Probing thermalization and system size effect on a hadron resonance gas for hydrodynamical study of hadronic phase

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Introduction

The study of matter prevailed in the microsecond old early universe has been made possible with the help of accelerators by colliding hadrons and nuclei at relativistic energies. The matter produced in quark gluon plasma in these collisions rapidly cools down and undergoes a phase transition to form a state of hot hadrons. Such a rapid cooling and phase transition from quark degrees of freedom to hadronic degrees of freedom means that the observables are to be defined in terms of hadrons. Thus the study of this particular phase in the evolution of hot QCD matter is critical. In this respect, the Excluded Volume Hadron Resonance Gas (EVHRG) model has been highly successful. It has also been shown that the effect of different collision energies can be introduced by appropriately chosen baryochemical potentials (μ_B) [1]. In this article, we use the EVHRG model with the inclusion of Hagedorn states for heavier masses to observe the effect of varying collision energies on the speed of sound (c_s^2) and Knudsen number (Kn) of a hadron gas. The effect of system size on Knudsen number is also explored explicitly.

Formalism

Speed of sound (c_s^2) is the characteristic property of a medium and has been considered to be an indicator of criticality and phase transition in relativistic nuclear collisions. With vanishing chemical potential, a dip in c_s^2 has been observed near the expected critical point in LQCD calculations. Speed of sound is defined in the EVHRG formalism by [1]

$$c_s^2 = \frac{\frac{\partial P}{\partial T} + \frac{\partial P}{\partial \mu_B}\frac{d\mu_B}{dT}}{\frac{\partial \varepsilon}{\partial T} + \frac{\partial \varepsilon}{\partial \mu_B}\frac{d\mu_B}{dT}}, \qquad (1)$$

which reduces to $c_s^2 = (\frac{\partial P}{\partial \varepsilon})$ for the case of $\mu_B = 0.0$ GeV. Here,

$$\frac{d\mu_B}{dT} = \frac{s\frac{\partial n}{\partial T} - n\frac{\partial s}{\partial T}}{n\frac{\partial s}{\partial \mu_B} - s\frac{\partial n}{\partial \mu_B}}. \qquad (2)$$

Here P, ε, s and n represent pressure, energy density, entropy density and number density of the hadron gas.

In addition, Knudsen number is an important parameter in hydrodynamics that relates the system's mean free path and the system size. A very low value for this parameter ($Kn << 1$) indicates that the particles in the medium undergo a large number of collisions, and the system thus attains equilibrium due to momentum transfer during these collisions. Thermalization being a prerequisite for hydrodynamics, this also means that fluid dynamics may be used to describe the evolution of such a system. Kn is given by,

$$Kn = \lambda/D \qquad (3)$$

where $\lambda = \frac{1}{\sqrt{2}n\sigma}$ and $D = 2R$ are the mean free path and characteristic system size, respectively. Here $\sigma = 4\pi r_h^2$, which gives the interaction cross-section with r_h being the hard-core radius which is chosen to be 0.3 fm in our calculations [1].

Results and Discussion

Fig.1 shows the effect of different collision energies on c_s^2 by studying the variation of c_s^2

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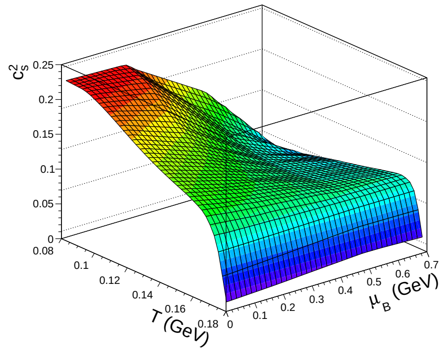

FIG. 1: Speed of sound in a hadron gas is shown as a function of temperature and μ_B [1].

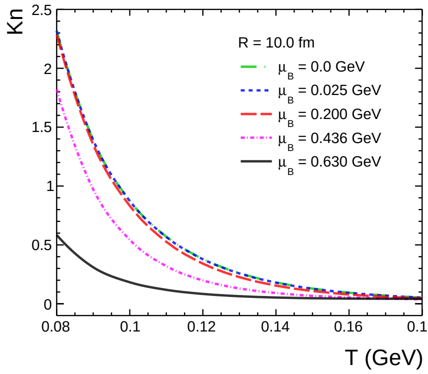

FIG. 2: The effect of different collision energies on Knudsen number is shown by varying μ_B [1].

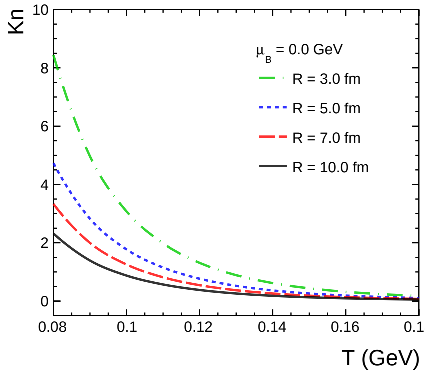

FIG. 3: The effect of system size on Knudsen number is shown [1]. As expected, a higher system size indicates more collisions, decreasing Kn.

as a function of both temperature and μ_B to be realized at different collision energies. The smooth variation of c_s^2 with a dip near the expected critical point at $T_c \approx 0.160$ GeV at $\mu_B = 0.0$ GeV is explicitly seen. On moving towards higher μ_B (lower collision energies), this dip is seen to move towards lower temperatures indicating a shift of the transition point. The sudden decrease at higher temperatures is due to the effect of Hagedorn states increasing energy density rapidly.

Figs.2 & 3 show the effect of μ_B and system size on Kn by studying its variation as a function of temperature. The values of μ_B shown in Fig.2 corresponds to LHC energies, RHIC at 200 GeV and 19.6 GeV, FAIR at 7.7 GeV and NICA at 3 GeV centre-of-mass collision energies in ascending order of μ_B, respectively. It can be seen that the system is thermalized at lower temperatures at lower colliding energy, indicating the applicability of hydrodynamics in this regime. The increase in number density with temperature also means that all the cases considered attains a similar degree of thermalization at higher temperatures due to the subsequent decrease in λ. A larger system size indicates a larger number of collisions, which subsequently reduces Kn. Thus, in collisions of heavier nuclei, the hydrodynamic region tends to extend further than for lighter nuclei, for which the system size is smaller in comparison.

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References

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