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Study of Fluctuations in Excluded Volume Hadron Resonance Gas Model

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We present temperature (T) dependence of higher order fluctuations of conserved baryon number in Excluded Volume Hadron Resonance Gas (EVHRG) model. Products of moments, such as ratio of variance to mean (σ^2/M), product of skewness and standard deviation ($S\sigma$), product of kurtosis and variance ($\kappa\sigma^2$), for net-proton has been evaluated on the phenomenologically determined freeze-out curve and has been compared with the experimental data measured by STAR experiment.

Key Words : Hadron Resonance Gas; Fluctuations; Susceptibilities; Higher Moments; Heavy-Ion Collisions; Critical Point

Introduction

A reliable way to look at the phase transition of strongly interacting matter is to study the susceptibilities, correlations and fluctuations of some conserved charges like baryon number, electric charge and strangeness. Susceptibilities are related to fluctuations via the fluctuation-dissipation theorem. A measure of the intrinsic statistical fluctuations in a system close to thermal equilibrium is provided by the corresponding susceptibilities. At finite temperature and chemical potential fluctuations of conserved charges are sensitive indicators of the transition from hadronic matter to QGP. Also the existence of the critical point (CP) can be signaled by the divergent fluctuations. Several experimental programs have been launched to study the phase transition of strongly interacting matter. The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory has been performing a beam energy scan program to locate CP in the phase diagram. The phase transition at high μ_B will be explored at the new Facility for Anti-proton and Ion Research (FAIR).

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In this paper we have analysed fluctuations of baryon number using Excluded Volume Hadron Resonance Gas Model (EVHRG) which has been very successful in describing the hadron yields in central heavy ion collisions from AGS up to RHIC energies.

HRG Model

The grand canonical partition function of a hadron resonance gas (Braun-Munzingerer *et al.*, 2004) can be written as $\ln Z^{id} = \sum_i \ln Z_i^{id}$, where sum is over all the hadrons upto mass 3 GeV. id refers to ideal i.e., non-interacting HRG. For particle i,

$$\ln Z_i^{id} = \pm\frac{Vg_i}{2\pi^2}\int_0^\infty p^2\,dp\ln[1\pm\exp(-(E_i-\mu_i)/T)], \tag{1}$$

where V is the volume of the system, g_i is the degeneracy factor, T is the temperature, $E_i = \sqrt{p^2+m_i^2}$ is the single particle energy, m_i is the mass and $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is the chemical potential where B_i, S_i, Q_i are the baryon number, strangeness and charge of the particle respectively and $\mu's$ are corresponding chemical potentials. The (+) and (-) signs correspond to fermions and bosons respectively. The partition function is the basic quantity from which one can calculate various thermodynamic quantities of the thermal system. For example, the partial pressure P_i can be calculated as, $P_i^{id} = \frac{T}{V}\ln Z_i^{id}$. The n^{th} order susceptibility is defined as $\chi_q^n = \frac{1}{VT^3}\frac{\partial^n(lnZ^{id})}{\partial(\frac{\mu_q}{T})^n}$, where μ_q is the chemical potential for conserved charge q. Detailed description can be found in (Bhattacharyya *et al.*, 2014).

Moments such as mean (M), standard deviation (σ), skewness (S), kurtosis (κ) of conserved charges are measured experimentally and those are used to characterize the shape of charge distribution. Products of moments are related to susceptibilities (χ_q) by the following relations,

$$\frac{\chi_q^2}{\chi_q^1} = \frac{\sigma^2}{M_q}, \quad \frac{\chi_q^3}{\chi_q^2} = S_q\sigma_q, \quad \frac{\chi_q^4}{\chi_q^2} = \kappa_q\sigma_q^2. \tag{2}$$

In HRG model non-interacting hadrons (point like particle) are considered. However, in EVHRG model (Yen *et al.*, 1977) hadronic phase is modeled by a gas of interacting hadrons, where the hard core radii of hadrons are explicitly incorporated to approximate a short-range repulsive hadron-hadron interaction. In EVHRG model pressure can be written as $P(T,\mu_1,\mu_2,..) = \sum_i P_i^{id}(T,\hat{\mu}_1,\hat{\mu}_2,..)$, with $\hat{\mu}_i = \mu_i - V_{ev,i}\,P(T,\mu_1,\mu_2,..)$, where $V_{ev,i} = 4\,\frac{4}{3}\,\pi R_i^3$ is the volume excluded for the i th hadron with hard core radius R_i. In an iterative procedure one can get the total pressure and hence various thermodynamic quantities and susceptibilities.

