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Nuclear Physics A 934 (2015) 133–147

NUCLEAR PHYSICS A

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Bulk and shear viscosities of hot and dense hadron gas

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Received 29 September 2014; received in revised form 12 December 2014; accepted 12 December 2014

Abstract

We estimate the bulk and the shear viscosity at finite temperature and baryon densities of hadronic matter within a hadron resonance gas model which includes a Hagedorn spectrum. The parameters of the Hagedorn spectrum are adjusted to fit recent lattice QCD simulations at finite chemical potential. For the estimation of the bulk viscosity we use low energy theorems of QCD for the energy momentum tensor correlators. For the shear viscosity coefficient, we estimate the same using molecular kinetic theory to relate the shear viscosity coefficient to average momentum of the hadrons in the hot and dense hadron gas. The bulk viscosity to entropy ratio increases with chemical potential and is related to the reduction of velocity of sound at nonzero chemical potential. The shear viscosity to entropy ratio on the other hand, shows a nontrivial behavior with the ratio decreasing with chemical potential for small temperatures but increasing with chemical potential at high temperatures and is related to decrease of entropy density with chemical potential at high temperature due to finite volume of the hadrons.

Keywords: Hadron resonance gas; Bulk viscosity; Shear viscosity

1. Introduction

Recently, the transport properties of hot and dense matter have attracted a lot of attention in the context of relativistic heavy ion collisions [1] as well as cosmology [2]. Such properties enter in the hydro dynamical evolution and therefore are essential for studying the near equilibrium evolution of a thermodynamic system. In the context of heavy ion collisions, the coefficient of

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http://dx.doi.org/10.1016/j.nuclphysa.2014.12.004

shear viscosity perhaps has been the mostly studied transport coefficient. The spatial anisotropy in a nuclear collision gets converted to a momentum anisotropy through a hydrodynamic evolution. The equilibration of momentum anisotropy is mainly controlled by shear viscosity. The elliptic flow measurement at RHIC led to η/s, the ratio of shear viscosity (η) to the entropy density s, close to $1/(4\pi)$ which is the smallest for any known liquid in nature [3]. Indeed, arguments based on ADS/CFT correspondence suggest that the ratio η/s cannot be lower than this 'Kovtun–Son–Starinets' (KSS) bound [4]. Thus the quark gluon plasma (QGP) formed in the heavy ion collision is the most perfect fluid.

Apart from shear viscosity, the transport coefficient that relates the momentum flux with a velocity gradient is the bulk viscosity. Generally, it was earlier believed that the bulk viscosity does not play any significant role in the hydrodynamic evolution of the matter produced in heavy ion collision experiments. The argument being that the bulk viscosity ζ scales like $\epsilon - 3p$ and therefore will not play any significant role as the matter might be following the ideal gas equation of state. However, in the course of the expansion of the fire ball the temperature can be near the critical temperature T_c where $\epsilon - 3p$ can be large as expected from the lattice QCD simulations [5,6] leading to a large value for the bulk viscosity. This, in turn, can give rise to phenomenon of cavitation when the pressure vanishes and the hydrodynamic description for the evolution breaks down [7]. Indeed, during last couple of years, there have been quite a few attempts to investigate the effects of the bulk viscosity on the hydrodynamic evolution of hot matter following a heavy ion collision and have found effects on particle spectra as well as flow coefficients [8–10]. The interplay of shear and bulk viscosity on the elliptic flow has also been looked into in Ref. [11] as well as more recently in Ref. [12]. Bulk viscosity effects from the hadronic phase on the transverse momentum spectra and elliptic flow have been investigated in Ref. [13]. Further, a large bulk viscosity appears to be essential to explain the flow harmonics in ultra central collisions [14].

There have been various attempts to estimate coefficients of bulk viscosity (ζ) for strongly interacting matter. The rise of bulk viscosity coefficient near the transition temperature has been observed in various effective models of strong interaction. These include chiral perturbation theory [15], quasi particle models [16] as well as Nambu–Jona-Lasinio model [17]. One of the interesting ways to extract this coefficient is using symmetry properties of QCD once one realizes that the bulk viscosity characterizes the response to conformal transformation. This was attempted in Ref. [18]. Based on Kubo formula for ζ and the low energy theorems [19], the coefficients of bulk viscosity get related to thermodynamic properties of strongly interacting system.

It may be noted that, it is also of both practical and fundamental importance to know the transport coefficients in the hadron phase to distinguish the signatures of QGP matter and hadronic matter. The computation of the transport coefficient of the hadronic mixture is not an easy task. There have been various attempts on this field over last few years involving various approximations like relaxation time approximation, Chapman–Enscog as well as Green Kubo approach to estimate the shear viscosity to entropy ratio using different effective models for hadronic interactions [17,20–23]. This apart, there have been attempts to estimate the transport coefficients using transport codes. The shear viscosity to entropy ratio in the hadronic phase has been estimated using UrQMD transport code in Ref. [24]. Both the bulk as well as the shear viscosity to entropy ratio has also been estimated using parton hadron string dynamics (PHSD) transport code within a relaxation time approximation [25].

In a different approach, η/s has also been calculated within a hadron resonance gas model (HRGM) in an excluded volume approximation [26] with a molecular kinetic theory approach to relate shear viscosity coefficient to the average momentum transfer. This was used later to include