Dissipative hydrodynamic effects on the quark-gluon plasma at finite baryon density

Akihiko Monnai
Department of Physics, The University of Tokyo
Theoretical Research Division, Nishina Center, RIKEN

Extreme QCD 2012
21st August 2012, George Washington University, DC, USA
Introduction

- Quark-gluon plasma (QGP): many-body system of deconfined quarks and gluons

The QGP created in high-energy heavy ion collisions is quantified as a relativistic fluid with extremely small viscosity.

Net baryon density has been neglected in viscous hydrodynamic analyses.

This talk: viscous hydro + net baryon
Motivation

- "CP asymmetry" of heavy ion collisions

Net baryon is conserved at forward rapidity
- Precision physics including particle identification (p/\bar{p} ratio, etc.)
- Finite-density transport properties

Baryon stopping

Baryon stopping can quantify kinetic energy available for QGP production

mean rapidity loss $\langle \delta y \rangle$
- rapidity of incoming projectile $y_p$
- mean rapidity of net baryon $\langle y \rangle$
Motivation

- Exploring the QCD phase diagram

  - Finite baryon density is a difficult issue in first-principle calculations

  - Hydrodynamics can be a help in the exploration

- Aim of this work

  - Estimate dissipative hydro evolution of net baryon rapidity distribution with viscosities and baryon diffusion

    (1+1)-D expansion is considered because dependence on transverse geometry is small
Dissipative hydrodynamics

- Decomposition of energy-momentum tensor and net baryon current in terms of flow $u^\mu$ in energy frame

\[
T^{\mu\nu} = (e_0 + P_0 + \Pi)u^\mu u^\nu - (P_0 + \Pi)g^{\mu\nu} + \pi^{\mu\nu}
\]
\[
N_B^\mu = n_{B0} u^\mu + V^\mu
\]

3 equilibrium quantities:
- Energy density: $e_0$
- Hydrostatic pressure: $P_0$
- Net baryon density: $n_{B0}$

9 dissipative currents:
- Bulk pressure: $\Pi$
- Shear stress tensor: $\pi^{\mu\nu}$
- Baryon dissipation current: $V^\mu$

- Naive interpretation of the dissipative processes
  - bulk viscosity: response to expansion
  - shear viscosity: response to deformation
  - baryon dissipation: response to chemical gradients
Dissipative hydrodynamics

- Relativistic hydrodynamic equations

Conservation laws \( \partial_{\mu} T^{\mu\nu} = 0 \) \( \partial_{\mu} N_{B}^{\mu} = 0 \)

The law of increasing entropy \( \Rightarrow \) Constitutive equations

\[
\Pi = -\zeta \nabla_{\mu} u^{\mu} - \xi \delta_{e} D \frac{1}{T} + \xi \delta_{B} \frac{D_{B}^{\mu}}{T} - \tau_{\Pi} D \Pi + \chi_{\Pi}^{a} \Pi D \frac{D_{B}^{\mu}}{T} + \chi_{\Pi}^{b} \Pi D \frac{1}{T} + \chi_{\Pi}^{c} \Pi \nabla_{\mu} u^{\mu}
\]

\[
+ \chi_{\Pi}^{a} V_{\mu} \nabla_{\mu} \frac{D_{B}^{\mu}}{T} + \chi_{\Pi}^{b} V_{\mu} \nabla_{\mu} \frac{1}{T} + \chi_{\Pi}^{c} V_{\mu} D u^{\mu} + \chi_{\Pi}^{d} \nabla_{\mu} V_{\mu} + \chi_{\Pi} \nabla_{\mu} \nabla^{\mu} u^{\nu}
\]

\[
V^{\mu} = \kappa_{V} \nabla_{\mu} \frac{D_{B}^{\mu}}{T} - \kappa_{V} \nabla \left( \frac{1}{T} D u^{\mu} + \nabla_{\mu} \frac{1}{T} \right) - \tau_{V} \Delta_{\mu\nu} D V_{\nu} + \chi_{V}^{a} V^{\mu} \frac{D_{B}^{\mu}}{T} + \chi_{V}^{b} V^{\mu} D \frac{1}{T}
\]

\[
+ \chi_{V}^{c} V^{\mu} D u^{\mu} + \chi_{V}^{d} \nabla_{\mu} \nabla_{\nu} u^{\mu} + \chi_{V, \Pi}^{a} \nabla_{\mu} \nabla_{\nu} u^{\mu} + \chi_{V, \Pi}^{b} \nabla_{\mu} \nabla_{\nu} \frac{1}{T} + \chi_{V, \Pi}^{c} \nabla_{\mu} D u^{\mu} + \chi_{V, \Pi}^{d} \frac{1}{T}
\]

