Electrical and thermal conductivities in a hadron resonance gas with van der Waals interactions

Kshitish Kumar Pradhan, Dushmanta Sahu, Ronald Scaria, and Raghunath Sahoo
Department of Physics, Indian Institute of Technology Indore, Simrol, Indore 453552, INDIA

Introduction

Transport properties play a crucial role in determining the dynamical evolution of the system produced in ultra-relativistic heavy ion collisions. With the advantage of being calculated from first principles, their dependencies on system parameters like temperature and chemical potential can help us locate the phase transition boundary in the QCD phase diagram. In the context of hydrodynamical models, which have been used to describe the particle spectra of hadrons emerging out of the heavy-ion collisions, the dissipative effects of the medium becomes evident through the transport coefficients, such as shear and bulk viscosities, etc.

In the non-central heavy ion collisions, on account of a large number of spectators which do not participate in the collisions and continue to travel along the beam trajectories, large electric and magnetic fields are expected to be produced. Analysis indicates the value of magnetic and electric fields at RHIC to be of the order of eB $\approx m_\pi^2 \approx 10^{18}$ G and eE $\approx m_\pi^2 \approx 10^{21}$ V/cm [1]. The magnetic field produced in the heavy ion collisions was earlier believed to decay instantaneously. However, the decrease in magnetic field induces an electric current which opposes the decrease of the magnetic field. This can be quantified through a parameter known as electrical conductivity. Along with the electrical conductivity, thermal conductivity plays a crucial role in the hydrodynamic evolution of the system in heavy ion collisions. It involves the relative flow of energy and is thus an important parameter to be studied in highly baryon reach environments.

The lattice QCD approach is an effective tool in studying the QCD thermodynamics. According to these studies, there exist a smooth crossover transition from hadronic matter to the quark-gluon plasma (QGP) at finite temperature and vanishing baryon chemical potential. The ideal Hadron resonance gas (HRG) model, which is used to describe the hadronic phase of the medium is able to reproduce the lattice QCD data at low temperatures. However, this model fails at high temperatures. Here comes the importance of the interactions between particles within the hadron gas. It is found that an interacting HRG model, the van der Waals (VDW) HRG model, including both attractive and repulsive interaction, is able to describe lattice QCD data even near the crossover region [2]. This VDW HRG model can also be helpful in exploring baryon-rich environments.

Formulation

In this work, we have considered an extension to the ideal HRG model by considering the VDW interaction among the hadrons. The meson-meson and (anti)baryon-(anti)baryon VDW interaction is considered where all other interactions are neglected [2]. We then calculated the transport properties, such as electrical and thermal conductivity, using the Boltzmann transport equation (BTE) in the relaxation time approach (RTA). Considering f_i^0 as the equilibrium distribution function and $E_i = \sqrt{p^2 + m_i^2}$ as the energy of the i^{th} hadron, $'m'$ being the mass of each hadron; The final expression for the electrical and thermal conductivities are respecticely [3],

$$\sigma_{el} = \frac{1}{3T} \sum_i g_i \tau_i q_i^2 \int \frac{d^3p}{(2\pi)^3} \frac{\mathbf{p^2}}{E_i^2} \times f_i^0, \quad (1)$$

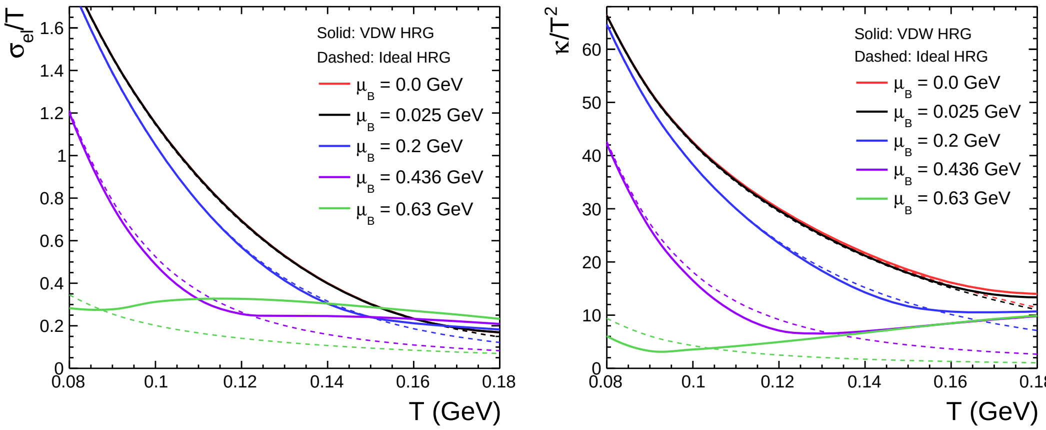

FIG. 1: (Color Online) Scaled electrical conductivity (left) and thermal conductivity (right) is plotted as a function of temperature for different baryon chemical potential under both HRG and VDWHRG scenarios [3].

and

$$\kappa = \frac{1}{3T^2}\sum_i g_i\tau_i \int \frac{d^3p}{(2\pi)^3}\frac{\mathbf{p^2}}{E_i^2}\left(E_i - \frac{t_i\omega}{n}\right)^2 \times f_i^0, \tag{2}$$

where g_i, q_i, τ_i and t_i are the degeneracy, charge, avg. relaxation time and baryonic charge of the i^{th} hadronic species, respectively. n is the number density, and ω is the enthalpy of i^{th} hadronic species. The number density, relaxation time, and enthalpy, etc., are modified from the ideal one on account of VDW interaction.

Results and discussion

We have explored the dependence of electrical and thermal conductivities on temperature and baryon density. In this respect five distinct baryochemical potentials are chosen: $\mu_B = 0.0$ GeV corresponding to LHC energies, $\mu_B = 0.025$ & 0.2 GeV corresponding to RHIC at $\sqrt{s_{NN}} = 200$ & 19.6 GeV, $\mu_B = 0.436$ and 0.630 GeV corresponding to RHIC/FAIR at $\sqrt{s_{NN}} = 7.7$ GeV and NICA at $\sqrt{s_{NN}} = 3$ GeV, respectively [3]. As shown in Fig. 1, both electrical and thermal conductivity decreases with temperature and baryochemical potential. However, when the results from ideal HRG and VDW HRG are compared a finite enhancement in the quantities is observed in VDWHRG model at high temperatures. This is because of the inclusion of attractive interactions along with the repulsive interactions (excluded volume approach). With increasing baryon density, a minima appears, which shifts towards low temperature, indicating a possible first-order liquid-gas phase transition at lower temperatures for high baryon densities.

Summary

In this work, we have studied the conductivities in the VDW HRG model as a function of temperature and baryochemical potential. We found that the VDW interactions impact high baryon densities. Detailed results will be presented.

References

[1] K. Tuchin, Adv. High Energy Phys. **2013**, 490495 (2013).

[2] V. Vovchenko, M. I. Gorenstein and H. Stoecker, Phys. Rev. Lett. **118**, 182301 (2017).

[3] K. K. Pradhan, D. Sahu, R. Scaria and R. Sahoo, [arXiv:2205.03149 [hep-ph]].