Transport coefficients of quark-gluon plasma in strong magnetic field

H. -U. Yee[*1,*2]

The quark-gluon plasma (QGP) created in relativistic heavy-ion collisions is subject to a strong magnetic field produced by heavily charged projectiles, whose scale is comparable to the temperature of the plasma. The question whether the magnetic field stays long enough to be able to induce interesting effects, such as chiral magnetic effect, on the plasma observables can be answered by realistic simulations of magneto hydrodynamics (MHD) that are planned, for example, in the Beam Energy Scan Theory collaboration (BEST). One of the key parameters in MHD simulations is electric conductivity, that should be rotationally asymmetric due to the magnetic field. Other key transport coefficients of the magnetized QGP that affect high energy probes such as jets and heavy quarks include jet quenching parameter $\hat{q}$ and heavy quark momentum diffusion constant κ. We report our attempts on computing them in complete leading order of perturbative QCD[1–3], and for some cases, also in strong coupling by AdS/CFT correspondence[2].

We work in the perturbative regime of $\alpha_s eB \ll T^2 \ll eB$, where the first inequality turns out to be essential to have a consistent Hard Thermal Loop (HTL) power counting scheme, and the second inequality brings us a simplification of working in the lowest Landau level (LLL) approximation for the quarks[1]. The LLL quarks are effectively 1+1 dimensional and carry only longitudinal currents flowing along the magnetic field direction. Their thermal density is $\sim (eB)\times T$, a product of transverse and longitudinal density of states, that dominates over the thermal density of hard gluons $\sim T^3$. This implies that the dominant HTL self-energy for gluons comes from the 1-loop LLL hard quark contribution that is of order $\Sigma \sim \alpha_s eB$, which sets a scale of dynamical screening $m_D^2 \sim \alpha_s eB$. Since $m_D^2 \ll T^2$ due to our assumption, hard particles of typical momentum T keep their free dispersion relation at leading order, while the soft gluons that are exchanged in infrared-sensitive scattering processes should include re-summation of HTL self-energy Σ: this gives us a consistent HTL power counting scheme we use for our leading order computations[1].

Electric conductivity in a magnetized plasma is asymmetric, with longitudinal conductivity being dominant over transverse one due to 1+1 dimensional nature of LLL states. Since the transverse dynamics is intrinsically quantum, we can use a semi-classical picture of kinetic theory of LLL quarks valid in leading order computation for only longitudinal conductivity[3]. In a massless quark limit, neglecting higher order effects from QCD sphalerons, the chiral anomaly dictates that a parallel electric and magnetic field imply a diverging longitudinal electric current, and hence an infinite longitudinal conductivity. The key dynamics taming this is the axial charge relaxation with the rate $\gamma_A \sim \alpha_s m_q^2/T$, and the longitudinal conductivity is parametrically given as $\sigma_L \sim e^2(eB)^2/(\chi\gamma_A)$ where χ is the charge susceptibility which grows linearly in B in LLL approximation $\chi \sim (eB)$, giving us an estimate[3] $\sigma_L \sim e^2(eB)T/(\alpha_s m_q^2)$. Our detailed computation reveals that the leading process in the collision term in the effective kinetic theory is 1-to-2 gluon decay into quark-antiquark pair and vice versa: $g \leftrightarrow q+\bar{q}$, which results in $\sigma_L \sim e^2(eB)T/(\alpha_s m_q^2 \log(T/m_q))$ in $m_q/T \ll 1$ limit.

For the heavy quark momentum diusion constant[1] and the jet quenching parameter[2], we compute them for both transverse and longitudinal directions with respect to magnetic field: $\kappa_{\perp,\parallel}$ and $\hat{q}_{\perp,\parallel}$. The leading order process is the t-channel 2-to-2 scatterings of heavy quark/energetic jet with hard LLL quarks via soft gluon exchange, that are enhanced by infrared divergence tamed by the HTL self-energy Σ. This is true for $\kappa_\perp$ and $\hat{q}_{\perp,\parallel}$, giving us the results of $\kappa_\perp \sim \alpha_s^2(eB)T\log(1/\alpha_s)$, $\hat{q}_\perp \sim \alpha_s^2(eB)^{\frac{3}{2}} + \alpha_s^2(eB)T\log(T^2/\alpha_s eB)$ and $\hat{q}_\parallel \sim \alpha_s^2(eB)T\log(1/\alpha_s)$, respectively. It should be noted that $\hat{q}_\perp$ does not vanish even at zero temperature: this is because a QCD gluon field from a jet can create a LLL quark-antiquark pair from the vacuum, which is consistent with 1+1 dimensional kinematics of LLL states[2]. The physics is similar to the Schwinger mechanism of pair creation.

However, the longitudinal momentum diffusion $\kappa_\parallel$ turns out to vanish at this order in massless quark limit due to 1+1 dimensional kinematics of LLL states[1]: only a light-like, longitudinal exchanged momentum is possible, $q^0 = \pm q^3$, and since κ is proportional to the static gluon spectral density at $q^0 = 0$, a longitudinal momentum transfer vanishes. The first non-vanishing contribution comes either from the t-channel scatterings with hard gluons or the effect of a finite quark mass m_q, the former being $\kappa_\parallel \sim \alpha_s^2 T^3 \log(1/\alpha_s)$ and the latter $\kappa_\parallel \sim \alpha_s(\alpha_s eB)^{\frac{1}{2}} m_q^2$, respectively[1].

References
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*1 Department of Physics, University of Illinois
*2 RIKEN Nishina Center