Results and Discussions

In Fig. 1 we have shown variation of $3P/T^4$, χ_B^2 and χ_B^4 with temperature at ($\mu_B = \mu_S = \mu_Q = 0$). It can be seen that there is almost no effect of interaction till $T = 130$ MeV, above which we see quite a substantial change. We compare our result with Lattice QCD (LQCD) data (Bazavov *et al*., 2014; Borsanyi *et al*., 2010; Bazavov *et al*., 2012; Borsanyi *et al*., 2012; Bazavov *et al*., 2012; Schmidt). Lattice data for pressure are taken from Bazavov *et.al*(Bazavov *et al*., 2014) and Borsányi *et.al* (Borsanyi *et al*., 2010). LQCD data for χ^2 are taken from Bazavov *et.al* (Bazavov *et al*., 2012) and Borsányi *et.al* (Borsanyi *et al*., 2012) whereas those for χ^2 are taken from (Bazaovv *et al*., 2012; Schmidt). It can be seen that, below $T = 0.15$ GeV, $3P/T^4$, χ_B^2 and χ_B^4 are in good agreement with LQCD data if we consider radii of hadrons to be 0.2 fm.

In terms of transverse momentum (p_T) and rapidity (y) and azimuthal angle (ϕ) d^3p and E_i can be written as $d^3p = p_T\, m_{Ti} \cosh y\, dp_T\, dy\, d\phi$ and $E_i = m_{Ti} \cosh y$, where $m_{Ti} = \sqrt{(p_T^2 + m_i^2)}$. These prescriptions have been used to set the momentum and rapidity acceptance range to compare the present results with the experimental data.

In Fig. 2 we have shown energy dependence of σ^2/M, $S\sigma$ and $\kappa\sigma^2$ for net-proton. σ^2/M for net-proton increases rapidly with increase of $\sqrt{s_{NN}}$ in our model. We compare our result with experimental data of net-proton fluctuations for $(0-5)\%$ central Au-Au collisions measured at STAR (Luo, 2013). Experimental data is measured at mid rapidity ($|y| < 0.5$) and within the transverse momentum range $0.4 < p_T < 0.8$ GeV. We have taken same acceptances range and different radii of hadrons. At low energy σ^2/M is almost unity and its value increases with increase of $\sqrt{s_{NN}}$ as can be seen from the Fig. 2(A). Both HRG and EVHRG model give almost same result. Also the result is same for all the radii. At low energy $S\sigma$ for HRG is almost unity and its value decreases with increase of $\sqrt{s_{NN}}$ as can be seen from the Fig. 2(B). At low $\sqrt{s_{NN}}$, $S\sigma$ for EVHRG is less than that of HRG model and suppression increases with increase of radii. However, at high $\sqrt{s_{NN}}$, both HRG and EVHRG model give almost same result. Experimental data of $S\sigma$ can be described well with EVHRG model for radii of hadrons between $0.3 - 0.4$ fm. At low energy $\kappa\sigma^2$ (Fig. 2(C)) in HRG model is slightly less than unity and its value reaches to unity as we move to high energy. There is prominent suppression of $\kappa\sigma^2$ in EVHRG model at low $\sqrt{s_{NN}}$. The $\kappa\sigma^2$ of net-proton matches within error-bar with EVHRG model at $\sqrt{s_{NN}} \geq 39$ GeV and $\sqrt{s_{NN}} \leq 11.5$ GeV but at intermediate energies EVHRG model over estimates the experimental data. Deviation of experimental data of $S\sigma$ and $\kappa\sigma^2$ for net-proton at intermediate energies ($\sqrt{s_{NN}} = 19$ GeV and 27 GeV) may be an indication of existence of critical point within this energies.

