rich environment and the phenomenology of saturated nuclear matter, e. g. the one presented in [40]. At high net-baryonic densities it is still under debate which slow mode is the real critical mode, the sigma mode, the density or the thermal mode [41]. The propagation of fluid dynamical fluctuations has recently been studied in a simplified Bjorken expansion and found to induce correlations extending over a unity in rapidity [42]. Applying a thermal conductivity from mode coupling theory and a parametrized equation of state with a critical point [43] it was shown in [44] that along a Bjorken-trajectory near the critical point these correlations are enhanced.

Further theoretical studies need to put special emphasis on realistically modeling the many sources of non-critical fluctuations in heavy-ion collisions, such as initial fluctuations and fluctuations due to final hadronic interactions in order to predict reliable signals of the critical point and the first-order phase transition. Recent results from the STAR collaboration on the higher moments of net-proton number fluctuations do show some deviations from a simulated Skellam distribution at lower beam energies [45]. A clear statement about a non-monotonic behavior is, however, not possible. It needs to be noted that the experimentally feasible measurement of net-protons does not directly compare to theoretical predictions on fluctuations in the conserved net-baryon number. Due to isospin randomization it is possible to generally relate fluctuations in net-protons to the fluctuations in net-baryon number, deviations from thermal models will however be hidden in the net-protons distributions [46, 47]. If efforts could be made to measure also neutrons it would be highly desirable because the comparison to theoretical models would be a lot cleaner.

3. Open charm production and propagation

At highest LHC and top-RHIC energies the production and propagation of open charm has been studied extensively, both theoretically and experimentally. Due to the higher masses charm-anticharm pairs are predominantly produced in the initial hard nucleon-nucleon scatterings. They are expected to not thermalize completely with the bulk medium, what makes them an interesting probe to study the properties of the QGP and the interaction mechanisms. While charm quarks are relatively abundant at LHC energies the production cross sections fall off rapidly toward lower beam energies. In the energy range of the CBM experiments charm quark production is at threshold. This makes charm quarks at CBM a very rare probe and the high beam intensities will pay off here. To study the medium modifications of charm quark spectra a reliable proton reference is needed. Initial spectra have been parametrized within the HSD transport approach [48] and can also be obtained from PYTHIA simulations [49]. Once reference proton-proton collisions are run at CBM these theoretical approaches need to be either validated or re-investigated.

Recently, first calculations of the charm quark observables, the nuclear modification factor R_{AA} and the elliptic flow v_2, within a Langevin+UrQMD hybrid model approach have been presented [50]. It was found that the initial spectra still had a large influence on the final observables, which is understandable due to lower temperatures and thus less thermalization at the CBM energies. Meaningful spectra only extend to $p_T \lesssim 1.5$ GeV such that the initially very soft spectra are pushed toward slightly higher p_T yielding a pronounced rise of the R_{AA}. In this study the transport coefficients were obtained from pQCD calculations including resonance scattering [51, 52]. Here, it was found that due to the baryon-rich environment the scattering cross sections are especially enhanced for anticharm quarks as compared to charm quarks. This leads to a significant difference between the final R_{AA} of D and $\bar{D}$ mesons and could thus enable us to obtain additional insight about the energy loss mechanism of heavy quarks, which as such cannot be investigated at LHC and RHIC. It should also motivate other groups to extend their calculations to lower energies. Interactions between D mesons and the hadronic medium are also expected to affect observables like the elliptic flow already at LHC energies. Understanding their contribution becomes more important at lower energies. Recently, the drag and diffusion coefficient of D mesons have been evaluated from an effective Lagrangian consistent with chiral and heavy-quark spin symmetries [53]. It was found that due to additional interactions with the baryons the relaxation times at CBM energies are reduced compared to those at LHC. It remains an interesting task to include those hadronic interactions in a dynamical setup.

4. Summary

The CBM experiment offers a broad range of theory questions to be addressed by reaching highest net-baryon densities with highest beam intensities. In this small overview I highlighted the opportunities to learn about the phase structure of QCD and the energy loss mechanism of charm quarks in a partonic medium and D mesons in a hadronic environment. This is of course not exhaustive and there are a lot more of interesting theory questions, like electromagnetic probes, their relation to chiral symmetry restauration and their hadronic or partonic origin, hidden charm production and propagation, signatures of color superconductivity and quarkyonic matter, the equation of state of neutron stars and nonequilibrium effects in transport approaches.

Acknowledgments

I acknowledge the continuous support by the Hessian LOEWE initiative Helmholtz International Center for FAIR and would like to thank the organizers of FAIRNESS 2013 for the inspiring conference and the many fruitful discussions.

