Quark contribution for center domain in heavy ion collisions†

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The quark-gluon plasma (QGP) is characterized by large color opacity and near-perfect fluidity in high-energy heavy ion experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). While hydrodynamic analyses have been quite successful in quantitative description of the hot media[1)], there are continuing debates on the origin of fluidity. It is recently proposed that center domain structure can be the key to the problem[2)]. QCD has SU(3) symmetry, and the Polyakov-loop potential has three minima in the QGP phase. Since the color glass condensate, a description of pre-collision state, implies that the typical correlation length on the transverse plane is characterized by the inverse of saturation scale in heavy ion collisions, a domain structure can appear in the hot medium. This indicates a short mean free path as the domains are separated by energy barrier.

In the present work, we introduce quark contribution to the center domain picture[3)]. We consider the gluon and quark perturbative one-loop effective potentials:

$$F_g = \frac{2\pi^2 T^4}{3} \sum_{a,b} \left(1 - \frac{\delta_{ab}}{3}\right) B_4(|q_a - q_b|_{\mathrm{mod}\ 1}), \quad (1)$$

$$F_f = -\frac{4\pi^2 N_f T^4}{3} \sum_a B_4\left(\left|q_a + \frac{1}{2}\right|_{\mathrm{mod}\ 1}\right), \quad (2)$$

where T is temperature, a and b are color indices, B_4 is the forth Bernoulli polynomial, N_f is the number of flavors. q_a is defined by the classical part of the time-like component of the vector potential $(A_4^{cl})^{ab} = (2\pi T/g) q_a \delta^{ab}$, where g is the gauge coupling.

The overall effective potential[4)] is shown in Fig. 1. One can see that the three minima have the same free energy in the pure gauge case while imbalance is induced as the number of flavors increases. We label the three states as $\nu = 0$, 1 and 2 corresponding to the fact that Polyakov loop at the minima can be written as $\Phi = \exp(2\pi i\nu/3)$ in the high temperature limit.

The emergence of the stable ($\nu = 0$) and the metastable ($\nu = 1, 2$) states is important because pressure imbalance among the domains can lead to longer mean free path. Schematic pictures of parton scattering with different number of flavors/temperatures are summarized in Fig. 2; (a) In the pure gauge system, the typical mean free path is characterized by the domain size. (b) When the system has small number of flavors, the stable domains expand while the metastable ones shrink, leading to the longer mean free path on average. (c) Domain percolation can occur as the temperature further increases. (d) Finally, the metastable states vanish completely and the system can become weakly coupled above the topological critical temperature defined as $T_{\mathrm{cri}} = T(P_1 = P_2 = 0)$ where P_ν is the pressure. The increase in shear viscosity from RHIC to LHC temperatures is roughly estimated as ~ 1.5-1.6 in our model, which is in agreement with the hydrodynamic implication from experimental data ~ 1.7[5)].

We developed a model that can provide a bridge from hydrodynamic to perturbative QCD pictures. A new critical temperature is proposed, which implies that the medium can suddenly lose fluidity in heavy ion collisions of very high energies. Future prospects include investigation on the system size dependence.

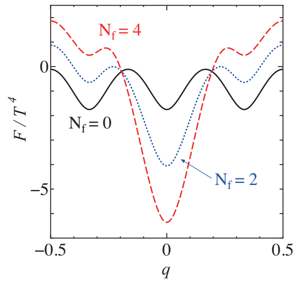

Fig. 1. Dimensionless effective potentials as a function of q for the number of flavors $N_f = 0$, 2 and 4.

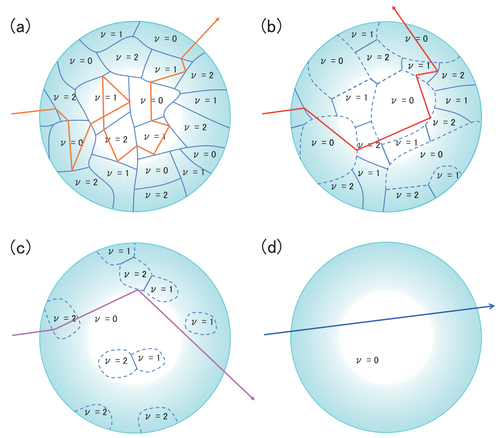

Fig. 2. Schematic pictures of the N_f dependence of the center domain structure and parton scattering.

† Condensed from the article in Phys. Rev. D 89, 011501(R) (2014)

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