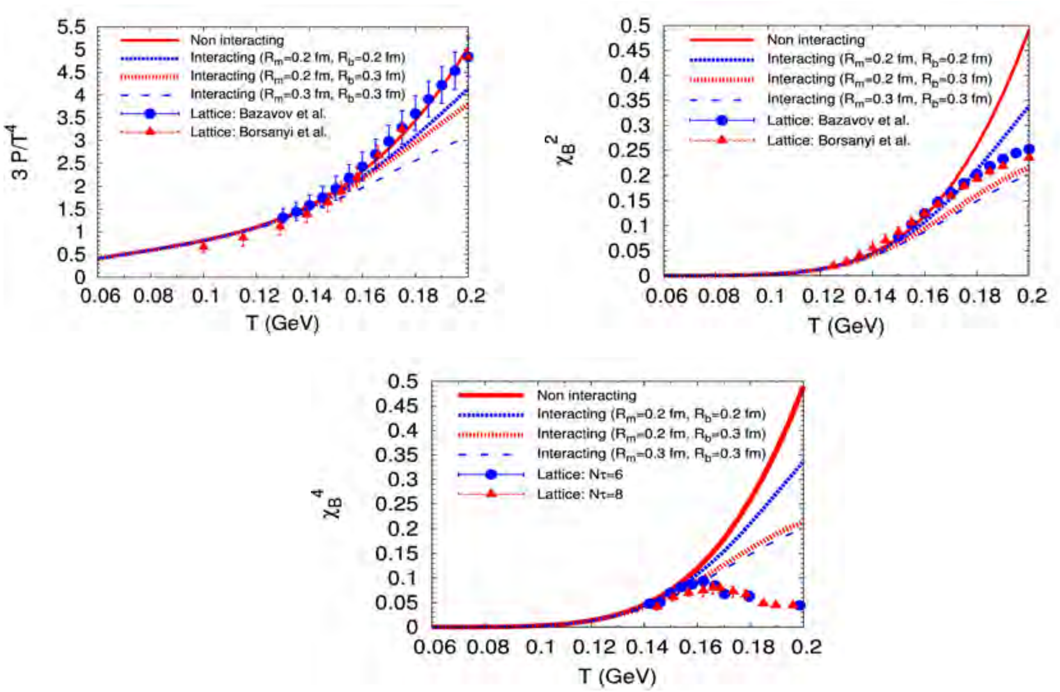

Fig. 1: Variation of $3P/T^4$, χ_B^2 and χ_B^4 with T at $\mu = 0$

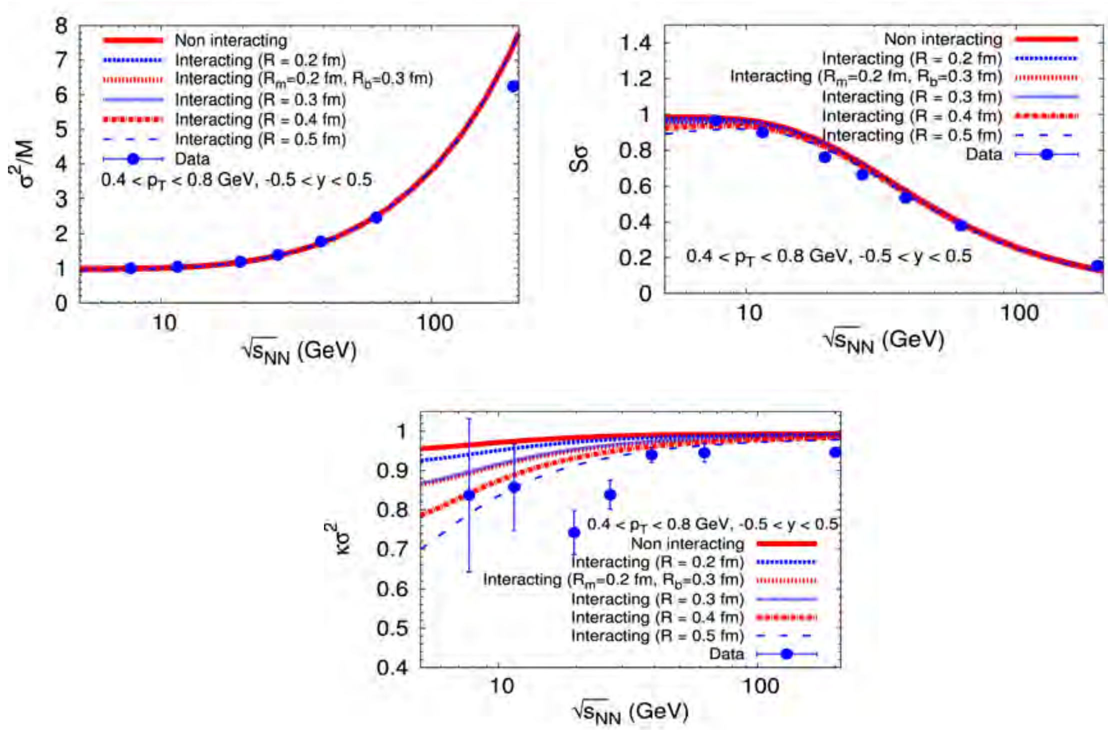

Fig. 2: Energy dependence of σ^2/M, $S\sigma$ and $\kappa\sigma^2$ for net-proton

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