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Lower bound of quark relaxation time and its conduction at finite magnetic field

Cho Win Aung[1], Thandar Zaw Win[1], Sabyasachi Ghosh[1]

[1]Indian Institute of Technology Bhilai, GEC Campus, Sejbahar, Raipur 492015, Chhattisgarh, India

Abstract

We have calculated microscopically electrical conductivity of massless quark matter by using relaxation time approximation of kinetic theory framework. The lowest possible quark relaxation time, tuned from the quantum lower bound of η/s for massless matter, is used to obtain its corresponding electrical conductivity $\sigma/T = 0.0135$. By comparing with earlier existing numerical values of electrical conductivity, we marked roughly $(0.25 - 15) \times 0.0135$ as strongly and beyond 20×0.0135 as weakly quark gluon plasma domain.

Introduction

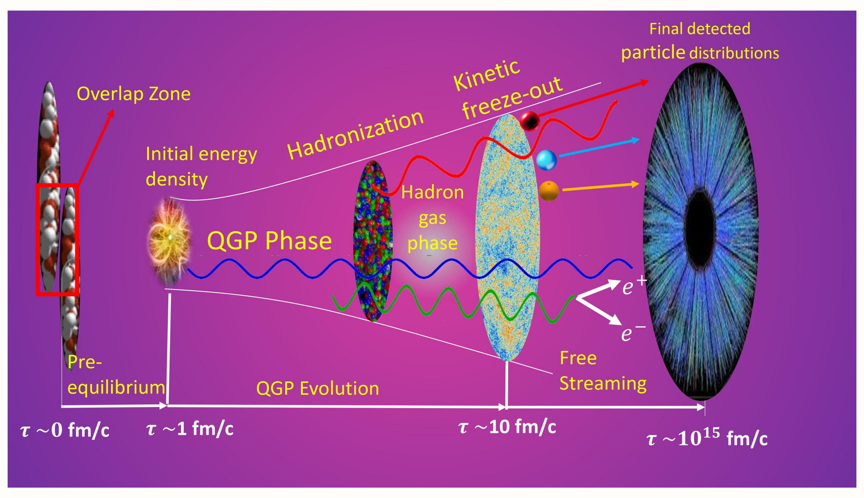

Figure 1: Heavy ion collision, QGP formation and its evolution

- Huge magnetic field produced in heavy ion collisions (HIC) has m_π^2 in RHIC energy and $10m_\pi^2$ in LHC energy that will decay with time Refs. [1, 2, 3].
- The decay time with respect to QGP life time decides whether QGP face strong [1] or weak [2, 3] magnetic field.
- The electrical conductivity of QGP controls the decay profile [1].
- The shear relaxation time scale (τ_c) can be expected to be close to its lower bound $\tau_c = 5/(4\pi T)$ (massless QGP) as η/s of QGP is experimentally expected to be close to its quantum lower bound. $\eta/s = 1/(4\pi)$.
- So present work has explored its numerical values from different microscopic models and their corresponding effective relaxation time scales and the numerical bands of the electric charge relaxation time scale in terms of the lower bound of shear relaxation time.

Framework

- The dissipative current density J_D due to external electric field $\tilde{E}$ in microscopic relation

$$J_D^i = g\sum_{u,d} e_Q \int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{p^i}{E}\delta f_\sigma \,, \qquad (1)$$

where $g = 12$ (total degeneracy factor of quark, spin, particle-anti-particle and color)

- The δf is the deviation from equilibrium distribution function $f_0 = 1/[\exp(\beta E) + 1]$.
- Relaxation time approximation(RTA) of Boltzmann transport equation,

$$e_Q\tilde{E}^i\frac{\partial f}{\partial p^i} = -\frac{\delta f}{\tau_c}, \qquad (2)$$

$$\delta f = \Big[e_Q\big(\frac{p^i}{E}\big)\tau_c\beta f_0(1-f_0)\Big]\tilde{E}_i \,. \qquad (3)$$

- The Eq.(1) becomes

$$J^i = g\sum_{u,d}\int e_Q^2\frac{d^3\mathbf{p}}{(2\pi)^3}\frac{p^ip^j}{E^2}\tau_c\beta f_0(1-f_0)\tilde{E}_j \,. \qquad (4)$$

- Comparison with the macroscopic description, J^i,

$$\sigma = \frac{g}{T}\sum_{u,d} e_Q^2\int\frac{d^3\mathbf{p}}{(2\pi)^3}\frac{p^2}{3E^2}\tau_c f_0(1-f_0) \,. \qquad (5)$$

Result and discussions

- Massless limit $E = p$ in Eq. (5) [4]

$$\sigma = \frac{10}{27}\,e^2\tau_c T^2, \qquad (6)$$

- Lower bound of η/s for that medium and lower bound of relaxation time[4],

$$\frac{\eta}{s} = \frac{\tau_c T}{5} = \frac{1}{4\pi}, \Longrightarrow \tau_c = \frac{5}{4\pi T}. \qquad (7)$$

