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Heavy-Quark Diffusion Dynamics in Quark-Gluon Plasma under Strong Magnetic Fields

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Abstract

We discuss heavy-quark dynamics in the quark-gluon plasma under a strong magnetic field induced by colliding nuclei. By the use of the diagrammatic resummation techniques for Hard Thermal Loop and the external magnetic field, we show analytic results of heavy-quark diffusion coefficient and drag force which become anisotropic due to the preferred spatial orientation in the magnetic field. We argue that the anisotropic diffusion coefficient gives rise to an enhancement/suppression of the heavy-quark elliptic flow depending on the transverse momentum.

Keywords:
Quark-gluon plasma, Heavy-quark diffusion, Strong magnetic fields

1. Introduction

In the relativistic heavy-ion collisions, the heavy quarks are dominantly produced in the initial hard scatterings among the partons from the colliding nuclei, and thus will serve as a probe of the dynamics in the QGP phase and the initial stage. This is because the thermal excitation is suppressed due to the large value of the heavy-quark mass compared to the temperature of the quark-gluon plasma (QGP).

In the RHIC and LHC experiments, the nuclear modification factor R_{AA} and the anisotropic spectrum v_2 of the open heavy flavors have been measured. Both of them are thought to be sensitive to the heavy-quark thermalization, and are closely related to each other in the diffusion dynamics [1]. However, a consistent theoretical modelling, which simultaneously reproduces R_{AA} and v_2, is sill under investigation.

In this contribution, we discuss effects of an extremely strong magnetic field on the heavy-quark diffusion dynamics in QGP. The strong magnetic field is induced by the highly accelerated incident nuclei, and its magnitude of the magnetic field is estimated to be of the order of pion mass square or even larger (see Ref. [2] and references therein). This magnetic field

[1] Speaker in the conference.

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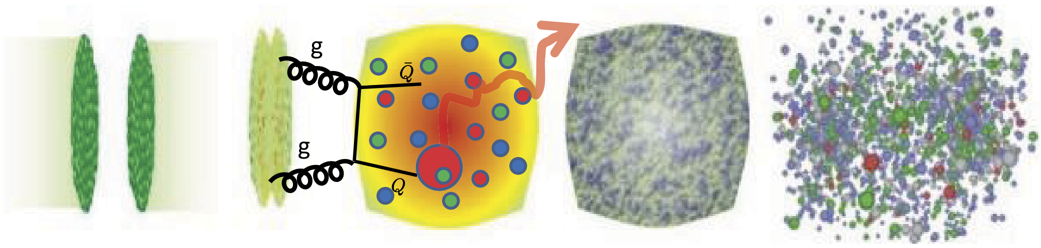

Figure 1: Brownian motion of heavy quarks created by the initial hard processes.

is so strong that the motion of thermal light quarks in QGP are strongly modified. Based on the Langevin equation for the Brownian motion of the heavy quarks (see Fig. 1), we investigate how this modification of the thermal excitation in QGP is reflected in the spectra of open heavy flavors [3]. The heavy-quark diffusion coefficient is computed by mean of the resummation techniques for Hard Thermal Loop and the strong external magnetic field. We will find that the heavy-quark diffusion coefficient becomes anisotropic, and argue that the anisotropic heavy-quark flow can be generated even before the full development of the background fluid flow in the initial stage of the heavy-ion collisions.

2. Modelling by Langevin equations

When the heavy quark is subject to the random kicks by the thermal particles, the heavy quark dynamics is modelled as a Brownian motion [1], which is described by the Langevin equations[2]:

$$\frac{dp_z}{dt} = -\eta_{\parallel} p_z + \xi_z \,, \qquad \frac{d\boldsymbol{p}_\perp}{dt} = -\eta_\perp \boldsymbol{p}_\perp + \boldsymbol{\xi}_\perp \,. \quad (1)$$

Since the external magnetic field provides a preferred spatial direction, we have a set of two equations for the heavy-quark motion, parallel and perpendicular to the magnetic field that is oriented in the z-direction.

The random forces are assumed to be white noises,

$$\langle \xi_z(t)\xi_z(t')\rangle = \kappa_{\parallel}\delta(t-t') \,, \quad (2a)$$

$$\langle \xi^i_\perp(t)\xi^j_\perp(t')\rangle = \kappa_\perp\delta^{ij}\delta(t-t') \quad (i,j=x,y) \,, \quad (2b)$$

and these coefficients, $\kappa_{\parallel}$ and $\kappa_\perp$, are related to the drag coefficients, $\eta_{\parallel}$ and $\eta_\perp$, through the fluctuation-dissipation theorem as

$$\eta_{\parallel} = 2M_Q T\kappa_{\parallel} \,, \quad \eta_\perp = 2M_Q T\kappa_\perp \,. \quad (3)$$

[2]In another contribution talk in the conference [4, 5], the authors discussed the Lorentz force exerting on the heavy quark with the inclusion of the Lorentz force in the Langevin equation (1).

At the leading order in g_s, the anisotropic momentum diffusion coefficients, $\kappa_{\parallel}$ and $\kappa_\perp$, are defined by

$$\kappa_{\parallel} = \int d^3\boldsymbol{q}\, \frac{d\Gamma(\boldsymbol{q})}{d^3\boldsymbol{q}}\, q_z^2 \,, \quad (4a)$$

$$\kappa_\perp = \frac{1}{2}\int d^3\boldsymbol{q}\, \frac{d\Gamma(\boldsymbol{q})}{d^3\boldsymbol{q}}\, \boldsymbol{q}_\perp^2 \,. \quad (4b)$$

where q is the amount of the momentum transfer from the thermal particles to the heavy quark, and the static limit ($q^0 \to 0$) is assumed in the above definitions. In the next section, we show perturbative computation of these transport coefficients in the hot medium and the strong magnetic field.

3. Diffusion coefficients in strong magnetic fields

We compute the diffusion coefficients defined in Eqs. (4a) and (4b). At the leading order, contributions to the momentum transfer rate $\frac{d\Gamma(\boldsymbol{q})}{d^3\boldsymbol{q}}$ come from Coulomb scatterings. In the diagrams shown in Fig. 2, effects of the magnetic field appear in two places (highlighted by red): (i) the Debye screening mass and (ii) the dispersion relation of the thermal-quark scatterers. On the other hand, the gluons are not directly coupled to the magnetic field, so that the modification of their dispersion relation is negligible at the leading order.

In a strong magnetic field, the fermion wave function is strongly squeezed along the magnetic field, corresponding to the small cyclotron radius. Indeed, from the Landau level quantization and the Zeeman effect, the fermions in the lowest Landau level (LLL) have the (1+1) dimensional dispersion relation, i.e., $\epsilon^2 = m^2 + p_z^2$ for massive fermions and $\epsilon = \pm p_z$ for massless fermions with right and left handed chiralities. To be specific, we focus on the strong-field regime such that the transition from the LLL to the hLL states are suppressed according to a hierarchy $T^2 \ll eB$.

(i) First, we compute the Debye screening mass. In the LLL, the gluon self-energy is completely factorized