Dense Baryonic Matter in Relativistic Nuclear Collisions

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Introduction

Relativistic heavy-ion collisions are the only terrestial tool known so far, to probe the exotic states of strongly interacting matter in the laboratory. By varying the collision energy and the colliding species, nuclear matter can be produced over a wide range of temperature and net baryon densities which allows to address two fundamental features of Quantum Chromodynamics (QCD): confinement and chiral symmetry. Our current understanding of the phase structure of QCD is mostly limited to the low baryon chemical potential (μ_B) domain. Here the first principle lattice QCD calculations provide evidence for a smooth cross-over transition from the hadronic phase to the quark-gluon plasma (QGP) phase at a pseudo-critical temperature of $T_c \simeq 154 \pm 9$ MeV [1]. Experimentally this low μ_B region is well studied in heavy-ion collisions at ultra-relativistic energies at CERN-SPS, BNL-RHIC and CERN-LHC. Compared to this, in the large μ_B regime, the QCD phase diagram is largely unexplored. The lattice QCD estimations are not yet applicable at these high net baryon densities whereas only a few experimental measurements mainly of bulk observables are available from first generation experiments. However this high density domain of QCD phase diagram is predicted to exhibit many interesting features [2] like a first order phase transition line with co-existence of hadron gas and QGP at moderate temperatures, a critical end point (CEP) where the transition is second order, a chirally symmetric but confined Quarkyonic phase or the color superconducting phase at almost zero temperature and extreme densities as displayed in Fig. 1. This has triggered a renewed interest to relativistic nuclear collisions at lower energies, where incoming baryons are stopped at mid-rapidity to produce a high baryon density medium. A number of experimental programs are currently operational or under development worldwide, with a focal aim to study the properties dense baryonic matter. The STAR Beam-Energy Scan (BES) program at RHIC-BNL has studied nuclear collisions down to $\sqrt{s_{NN}} = 3$ GeV. The Multi-Purpose Detector (MPD) experiment at the new accelerator facility NICA at JINR Dubna coming will cover an energy range ($\sqrt{s_{NN}} = 4 - 11$ GeV) in collider mode and will be ready for commissioning in 2025. The Compressed Baryonic Matter experiment (CBM) at the FAIR SIS100 accelerator complex, currently under construction at GSI Darmstadt, will study nuclear collisions at even lower energies ($E_{lab} = 2A$ to $11A$ GeV), with emphasis on extremely rare probes with unprecedented interaction rates. The underlying motivation for these experimental activities is the fact that the strongly interacting matter can undergo deconfinement and chiral phase transition not only by heating, but also by compression.

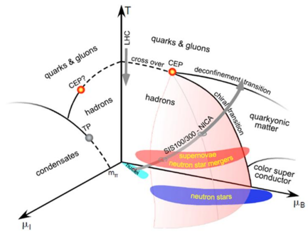

FIG. 1: (Schematic of the conjectured QCD phase diagram in 3D representation, in terms of temperature (T), baryon chemical potential (μ_B and iso-spin chemical potential (μ_I), as adopted from Ref. [3].

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Promising Diagnostic Observables

Till date no unique key measurement has been identified in literature, to unambiguously probe the hot and dense matter created in relativistic nuclear collisions. A common experimental strategy is to perform systematic multi-differential measurements of a set of identified observables as a function of beam energy and system size [4–6]. The yields and phase-space distributions of multi-strange hyperons (Ξ, Ω) for example, are identified as useful daignostic tool to study the properties and the degrees of freedom of dense QCD matter and a possible transition to Quarkyonic matter. The production of multi-strange hyperons is predicted to be enhanced at high densities, and their yield to be sensitive to both the strangeness content and the baryon density reached in the fireball. The production of anti-hyperons, on the other hand, is strongly suppressed in a baryon-dense environment. The collective flow of the measured final state hadrons driven by the initial state spatial anisotropy and the resulting pressure gradients developed in the fireball help to get insights about the equation-of-state (EoS) governing the evolution of the produced medium. Data collected by the STAR-BES program indicate an increasing difference between particle and antiparticle flow with decreasing energy of the collision. On the other hand, event by event fluctuation in the multiplicity distribution of conserved charges are useful to detect critical behaviour as anticipated in the vicinity of the QCD critical point. Charmed hadrons are very promising diagnostic probes of hot and dense nuclear matter. Because of large mass, their thermal production in nuclear reactions is suppressed and they can be created only in the initial stage by first-chance collisions of the participating nucleons. Once produced they propagate through the dense medium. The upcoming experiments at SPS and FAIR will address the issue of charm production and propagation through dense baryonic matter via measurement of open (eg: D^0, Λ_c) and hidden charm (J/ψ, ψ') hadrons. The experimental challenge lies in the extremely low abundances of both open and hidden charm particles at lower collision energies. The other useful experimental observables include the dilepton production (e^+e^- and $\mu^+\mu^-$) which based on the selected pair mass range is believed to carry useful inofmation about the chiral transition, initial temperature and the life time of the fireball.

Summary

A broad spectrum of running and forthcoming experimental activities are in operation to investigate the high-μ_B regime of the QCD phase diagram. A set of promising measurements have been made available by STAR-BES and NA61/SHINE experiments in recent years. In the near future the accelerator facilities like FAIR, CERN-SPS or NICA will collectively offer unique opportunites to systematically collect high preecision data including extremely rare probes inaccessible to experimental measurements till date. Together this measurements will open up new avenues to explore the QCD phase diagram at high net baryon densities.

References

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