Effect of rotation on the liquid-gas phase transition in a hadron resonance gas

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Introduction

One of the primary goals of theoretical and experimental high-energy physics is to understand the quantum chromodynamics (QCD) matter at extreme temperature (T) and baryochemical potential (μ_B) and to study its phase diagram. Lattice QCD (lQCD) calculations predict a smooth crossover transition from hadronic to partonic phase at vanishing μ_B and high T. Many theoretical calculations, however, predict a first-order phase transition at high μ_B and low T that ends at a possible critical point. Recent experimental observations found that the peripheral heavy-ion collision leads to the creation of a large amount of vorticity in the QCD matter, allowing a new domain to study the QCD phase diagram. In addition to the parameters like T, μ_B, and magnetic field (B), the rotation (ω) effect can play a crucial role in determining the properties of the hot dense matter produced in heavy-ion collisions. The rotation adds a new kind of chemical potential to the system called rotational chemical potential, which, like μ_B, can help achieve the phase transition, thereby affecting the critical point.

This work uses the hadron resonance gas model (HRG) to study the strongly interacting matter at finite T and μ_B. The HRG model successfully describes the hadron yields from experimental observations and is also able to reproduce the lQCD results at $\mu_B = 0$ GeV up to a temperature $T \sim 150$ MeV. However, it fails at higher T. The ideal HRG model is then improved by incorporating a van der Waals (VDW) kind of interaction among the hadrons through the attractive and repulsive parameters, a and b, respectively. This VDW interaction among the hadrons leads to a liquid-gas phase transition at high μ_B, which can be affected in the presence of a magnetic field as well as the rotation produced in the medium. Here, we study the effect of rotation on the thermodynamic properties of hadron gas as well as on the liquid-gas phase transition.

Formalism

In this work, we consider a rotating thermodynamically equilibrated gas with a constant angular velocity, $\boldsymbol{\omega}$, so as to have the rigid velocity, $\boldsymbol{v} = \boldsymbol{\omega} \times \boldsymbol{x}$, with a constraint of $|\boldsymbol{\omega} \times \mathbf{x}| \ll 1$, $\boldsymbol{x}$ being the system size. The distribution function for the relativistic rotating hadron gas is then obtained as [1],

$$f(\mathbf{x}, \mathbf{p}) = (e^{(E-\mu q)/T} \pm 1)^{-1} e^{(\mathbf{p}\cdot\mathbf{v})/\mathbf{T}} \chi\Big(\frac{\omega}{T}\Big), \quad (1)$$

with

$$\chi\Big(\frac{\omega}{T}\Big) = \frac{\sinh(S+\frac{1}{2})\frac{\omega}{T}}{\sinh(\frac{\omega}{2T})}. \quad (2)$$

Here, E, μ, and S are the free energy, chemical potential, and spin of each hadron, respectively. The q is the conserved charge. Various thermodynamic quantities are now calculated using the distribution function given in Eq. (1). In the VDWHRG model, the chemical potential is modified, and hence, all the thermodynamic variables, because of the interaction [1, 2].

Results and discussion

We estimate the thermodynamic quantities like pressure (P) and energy density (ε) along

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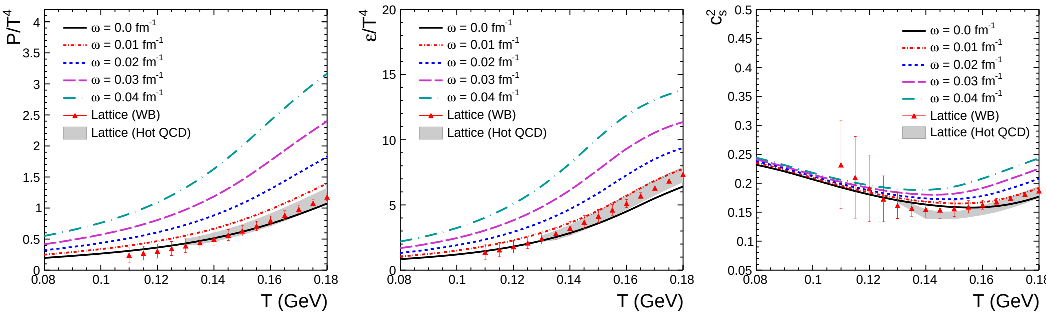

FIG. 1: (Color Online) Variation of scaled pressure and energy density along with the squared speed of sound as functions of temperature at $\mu_{\rm B} = 0$ GeV for different values ω [1].

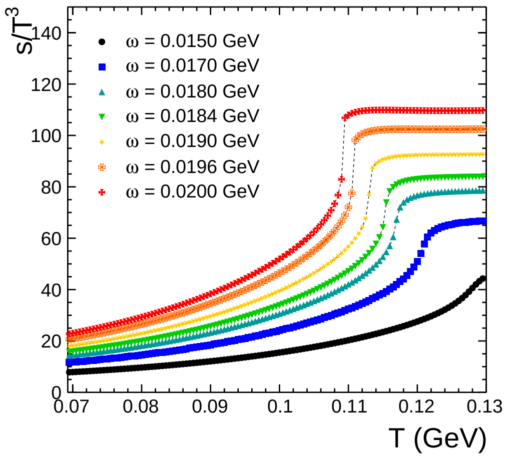

FIG. 2: (Color Online) Variation of scaled entropy density for $\mu_B = 0$ GeV at low temperature and higher values of ω are shown [1].

with the square of the speed of sound (c_s^2) within the VDWHRG model for a rotating hadron gas. Fig. 1 shows the variation of scaled pressure and energy density as well as c_s^2 as functions of temperature for different values of ω. The solid black line for $\omega = 0$ fm^{-1} (and $\mu_B = 0$ GeV) agrees well with the lQCD results at $\mu_B = 0$ GeV. All these quantities increase with increasing ω, which shows that the rotation has a similar effect as that of baryochemical potential μ_B. To see further if this rotation can lead to the liquid-gas phase transition, we plot scaled entropy density as a function of temperature by taking different values of ω. As shown in Fig. 2, the smooth curve of entropy density for smaller values of ω changes as one goes towards higher ω. The discontinuity starts at around $T \sim 113$ MeV for $\omega = 0.019$ GeV, pointing to a first-order phase transition onwards.

Summary

In this work, we present the effect of rotation on the thermodynamic properties of the hadron gas by taking an interacting HRG model. We find that the rotation has a similar effect as that of baryochemical potential and can lead to a first-order liquid-gas phase transition even at $\mu_B = 0$ GeV. In addition to this, we also look into the effect of rotation on fluctuations of conserved charges as well as an estimation of spin density associated with the rotational chemical potential is done. For detail, one can refer [1].

References

[1] K. K. Pradhan, B. Sahoo, D. Sahu and R. Sahoo, [arXiv:2304.05190].
[2] K. K. Pradhan, D. Sahu, R. Scaria and R. Sahoo, Phys. Rev. C **107**, 014910 (2023)