Theory of hot and dense baryon-rich matter: heavy-ion collisions and compact stars

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The QCD phase diagram at high baryon densities offers unique insights into the strong interaction under extreme conditions. In this contribution we highlight the theoretical progress that needs to be made in order to obtain information about the equation of state (EoS), the chiral and the deconfinement phase transition. These challenges span from QCD to effective field theories and from the phenomenology of heavy-ion collisions (HIC) to compact stars. Various approaches to QCD (lattice, FRG, effective models) will examined to extend the region of validity further toward the baryon-dense side. We will further develop the theory of dynamical fluctuations at the critical point and the first-order phase transition, such that it can properly be included into the quantitative description of HIC. At this point, several improvements to the phenomenological modeling of HIC are in order, such as the dynamical fluidization in the initial state. Finally, any parameters in the EoS or transport coefficients will be systematically determined by statistical model-to-data analysis considering high-precision data from HIC experiments and astrophysical observation.

1 Theoretical challenges

1.1 Lattice QCD and effective field theory

At small baryochemical potential lattice QCD is the computational tool to calculate equilibrium properties of QCD, such as the location and nature of the deconfinement transition, the restoration of chiral symmetry at high temperature and the equation of state. Due to the sign problem in the presence of finite baryochemical potential, pressing questions such as the existence and location of the critical point and the nature of various conjectured phases at high density remain out of reach for the current lattice techniques. It is, therefore, necessary to:

- Advance approaches aiming to alleviate the sign problem by either finding a formulation where there is no sign problem, e.g. duality transformations, changing the sampling techniques, e.g. complex Langevin dynamics, or complexifying the fields, e.g. Lefschetz thimbles.
- Construct effective models, e.g. Polyakov-loop-extended-Nambu-Jona-Lasinio model, Polyakov-Quark-Meson model or quasi-particle models, whose parameters can be constrained by the lattice at small $\mu_B/T \approx \mathcal{O}(1)$ and experimental data from HIC and astrophysical observations. The advantage of those approaches is that they allow a controlled interpolation of data on the whole temperature and density range and also interpret the data with microscopic degrees of freedom.
- Extend truncation schemes such as the functional renormalization group or Dyson-Schwinger approaches, to perform calculations at high chemical potential,
- Examine new directions of many-body theory to obtain information of the in-medium modifications of hadrons for baryon rich matter.

1.2 Equation of state (EoS) from and for HIC and astrophysics

The EoS contains all the information about the equilibrium state of strongly interacting matter. It serves as important ingredient into the modeling of nuclear reactions or compact stars, and can thus be constrained by experimental data from HIC or astrophysical observations.

In HIC, the EoS is either an explicit ingredient into the fluid dynamical simulations or information from it is implicitly used in the construction of quasiparticle models and microscopic transport approaches. As HIC at finite net-baryon density probe the region of the conjectured critical point and the adjacent line of the first-order phase transition, it should in principle be possible to access these important features of the EoS. In a recent attempt classes of EoS have been constructed from the Taylor coefficients of the pressure obtained in lattice QCD and the $3D$ Ising universality class in order to test the effect of a critical point on potential observables [1]. Beyond the critical point the first-order phase transition can be included into the EoS obtained from effective field theory approaches. In order to compare well to HIC at high densities, the correct inclusion of the hadronic degrees of freedom is crucial and constraints from the nuclear ground state need to be taken into account, as e.g. in [2]. These models typically contain a number of free parameters, which should be obtained by an unbiased model-to-data comparison, using e.g. Bayesian statistical analysis techniques. This has proved successful at LHC energies [3] but not yet been investigated for lower beam energies.

In astrophysics, at high density and moderate or zero temperature, the microscopic theory is mainly dominated by nucleonic degrees of freedom but also other hadrons as hyperons or even quark degrees of freedom (may be inside the star or also during mergers when the temperature can reach up to $50-100$ MeV). Already with only one confirmed binary neutron star merger some constraints can be put on the nuclear EoS (via the measurement of the tidal deformability for example). It is expected that during the current LIGO/Virgo O3 run more mergers will be observed (4 already confirmed and maybe one black-hole neutron star merger?) to strengthen this analysis. The formation of a supra-massive neutron star resulting from the merger of two neutron stars is expected to put limits on the densest stable baryonic state, such as the maximum mass/density matter can support before collapsing to a black hole. This limits has strong impact on the dense matter equation of state, as well as on the understanding of the matter component. It requires however to observe post-merger gravitational waves, which is expected in the near future. More details and common means have already been presented in the two contributions "Compact stars and matter at extreme conditions" (GT02) in the section "Microscopic theory" and "Probing extreme matter physics with gravitational waves" (GT04).

1.3 Initial state of nuclear collisions

Fluid dynamical simulations have proved extremely successful in the description of HIC, where results depend on the choice of the initial state. For baryon rich systems the understanding of the correct initial states requires more theoretical effort:

- The stopping of the initial baryon current becomes increasingly important. As a consequence boost-invariance is not a good approximation anymore and the full 3-dimensional information needs to be obtained.
- The penetration time of the two incoming nuclei gets extremely long at lower beam energies, so that some regions of the fireball are already fullfilling the conditions of local equilibration, while the edges are not yet fluidized. Two possible directions to follow would be multi-fluid approaches [4] or dynamical fluidization [5], both of which have recently been presented in preliminary versions.
- For the application of the fully operational multiparton scattering approach EPOS [6] at finite baryon densities the transition from the pure EPOS, i.e. all collisions in parallel, to a cascade with sequential collisions needs to be implemented.

1.4 Dynamics of fluctuations

Observables based on fluctuations are promising signals of the phase transition. At a critical point this is due to a growing correlation length in the scaling regime and at a first order phase transition because of domain formation in the coexistence region. Current models of the space-time evolution for HIC do not fully evolve these fluctuations (which is equally true at LHC energies). In order to be able to predict observables for the phase transition the following challenges need to be met

- Including fluctuations into the fluid dynamical equations, both for the stress tensor and the nonzero charge densities. Many conceptual questions are still open.
- Including fluctuations of the order-parameters, such as the chiral condensate [7].
- It will be crucial to construct a *non-equilibrium* EoS, that can take local fluctuations of order-parameters into account.
- Knowledge of all transport coefficients is needed as a function of temperature and density.
- Interesting applications can arise in other strongly-coupled quantum systems, such as cold atoms.

2 Conclusions

Many open questions need to be addressed theoretically in order to explore the rich structure of QCD in the baryon rich regime. These questions have strong overlap with the experimental investigation via HIC and astrophysical observations (traditional observations in the electromagnetic spectrum but also newly observed gravitational waves signal from binary neutron star mergers).

References

[1] P. Parotto *et al.*, arXiv:1805.05249 [hep-ph].

[2] V. A. Dexheimer and S. Schramm, Phys. Rev. C **81** (2010) 045201

[3] S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Phys. Rev. Lett. **114** (2015) 202301

[4] P. Batyuk *et al.*, Phys. Rev. C **94** (2016) 044917

[5] Y. Akamatsu *et al.*, Phys. Rev. C **98** (2018) no.2, 024909

[6] K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, Phys. Rev. C **82** (2010) 044904

[7] C. Herold, M. Nahrgang, Y. Yan and C. Kobdaj, Phys. Rev. C **93** (2016) no.2, 021902