Speed of Sound in a System Approaching Thermodynamic Equilibrium

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Introduction

Experimental high energy collisions at RHIC and LHC give an opportunity to study the space-time evolution of the created hot and dense matter known as QGP at high initial energy density and temperature. As the initial pressure is very high, the system undergo expansion with decreasing temperature and energy density till the occurrence of the final kinetic freeze-out. This change in pressure with energy density is related to the speed of sound inside the system. The QGP formed in heavy ion collisions evolves from the initial QGP phase to a hadronic phase via a possible mixed phase. The speed of sound reduces to zero on the phase boundary in a first order phase transition scenario as the specific heat diverges. The temperature dependence of speed of sound in a medium is well established but the effect of temperature fluctuations is less explored, particularly in the case of heavy-ion collisions. Since, in non-extensive statistics, the Tsallis parameter (q) is related to the temperature fluctuations [1], we have explored it to estimate the speed of sound using Tsallis statistics in hadronic medium.

Speed of Sound in a Physical Hadron Resonance Gas

A hadron resonance gas consists of mesons and baryons obeying Bose-Einstein (BE) and Fermi-Dirac (FD) statistics, respectively. The Tsallis form of the Fermi-Dirac and Bose-Einstein distributions as proposed in Refs. [1] uses

$$f_T(E) \equiv \frac{1}{\exp_q\left(\frac{E-\mu}{T}\right) \pm 1}. \quad (1)$$

where the function $\exp_q(x)$ is defined as

$$\exp_q(x) \equiv \begin{cases} [1+(q-1)x]^{1/(q-1)} & \text{if} \quad x > 0 \\ [1+(1-q)x]^{1/(1-q)} & \text{if} \quad x \leq 0 \end{cases} \quad (2)$$

and, in the limit where $q \rightarrow 1$ it reduces to the standard exponential; $\lim_{q\rightarrow 1} \exp_q(x) \rightarrow \exp(x)$. In the present context we have taken $\mu = 0$, therefore $x \equiv E/T$ is always positive. In Eqn. 1, the negative sign in the denominator stands for BE and the positive stands for FD distribution.

For an ideal gas with zero chemical potential, the temperature dependent speed of sound, $c_s(T)$ is given by

$$c_s^2(T) = \left(\frac{\partial P}{\partial \epsilon}\right)_V = \frac{s(T)}{C_V(T)},$$

Where, $s = \left(\frac{\partial P}{\partial T}\right)_V$ is the entropy density and $C_V(T) = \left(\frac{\partial \epsilon}{\partial T}\right)_V$ is the specific heat at constant volume.

Results and discussion

Figure 1 shows the speed of sound for hadron resonance gas taking different mass cut-offs of hadrons for $q = 1.05$. The mass cut-off, M is introduced as the highest mass of the resonances contributing to the hadron resonance gas. This shows that, adding more massive resonances to the system the speed of sound decreases near T_H.

To explore this, we have studied the square of the speed of sound as a function of the

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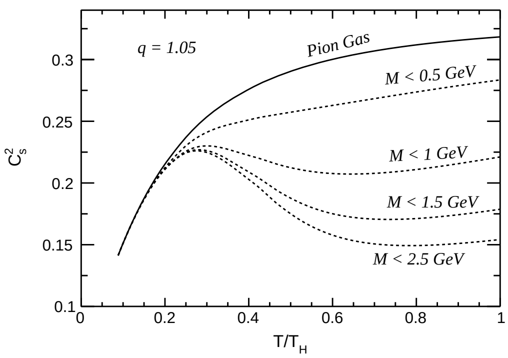

FIG. 1: Speed of sound for q=1.05 for hadron resonance gas with different cut-off on mass.

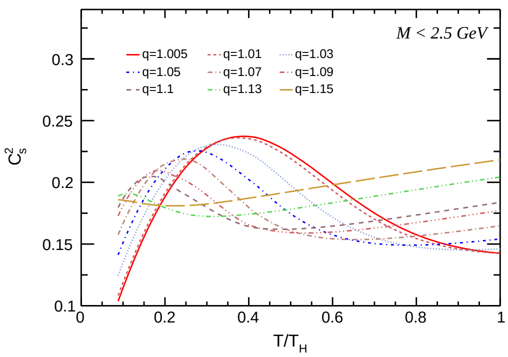

FIG. 2: Speed of sound for different values of the non-extensivity parameter, q, for a mass cut-off of $M < 2.5$ GeV.

scaled temperature for different values of q, taking a mass cut-off of 2.5 GeV. This is shown in Figure 2. It could be inferred from the figure that with progressive increase of the q-values, when the system goes away from equilibrium, the speed of sound slowly decreases to a minimum value up to $q = 1.13$. This behavior, however, vanishes for higher values of q. This indicates the softening of equation of state and a possible phase transition. Interestingly, this critical value of q is close to the value one obtains in the analysis of $p_{\rm T}$ spectra in $p + p$ collisions at high energies [1]. Again for higher q-values the criticality of speed of sound shifts towards the lesser value of temperature.

Conclusion

The speed of sound c_s^2 has been studied for systems those deviate from thermalised Boltzmann systems as a function of temperature taking different q values using Tsallis non-extensive statistics. Taking higher q-values in non-extensive statistics, c_s^2 increases near T_H as compared to the extensive Boltzmann statistics. It is also observed that the criticality effect appears at lesser temperature for higher values of "q", which indicates that if there are temperature fluctuations inside the system then the critical behavior, if any, possibly the boundary of the phase transition shifts towards lesser temperature in the phase diagram or the phase transition is achieved earlier as compared to the systems described by extensive statistics. Our results leave open the possibility that there exists a special value of q where a phase transition is no longer present. Taking a mass cut-off of 2.5 GeV in the physical resonance gas, we have studied the c_s^2 as a function of system temperature, for different q-values and found that for q-values higher than 1.13, criticality disappears.

References

[1] A. Khuntia, P. Sahoo, P. Garg, R. Sahoo and J. Cleymans, arXiv:1602.01645 [hep-ph][Eur. Phy. J. A(Press)].