Hydrodynamic modeling of QCD fluid with critical point in the equation of state

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Introduction

Quantum chromodynamics (QCD), the quantum field theory of strong interaction, has a rich phase diagram suggested by lattice QCD and effective models. The strongly interacting matter exists as hadrons under ordinary conditions of temperature (T) and nuclear density (ρ). However, when the conditions are extreme ($T \sim 10^{12}$ K , $\rho \sim 5-10\rho_0$, where $\rho_0 = 0.16$ fm^{-3} is the normal nuclear matter density), the matter exists in a phase where the fundamental degrees of freedom are quarks and gluons. This phase is called the Quark-Gluon Plasma (QGP). The transition from hadronic to QGP phase at zero baryon chemical potential (μ_B) is a smooth crossover, whereas at large μ_B but small T the transition becomes first-order. A critical point (CP) is thus expected somewhere in the QCD phase diagram where the line of first-order transition ends and crossover begins. Locating the QCD critical point is one of the primary goals of heavy-ion physics programs.

The formation of QGP in the laboratory is achieved through relativistic collisions of heavy ions. In such collisions, a large amount of energy (or matter) is deposited in a very small volume. The energy (or matter) density so created is sufficient for the formation of a fireball of quarks and gluons. The fireball undergoes complex dynamics within its short lifetime ($\sim 10^{-23}$ s). Experimental data suggest that the fireball is close to local thermodynamic equilibrium, so its expansion can be modeled through the equations of relativistic dissipative causal hydrodynamics. The solution of relativistic dissipative hydrodynamics should provide the fireball's spacetime dependence of T and μ_B. However, the highly nonlinear nature of these equations makes it extremely difficult to obtain analytical solutions . A numerical solution to the equations is thus imperative. To solve the equations, we need a model for initial condition (IC) as there is no first principle calculation for IC. We further need an equation of state (EoS) to close the system of hydrodynamic equations. The EoS must contain a CP in order to capture the essential physics due to CP. We further require a prescription to stop the hydrodynamical evolution. This is usually done at chemical freezeout temperature.

In this work, we develop a state-of-the-art simulation package for relativistic heavy-ion collisions which we employ to study the effects of CP on various QGP observables, in particular, the spin polarization of Λ hyperons. We propose that its suppression can be used as an indicator of CP. We also study the effect on the nature of chemical freezeout of strange hadrons due to the expansion of the system. Further, by computing chemical relaxation time in a gas of low mass mesons, we answer a fundamental question of heavy-ion physics: why should hadrons chemically freezeout at the chiral crossover temperature?

Hydrodynamic equations

We develop a numerical code to solve (3+1)-dimensional causal relativistic viscous hydrodynamics at finite μ_B. The code has been rigorously tested against known analytical results in one and two spatial dimensions. For three spatial dimensions, we test the code by

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comparing with the output of publicly available codes, and by reproducing the experimental data like momentum specta, elliptic flow, charged particle pseudorapidty dependence etc.

Initial condition

The conventional Glauber model used as IC does not explain the experimental data on the centrality dependence of elliptic flow in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV and fluctuations of scaled elliptic flow at $\sqrt{s_{NN}} = 193$ GeV and 2.76 TeV for most central events. The shortcomings of the model are overcome by including the physics of nucleon shadowing and proposing a different mechanism for entropy deposition [1]. The results using the improved model, the shadowed Glauber model, explains the data as well as matches with the predictions of the QCD based dynamical IP-Glasma model. We include the Monte-Carlo shadowed Glauber model as an IC in our hydrodynamical setup.

Equation of state

We use a model for EoS from the literature that introduces CP by mapping QCD to the 3D Ising model. We also include the scaling behavior of the transport coefficients (shear and bulk viscosity) that diverge near the critical point. We explore the effect of critical point on experimental observables like thermal particle spectra, directed and elliptic flow. We also study the time evolution of thermal vorticity with and without the critical point. We observed a significant suppression in thermal vorticity near CP at late times due to enhanced viscosities. The polarization vector for spin-1/2 particles is known to be related linearly to thermal vorticity at the leading order. Hence any suppression in thermal vorticity should lead to a suppression in the polarization of spin-1/2 particles. We confirm this by showing that the polarization of Λ-hyperons is suppressed as the critical point is approached [2]. We argue that the study of spin polarization of Λ-hyperons can be useful as a possible candidate for the efforts towards the search for the QCD critical point.

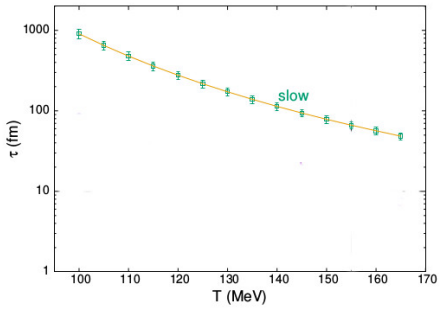

FIG. 1: The relaxation time, τ , for the slow mode of the linearized chemical rate equations. Image source: Ref [3].

Freezeout

At zero baryon chemical potential, thermal models predict a temperature for the chemical freezeout which is numerically equal to the chiral crossover temperature. In order to understand such a numerical coincidence, we examine the thermalization of an ensemble of the octet of pseudoscalar mesons in the isospin symmetric limit. Using previous calculations for scattering amplitudes, we compute the cross-sections of all possible reactions within the system using next-to-leading order chiral perturbation theory. We compute chemical relaxation time in the linear response approximation of momentum integrated Boltzmann equation. We argue that the breaking of chiral symmetry is responsible for the system to have large relaxation time, as shown in Fig. 1, that forces it to chemically freezeout at the chiral crossover temperature [3].

References

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