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Effects of dissipative baryon current in heavy-ion collisions at RHIC-BES energies

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Abstract

The CLVisc (3+1)D viscous hydrodynamic model is extended to include the equation of net baryon conservation and the Israel-Stewart-like equations for dissipative baryon current. Using the NEOSB equation of state, we simulate the dynamical evolution and collectivity of the quark-gluon plasma with finite chemical potential, assuming smooth energy density and net baryon density distributions at the initial proper time. Numerical results are shown for the impact of net-baryon dissipation on particle yields and p_T spectra in heavy-ion collisions at beam energy scan energies.

Keywords:
quark-gluon plasma, anisotropic flow, beam energy scan, baryon diffusion, relativistic hydrodynamics

1. Introduction

One of the most important objectives of the beam energy scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) is to search for the critical end point in the QCD phase diagram via performing nucleus-nucleus collisions with a wide range of collision energies (7.7-200 GeV). At such energies, the nuclei are not transparent enough to pass through each other due to the power of baryon stopping. Therefore, the quark-gluon plasma (QGP) produced in these collisions has sizable net baryon density in the central rapidity region. Various studies have shown that relativistic hydrodynamics is successful to describe the collective behaviors of QGP at zero baryon chemical potential, not only in the transverse plane but also in the longitudinal direction [1, 2, 3, 4, 5]. At RHIC-BES energies, the evolution of finite baryon current can no longer be ignored and the dissipation of net-baryon current may play an important role in the dynamical evolution of the hot and dense QCD matter produced in BES heavy-ion collisions. In this work, we extend the CLVisc hydrodynamics model [1, 2] to include the effect of baryon number conservation and diffusion.

2. (3+1)D CLVisc hydrodynamics model with dissipative baryon current

In this work, we extend the (3+1)D CLVisc hydrodynamic model to study the properties of QGP and dissipative phenomena of net baryon current at RHIC-BES energies. Firstly, one needs to solve the energy-

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momentum conservation as well as the net baryon number conservation:

$$\nabla_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}, \tag{1}$$
$$\nabla_\mu J^\mu = 0, \quad J^\mu = nU^\mu + V^\mu, \tag{2}$$

where the V^μ is the baryon diffusion current. In this work, we neglect the contribution from the bulk viscosity. For the evolution of dissipative current, we consider Israel-Stewart-like equations of motions [6]:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma^{\nu>}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{<\mu}_{\alpha}\pi^{\nu>\alpha}, \tag{3}$$
$$\Delta^{\mu\nu} DV_\mu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}, \tag{4}$$

where $\sigma^{\mu\nu}$ is symmetric shear tensor and θ is expansion rate. In the Navier-Stokes limit, one can easily find that the transport coefficients η and the baryon diffusion coefficient κ_B control the relative magnitudes of shear tensor $\pi^{\mu\nu}$ and baryon diffusion current V^μ, respectively. In this work, we consider the kinematic transport coefficients C_η and the baryon diffusion coefficient κ_B which are defined as follows [6, 7]:

$$C_\eta = \frac{\eta T}{e+P}, \quad \kappa_B = \frac{C_B}{T} n\left(\frac{1}{3}\cot\left(\frac{\mu_B}{T}\right) - \frac{nT}{e+P}\right), \tag{5}$$

We set $C_\eta = 0.08$ and vary the value of C_B to study the effects of dissipative baryon current.

