Thermalized hadron gas of different sizes approach common mean free path at high temperature

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Introduction

After the discovery of thermalized partonic medium at in $AuAu$ collisions at $\sqrt{s}_{NN} = 130$ and 200 GeV at the Relativistic Heavy Ion Collider (RHIC), collisions at lower $\sqrt{s}_{NN}$ and among comparatively lighter nuclei, also, revealed the QGP-like signals. On the other hand, the Large Hadron Collider (LHC), by unrevealing the long-range two-particle angular correlations in high-multiplicity pp events at $\sqrt{s} = 7$ and 13 TeV [1–4] indicates the formation of collective medium in the high-multiplicity pp events. The possibility of formation of the collective medium in high-multiplicity pp events is yet to emerge as a consensus view and the main issue of disagreement lies with the question of thermalization in a small system of short lifetime that is supposed to be formed in the pp events. In this scenario, we present a study on thermalized hadron gas of different finite sizes, which may represent thermalized systems of final state particle production, created in ultra-relativistic collisions of different combinations of projectiles and at different energies. We adopt Hagedorn mass spectrum [5] over and above the experimentally measured hadrons and resonance states in the ideal HRG model [6] and include the finite size of the constituents hadrons [7] and study the effect of the finite system-size [8].

HRG Model with Hagedorn mass spectrum and EV effect

Considering the grand canonical system, with Boltzmann approximation, the thermodynamical variables, pressure ($P(T)$), energy density ($\epsilon(T)$) of hadron resonance gas including the Hagedorn mass spectrum, given by [5]:

$$\rho(m) = C\frac{\theta(m - M_0)}{(m^2 + m_0^2)^a}\exp(\frac{m}{T_H}) \qquad (1)$$

can be written [6], at zero chemical potential, as:

$$P^H(T) = \frac{T}{2\pi^2}\int dm\int_0^\infty p^2 dp\exp\Big(-\frac{\sqrt{m^2+p^2}}{T}\Big)\Big[\sum_i g_i\delta(m - m_i) + \rho(m)\Big] \qquad (2)$$

$$\epsilon^H(T) = \frac{1}{2\pi^2}\int dm\int_0^\infty p^2 dp\sqrt{m^2+p^2}\exp\Big(-\frac{\sqrt{m^2+p^2}}{T}\Big)\Big[\sum_i g_i\delta(m - m_i) + \rho(m)\Big] \qquad (3)$$

Implementation of the excluded volume effect(EV) [7] in terms of hard core description of constituent hadrons, resonances and the Hagedorn states results into following expressions for the thermodynamic variables [6]: $P_{EV}^H(T) = \kappa^H P^H(T)$, $\epsilon_{EV}^H(T) = \frac{\kappa^H\epsilon^H(T)}{1+v\kappa^H n^H(T)}$, where κ^H is the excluded volume suppression factor and is given by $\kappa^H = \exp(-vp^{EV}/T)$.

We implement the finite size effect down to $R = 2.5$ fm., by introducing finite non-zero

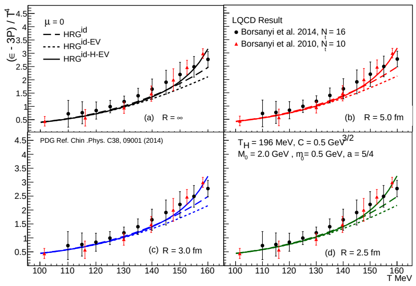

FIG. 1: The trace anomaly as a function of T for different system sizes of hadron gas with different options, as described in the text.

lower limit of momentum of the particles [9], given by $p_{cutoff}(in MeV) = 197\ \pi/R(in fm.))$, where R is the size of a cubic volume. The trace anomaly, $I(T) = \frac{(\epsilon-3P)}{T^4}$ calculated for different size of the hadron gas, corresponding to R $=\infty$, 5.0, 3.0 and 2.5 fm, have been contrasted with Lattice QCD (LQCD) results for [9, 10] different options of HRG in the figure 1. We have used the mass table provided in the [11]. It is clear from the figure 1, for the hadron gas down to the size corresponding to R = 2.5 fm., follow the LQCD EoS satisfactorily and at high temperature ($T > 145$ MeV) the LQCD results are better matched with the inclusion of Hagedorn states.

We calculate the mean free path ($\lambda = 1/n\sigma$) of pions in the thermalized hadron gas of the considered sizes, as a function of temperature for hadron resonance gas, including the Hagedorn states and corrected with EV effect from the temperature dependent number density and obtaining the pion-pion total cross-sections (from Ref. [12]), which vary from $\sim$ 12 to 23 mb in the temperature range from $T = 100 - 160$ MeV.

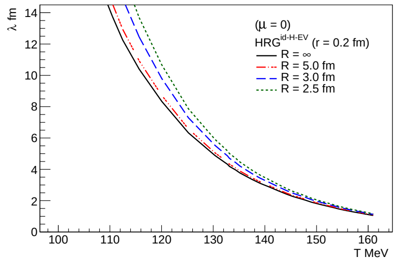

FIG. 2: Temperature dependent pion mean free path in different sizes of hadron gas.

Conclusion

As can be seen in the figure 2, the mean free path for all the considered system-sizes of hadron gas, following the LQCD EoS, approach the universal pion freeze-out value of 1 fm., as has been observed [13] in relativistic heavy-ion collisions.

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