- The conductivity

$$\sigma(T) = \frac{25}{54}\frac{e^2}{\pi}T \approx 0.0135T \,. \qquad (8)$$

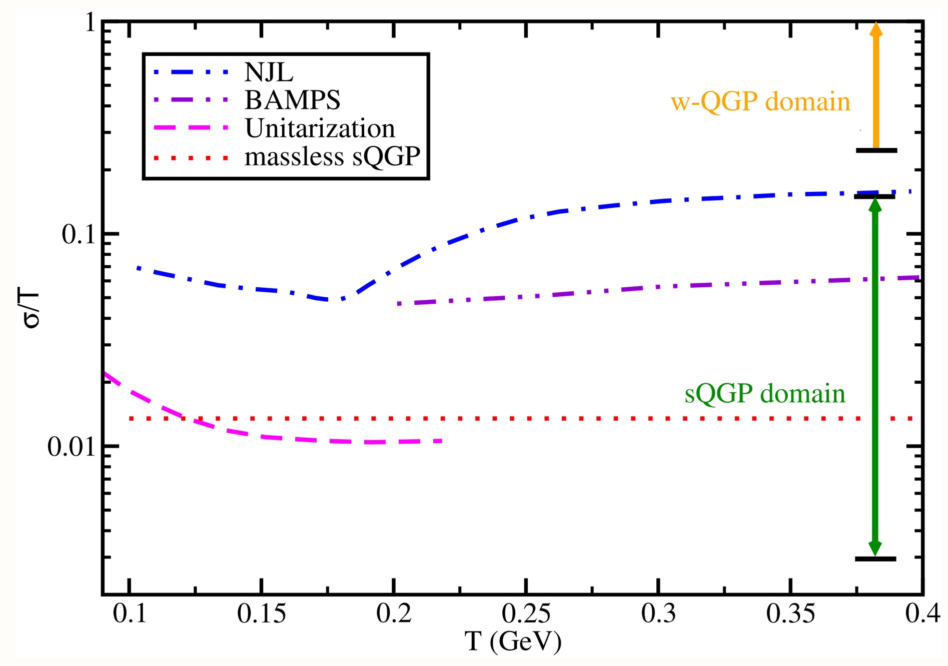

Figure 2: Normalised conductivity of different estimations with temperature, based on NJL (blue dash-dotted line), BAMPS (violet dash-double dotted line) and uniterization (pink dash line) with respect to the massless sQGP estimation (red dotted line)

- We assumed $\sigma/T = 0.0135$ as lowest reference point, plotted it by red dotted line marking as sQGP.
- The results of σ/T from Refs.[5] , [6] , [7] covers a large numerical band of electrical conductivity.
- In Ref. [5](the transport quark model), its estimated values $\approx$ 5 times the massless sQGP values.
- In Ref. [6](an effective QCD model), its values are in the range 5-15 times larger than 0.0135.
- Hadronic conductivity estimation, based on unitarization methodology, is close to 0.0135.
- LQCD calculations [10] provides 0.003 to 0.015.
- It means that 4 times smaller than 0.0135 should have to be considered also within the numerical band of σ/T.
- The numerical band of σ/T from 0.003 to 0.2 might be considered as sQGP domain for electrical conductivity because weakly QGP (w-QGP) estimation from perturbative QCD (pQCD) calculation [8, 9] provides more than 20 times larger values of η/s with respect to its quantum lower bound $1/(4\pi) \approx 0.08$.
- τ_c may be larger than $25/(\pi T)$ and using that relaxation time range for electrical conductivity, one can expect $\sigma/T \geq 20\times 0.0135$ as wQGP domain.
- Our exploration of sQGP and wQGP domain of σ/T might be very important information for decay profile of magnetic field.

Summary and conclusions

- Microscopically electrical conductivity of massless quark matter have been calculated.
- The lowest possible relaxation time for massless matter is derived from quantum lower bound of η/s.
- Electric charge transportation in terms of that quantum bound. $\sigma/T = 0.0135$ might be considered as a reference point for charge transportation of QGP.
- LQCD estimations of σ/T can be 4 times smaller to 3 times larger than 0.0135 by comparing with earlier existing numerical values.
- The ratio may go up to 15 times larger than 0.0135 from earlier model calculations like NJL, BAMPS, and unitarization.
- So we may assign roughly $\sigma/T = (0.25 - 15) \times 0.0135$ as sQGP domain.
- Since earlier perturbative QCD calculation by Arnold et. al. indicate 20×0.0135 and, beyond this range, it can be considered as wQGP domain.
- These strongly and weakly interacting domains of σ will be very important inputs to investigate the decay profile of magnetic field in HIC experiments.

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