To close the hydrodynamic equations, we use the NEOSB equation of state [8], which combines the lattice QCD simulation at the high temperature and hadron gas at lower temperature via a smooth crossover transition. For the initial condition, we utilize the averaged Monte-Carlo Glauber model. The local entropy density $s(x, y, \eta)|_{\tau_0}$ and the local baryon density $n(x, y, \eta)|_{\tau_0}$ can be constructed as follows:

$$s(x,y,\eta)|_{\tau_0} = \frac{K}{\tau_0}\left(H^s_P(\eta)s_p(x,y) + H^s_T s_T(x,y)\right), \quad n(x,y,\eta)|_{\tau_0} = \frac{1}{\tau_0}\left(H^n_P(\eta)s_p(x,y) + H^n_T s_T(x,y)\right), \tag{6}$$

where $s_{P/T}$ is the Gaussian smearing function in the transverse plane and $H^s_{P/T}, H^n_{P/T}$ are the envelop functions in the longitudinal plane [6]. The shape of envelope functions can be determined by comparing hydrodynamic numerical results with the charged hadron distributions and net-proton distributions. The momentum distributions of final produced particles can be calculated according to the Cooper-Fype formula. Due to the baryon current diffusion, one needs to add the correction $\delta f^n(x, p)$ in the phase-space distribution,

$$\delta f^n(x,p) = f^{\rm eq}(1 \pm f^{\rm eq}(x,p))\left(\frac{n}{e+P} - \frac{b}{u^\mu p_\mu}\right)\frac{p^\mu V_\mu}{\kappa_B T/C_B} \tag{7}$$

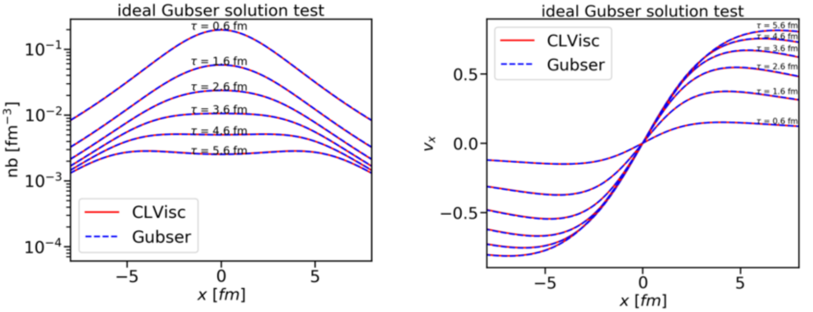

Fig. 1. Time evolutions of baryon density n and transverse flow velocity v_x from our CLVisc simulation and from the analytical solutions of ideal Gubser flow.

We first test the numerical accuracy of our extended CLVisc code by comparing to the analytical hydrodynamics solutions and other numerical hydrodynamics codes. To check for the hydrodynamic evolution in the transverse plane, we compare in Figure. 1 our result to the analytical solution from Gubser flow[6, 9], which describes a conformed system with strong radial flow and longitudinal boost invariance. One can see that our CLVisc hydrodynamics code can reproduce the baryon density and transverse fluid velocity evolution from Gubser solution perfectly. For the longitudinal directions, in Figure. 2 we compare our result to Monnai's (1+1)-dimensional hydrodynamics code [8]. Note that here we neglect the shear tensor and solve the equation of baryon diffusion current that only contains the Navier-Stokes and linear terms as in Ref. [8]. One can see that our time evolution profiles for the energy and baryon densities agree very well with Ref. [8].

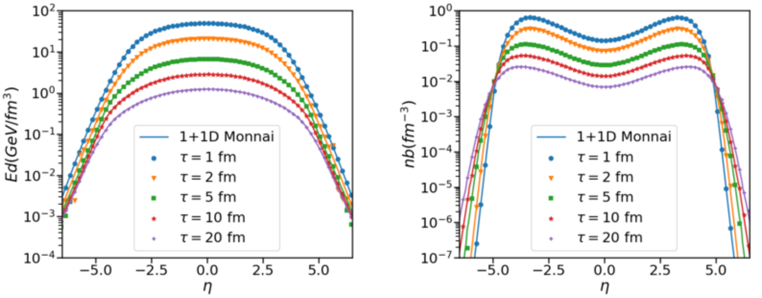

Fig. 2. Time evolutions of energy density e and baryon density n from our CLVisc simulation and Monnai's (1+1)-dimensional hydrodynamics code simulation [8] .