\[
\pi^{\mu\nu} = 2\eta \nabla^{\mu} u^{\nu} - \tau_{\pi} D \pi^{\mu\nu} + \chi_{\pi} \Pi D \nabla^{\mu} u^{\nu} + \chi_{\pi} \nabla_{\mu} \pi^{\mu\nu} D \frac{1}{T} + \chi_{\pi} \nabla_{\mu} \pi^{\mu\nu} D \frac{1}{T} + \chi_{\pi} \nabla_{\mu} \nabla_{\nu} u^{\rho}
\]

\[
+ \chi_{\pi} D \nabla_{\mu} \nabla_{\nu} u^{\rho} + \chi_{\pi, V}^{a} V^{\mu} \nabla_{\nu} \frac{1}{T} + \chi_{\pi, V}^{b} V^{\mu} \nabla_{\nu} \frac{1}{T} + \chi_{\pi, V}^{c} V^{\mu} D u^{\nu} + \chi_{\pi, V}^{d} \nabla_{\mu} V^{\nu}
\]
Model input for hydro

- **Equation of state**: Lattice QCD with Taylor expansion

\[
\frac{P(T, \mu_B)}{T^4} = \frac{P(T, 0)}{T^4} + \frac{\chi_B^{(2)}(T, 0)}{2} \left( \frac{\mu_B}{T} \right)^2 + \mathcal{O} \left( \frac{\mu_B}{T} \right)^4
\]

- **Transport coefficients**: AdS/CFT + phenomenology

  - Shear viscosity: \( \eta = s / 4\pi \)
  - Bulk viscosity: \( \zeta = 5 \left( \frac{1}{3} - c_s^2 \right) \eta \)
  - Baryon dissipation: \( \kappa_V = \frac{c_V}{2\pi} \left( \frac{\partial (\mu_B)}{\partial n_B} \right)^{-1} \)

- **Initial conditions**: Color glass theory

  - Energy density: MC-KLN
  - Net baryon density: Valence quark dist.
Results

- Net baryon rapidity distributions at RHIC and LHC

- Hydrodynamic evolution carries the net baryon number to forward rapidity
- Effects of viscosities and dissipation are visible at RHIC
Results

Mean rapidity loss at RHIC

Mean rapidity loss \( \langle \delta y \rangle = y_p - \langle y \rangle \)

\[ \langle y \rangle = \int_{y_p}^{0} y \frac{dN_{B-B}(y)}{dy} dy / \int_{0}^{y_p} \frac{dN_{B-B}(y)}{dy} dy \]

Initial loss (RHIC): \( \langle \delta y \rangle = 2.67 \)

Ideal hydro: \( \langle \delta y \rangle = 2.09 \)

Viscous hydro: \( \langle \delta y \rangle = 2.16 \)

Dissipative hydro: \( \langle \delta y \rangle = 2.26 \)

- Transparency of the collision is effectively enhanced in hydrodynamic evolution

More kinetic energy is available for QGP production
Discussion

- New result from LHC (QM 2012)

CMS PRELIMINARY

More transparent initial conditions are preferred

Note: a different observable

$$\langle \delta y \rangle_E = \frac{2}{E_N N_{\text{part}}} \int_{-\infty}^{y_{\text{beam}}} y \frac{dE}{dy'} dy'$$
Results

- Thermo-diffusion effect (a.k.a. Soret effect)

\[ V^\mu = \kappa_V \nabla^\mu \frac{\mu_B}{T} - \kappa_{VV} \left( \nabla^\mu \frac{1}{T} + \frac{1}{T} D u^\mu \right) \]

at the linear order

- The cross coefficient can be either positive or negative

- Baryon dissipation can be induced by thermal gradients (and acceleration)

- The effect of the cross coupling is likely to be small in high-energy collisions

because of the matter-antimatter symmetry

\[ V^\mu(\mu_B) = -V^\mu(-\mu_B) \] which leads to \( \kappa_{VV}(\mu_B = 0) = 0 \)
Summary and outlook

- Dissipative hydrodynamic model is developed at finite baryon density for the first time
  - Net baryon distribution is widened in hydrodynamic evolution
  - Transparency of the collision is effectively enhanced
  - More kinetic energy may be available at QGP production in early stage
  - Results are sensitive to baryon diffusion coefficient
  - Ambiguities remain in the initial condition, but the distribution has important information

- Future prospects include:
  - Estimation of transverse expansion, inclusion of more realistic transport coefficients, etc.
The end

- Thank you for listening!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/