References

[1] J. Adams *et al.* [STAR Collaboration], Nucl. Phys. A **757** (2005) 102.
[2] B. B. Back *et al.* [PHOBOS Collaboration] Nucl. Phys. A **757** (2005) 28.
[3] I. Arsene *et al.* [BRAHMS Collaboration], Nucl. Phys. A **757** (2005) 1.
[4] K. Adcox *et al.* [PHENIX Collaboration], Nucl. Phys. A **757** (2005) 184.
[5] B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. Lett. **109** (2012) 252301.
[6] H. Caines [STAR Collaboration], arXiv:0906.0305 [nucl-ex].
[7] I. C. Arsene, L. V. Bravina, W. Cassing, Y. .B. Ivanov, A. Larionov, J. Randrup, V. N. Russkikh and V. D. Toneev *et al.*, Phys. Rev. C **75** (2007) 034902 [nucl-th/0609042].
[8] J. Randrup and J. Cleymans, Phys. Rev. C **74** (2006) 047901.
[9] B. Friman, C. Hohne, J. Knoll, S. Leupold, J. Randrup, R. Rapp and P. Senger, Lect. Notes Phys. **814** (2011) 1.
[10] Y. Aoki, G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, Nature **443** (2006) 675.
[11] S. Borsanyi *et al.* [Wuppertal-Budapest Collaboration], JHEP **1009** (2010) 073.
[12] A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H. T. Ding, S. Gottlieb, R. Gupta and P. Hegde *et al.*, Phys. Rev. D **85** (2012) 054503.
[13] Z. Fodor and S. D. Katz, JHEP **0203** (2002) 014 [hep-lat/0106002].
[14] R. V. Gavai and S. Gupta, Phys. Rev. D **78** (2008) 114503 [arXiv:0806.2233 [hep-lat]].
[15] P. de Forcrand, PoS LAT **2009** (2009) 010 [arXiv:1005.0539 [hep-lat]].
[16] O. Kaczmarek, F. Karsch, E. Laermann, C. Miao, S. Mukherjee, P. Petreczky, C. Schmidt and W. Soeldner *et al.*, Phys. Rev. D **83** (2011) 014504 [arXiv:1011.3130 [hep-lat]].
[17] G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP **1104** (2011) 001 [arXiv:1102.1356 [hep-lat]].
[18] J. Luecker, C. S. Fischer, L. Fister and J. M. Pawlowski, PoS CPOD **2013** (2013) 057 [arXiv:1308.4509 [hep-ph]].
[19] O. Scavenius, A. Mocsy, I. N. Mishustin and D. H. Rischke, Phys. Rev. C **64** (2001) 045202.
[20] K. Fukushima, Phys. Lett. B **591** (2004) 277.
[21] B. -J. Schaefer and J. Wambach, Nucl. Phys. **A757** (2005) 479
[22] C. Ratti, M. A. Thaler, W. Weise, Phys. Rev. D **73** (2006) 014019.
[23] B. -J. Schaefer, J. M. Pawlowski, J. Wambach, Phys. Rev. D **76** (2007) 074023.
[24] V. Skokov, B. Friman and K. Redlich, Phys. Rev. C **83** (2011) 054904
[25] M. A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. Lett. **81** (1998) 4816
[26] M. A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. D **60** (1999) 114028.
[27] M. A. Stephanov, Phys. Rev. Lett. **102** (2009) 032301.
[28] B. Berdnikov and K. Rajagopal, Phys. Rev. D **61** (2000) 105017.
[29] P. C. Hohenberg and B. I. Halperin, Rev. Mod. Phys. **49** (1977) 435.
[30] L. P. Csernai and I. N. Mishustin, Phys. Rev. Lett. **74** (1995) 5005.
[31] I. N. Mishustin, Phys. Rev. Lett. **82** (1999) 4779.
[32] O. Scavenius, A. Dumitru, E. S. Fraga, J. T. Lenaghan and A. D. Jackson, Phys. Rev. D **63** (2001) 116003
[33] J. Randrup, Phys. Rev. C **82** (2010) 034902.
[34] J. Steinheimer and J. Randrup, Phys. Rev. Lett. **109** (2012) 212301
[35] M. Nahrgang, S. Leupold, C. Herold and M. Bleicher, Phys. Rev. C **84** (2011) 024912.
[36] M. Nahrgang, S. Leupold and M. Bleicher, Phys. Lett. B **711** (2012) 109.
[37] M. Nahrgang, C. Herold, S. Leupold, I. Mishustin and M. Bleicher, J. Phys. G **40** (2013) 055108.
[38] C. Herold, M. Nahrgang, I. Mishustin and M. Bleicher, Phys. Rev. C **87** (2013) 014907.
[39] C. Herold, M. Nahrgang, I. Mishustin and M. Bleicher, arXiv:1304.5372 [nucl-th].
[40] V. A. Dexheimer and S. Schramm, Phys. Rev. C **81** (2010) 045201 [arXiv:0901.1748 [astro-ph.SR]].
[41] Y. Minami and T. Kunihiro, Prog. Theor. Phys. **122** (2010) 881 [arXiv:0904.2270 [hep-th]].
[42] J. I. Kapusta, B. Muller and M. Stephanov, Phys. Rev. C **85** (2012) 054906 [arXiv:1112.6405 [nucl-th]].
[43] J. I. Kapusta, Phys. Rev. C **81** (2010) 055201 [arXiv:1001.3650 [nucl-th]].
[44] J. I. Kapusta and J. M. Torres-Rincon, Phys. Rev. C **86** (2012) 054911 [arXiv:1209.0675 [nucl-th]].
[45] L. Adamczyk *et al.* [STAR Collaboration], arXiv:1309.5681 [nucl-ex].
[46] M. Kitazawa and M. Asakawa, Phys. Rev. C **85** (2012) 021901 [arXiv:1107.2755 [nucl-th]].
[47] M. Kitazawa and M. Asakawa, Phys. Rev. C **86** (2012) 024904 [Erratum-ibid. C **86** (2012) 069902] [arXiv:1205.3292 [nucl-th]].
[48] W. Cassing, E. L. Bratkovskaya and A. Sibirtsev, Nucl. Phys. A **691** (2001) 753 [nucl-th/0010071].
[49] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026 [hep-ph/0603175].
[50] T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1305.1797 [hep-ph].
[51] H. van Hees and R. Rapp, Phys. Rev. C **71** (2005) 034907 [nucl-th/0412015].
[52] H. van Hees, V. Greco and R. Rapp, Phys. Rev. C **73** (2006) 034913 [nucl-th/0508055].

[53] L. Tolos and J. M. Torres-Rincon, Phys. Rev. D **88** (2013) 074019 [arXiv:1306.5426 [hep-ph]].