3. Effects of dissipative baryon current

Now we study the effects of baryon diffusion current on the final observables. Here we use the extended CLVisc code to study the particle yields and spectra in Au-Au collisions at 19.6A GeV. Figure 3 shows the pesduorapidity distribution of charged hardons at 0-6% centrality compared to the PHOBOS data [10] and the rapidity distribution of net protons at 0-5% centrality compared to the STAR data [11]. One can see that the pesduorapidity distribution of charged hadrons is insensitive to the baryon diffusion current. In contrast, the rapidity distribution of net protons shows strong sensitivity to the size of baryon diffusion current. Note that the rapidity distribution of net protons is also sensitive to the initial conditions [6].

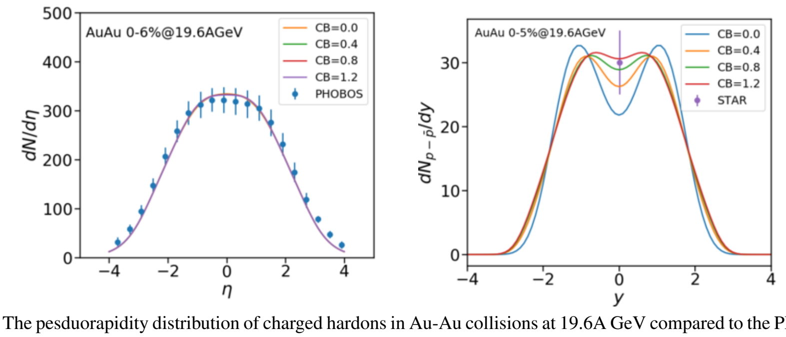

Fig. 3. Left: The pesduorapidity distribution of charged hardons in Au-Au collisions at 19.6A GeV compared to the PHOBOS data [10]. Right: The rapidity distribution of net protons in Au-Au collisions at 19.6A GeV compared to STAR data [11].

Figure 4 shows the p_T spectra of identified particles in Au-Au collisions at 19.6A GeV compared to STAR data [11]. The left figure indicates that the baryon current diffusion has small effect on the p_T spectra

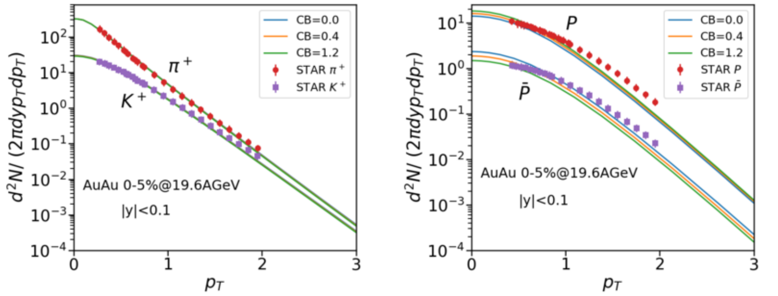

Fig. 4. The p_T spectra of identified particles in Au-Au collisions at 19.6A GeV compared to STAR data [11].

of mesons. The right figure shows that the baryon current diffusion has sizable and opposite effects on the proton and anti-proton spectra. For larger baryon diffusion coefficients, the yield increases for protons while for anti-protons the yield decreases.

4. Conclusions

In this work, we extend the CLVisc hydrodynamic model to include net baryon charge conservation and baryon current dissipation. Using the equation of state from NEOSB, we study the effect of dissipative baryon current on the particle yields and p_T spectra in Au-Au collisions at 19.6A GeV. It is found that the pseudo-rapidity distribution of charged hadrons and the p_T spectra of mesons are not sensitive to the baryon current diffusion. In contrast, the rapidity distribution of net-protons and the p_T spectra of protons and anti-protons have sizeable dependences on the baryon current diffusion. The effects of dissipative baryon current on other observables and in various collision energies will be studied in the future.

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