Physica A 498 (2018) 10–16

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Transport coefficients of Quark–Gluon plasma with full QCD potential

Prasanth J.P. *, Vishnu M. Bannur

Department of Physics, University of Calicut, 673635, India

HIGHLIGHTS

- The ratio of shear and bulk viscosity to entropy density of QGP are studied.
- Modified Cornell potential is the interaction between the partons.
- Transport coefficients and equation of state are correlated.
- Cluster expansion method in Plasma is used to calculate the Equation of State.
- The results are compared with the lattice QCD results, we get a good fit.

ARTICLE INFO

Article history:
Received 14 November 2017
Received in revised form 12 January 2018

Keywords:
Quark–Gluon plasma
Modified Cornell potential
Cluster expansion method
Shear viscosity
Bulk viscosity

ABSTRACT

The shear viscosity η, bulk viscosity ζ and their ratio with the entropy density, η/s, ζ/s have been studied in a quark–gluon plasma (QGP) within the cluster expansion method. The cluster expansion method allows us to include the interaction between the partons in the deconfined phase and to calculate the equation of state of quark–gluon plasma. It has been argued that the interactions present in the equation of state, the modified Cornell potential significantly contributes to the viscosity. The results obtained within our approaches agree with lattice quantum chromodynamics (LQCD) equation of state. We obtained $\eta/s \approx 0.128$ within the temperature range $T/T_c \in [0.9, 1.5]$ which is very close to the theoretical lower bound $\eta/s \geq 1/(4\pi)$ in Yang–Mills theory. We also demonstrate that the effects of ζ/s at freezeout are possibly large.

1. Introduction

The experimental findings of Relativistic Heavy-Ion Collider (RHIC) at the Brookhaven National Laboratory [1] and ALICE detector at the CERN Large Hadron Collider [2], confirms the "almost perfect fluidity" of the strongly coupled quark–gluon plasma (sQGP). The analysis of elliptic flow based on viscous hydrodynamic model showed that the QGP has a very small value of specific viscosity η/s 0.08–0.24 [3–6] , quite close to the conjectured lower-bound limit $\eta/s \geq 1/(4\pi)$ within the anti-de Sitter/conformal field theory (AdS/CFT) correspondence [7,8]. This suggests that hot QCD matter could be a nearly perfect fluid, i.e, η/s reaches a minimum at near the critical temperature and increases thereafter in the deconfined phase [9,10]. The lattice calculation [11–13] of QCD plasma do support the current estimates.

The role of bulk viscosity of QGP has achieved considerable attention in the late stage of relativistic heavy-ion collisions. The bulk viscosity in the context of the violation of scale invariance in QCD [14,15] is reported. It was found that the bulk viscous coefficient ζ has a prominent peak around the critical region. The effect of bulk viscosity in freeze-out [16,17] and

* Corresponding author.
E-mail address: prasanthjp36@gmail.com (Prasanth J.P).

https://doi.org/10.1016/j.physa.2018.01.023
0378-4371/

in hadronic phase have been reported in [18]. Several calculations of the bulk viscosity in the context of cosmology [19], strange quark matter [20], and neutron stars [21] have been performed.

We focus on the effects of shear viscosity and bulk viscosity in the relativistic heavy-ion collisions, in particular near the transition region. Earlier calculations of the ratio of shear viscosity to the entropy density η/s in the deconfined phase were done in [22], calculated the QCD equation of state using the virial expansion approach [23]. For an application of this formalism to the QGP, the interaction between the quark includes nonperturbative effects from dimension two gluon condensates that describe the free energy of quenched QCD. Instead of virial series expansion, we consider cluster expansion method [24,25]. Mayer's theory of plasma is described by Balescu [26] is used to derive a compact expression for the equation of state of quark–gluon plasma. We use modified Cornell potential [27,28] to take into account the interaction between partons in the QGP.

An imperfection of Mayer's cluster expansion method [24] is that the density should be small so as to satisfy the convergence condition. An equation is derived by Ushcats [29,30] which establish the process of condensation in high density regions and find an equation of state (EoS) for real gas using the Lennard-Jones potential. Quark–gluon plasma phase transition was studied and an EoS derived using the same in [31], where a satisfactory result was obtained for the phase transition and region of condensation of QGP with the modified Cornell potential. A modified generating function for the canonical partition function has been derived in [32]. Using this generating function the author studied the Mayer's theory of virial expansion and condensation at thermodynamic limit. Mayer's theory of plasma is described in [26], where one sums a certain set of infinite diagrams. Going beyond, a generalization of the cluster expansion method was developed in [33,34] to calculate the QCD equation of state. Here we use the cluster expansion method to take into account and present a detailed derivation of the equation of state and hence the entropy density of the QGP at vanishing μ_q. Instead of phenomenological models like quasi-particle models [35,36], the cluster integral in the cluster expansion method includes the interaction potential between the partons.

The interaction between the partons is described by modified Cornell potential [27,28], which incorporates the screened color-Coulomb potential and the screened linear potential [37]. The well-known Cornell potential (or the funnel potential),

$$V = -\frac{\alpha}{r} + \lambda r \tag{1}$$

contains the perturbative expectation plus an additional linear term. λ is the string tension, and $\alpha = \frac{4\alpha_s}{3}$, α_s is the strong coupling constant of the color-Coulomb potential. Here the modified Cornell potential is considered,

$$V = V_Y + V_L \tag{2}$$

where V_Y is the screened Coulomb potential (or the Yukawa potential), V_L is the screened confinement potential.

$$V(r,T) = -\frac{\alpha}{r}e^{(-m_D r)} + \frac{\lambda}{m_D}\left[1 - e^{(-m_D r)}\right] \tag{3}$$

where $m_D(T) = \left[1 + \frac{N_f}{6}\right]^{1/2} g(T)T$ is the Debye mass and is temperature dependent. When the temperature rises, λ decreases. Above the critical temperature T_c the string breaks and the quarks are deconfined.

To calculate the transport coefficients, we use the relativistic extension of the Chapman–Enskog method [38,39]. The Chapman–Enskog approximation features the transport cross section and hence the interaction. A quantitative comparison between the results of shear viscosities from the Chapman–Enskog and relaxation time methods for selected test cases is performed in [40]. This leads to the calculation of transport coefficients in the case of the QGP. From the modified Cornell potential we have directly extracted the effective coupling α_V to be employed for the determination of the transport cross section which enters the transport coefficients η and ζ.

2. EoS using cluster expansion method

Mayer's theory of plasma is described in [26]. The pressure is given

$$\frac{P}{T} = \sum_{i=1}^{N} n_i + D - \sum_{i\geq 1}^{N} n_i \frac{\partial D}{\partial n_i} \tag{4}$$

in natural units. For gluons let the number density n_i be represented by n_g, for quarks and the antiquarks n_q, $n_{\bar{q}}$ respectively. D is the sum over all clusters.

$$D = \frac{1}{4\pi^2}\int_0^\infty l^2 dl \left[\frac{(-\kappa^2 V_l)^2}{2} + \frac{(-\kappa^2 V_l)^3}{3} + \ldots\right] \tag{5}$$

The inverse Debye length squared varies as,

$$\kappa^2 = \frac{n_g}{T}, \tag{6}$$