Thermodynamic response functions in high energy collisions from experiment

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Introduction

Nature of Quantum Chromo Dynamic (QCD) phase transition can be understood in high energy collisions by the measurement of thermodynamic response functions (i.e, isothermal compressibility (k_T), specific heat (c_v), etc). These quantities are related by the equation of state (EOS), which governs the evolution of the system. k_T and c_v are sensitive to the nature of the phase transition, and their experimental determination would provide very important measures for the understanding of the Quark Gluon Plasma (QGP) phase.

Methodology

In the Grand Canonical Ensemble (GCE) framework, the variance (σ^2) of the number of particles (N) is directly related to k_T [1, 2], i.e,

$$\sigma^2 = \frac{k_\mathrm{B} T \langle N \rangle^2}{V} k_\mathrm{T}, \tag{1}$$

Charged particle multiplicity fluctuations have been characterised by the scaled variances of the multiplicity distributions, defined as,

$$\omega_\mathrm{ch} = \frac{\langle N_\mathrm{ch}^2 \rangle - \langle N_\mathrm{ch} \rangle^2}{\langle N_\mathrm{ch} \rangle} = \frac{\sigma^2}{\mu} \tag{2}$$

where, N_ch is the charged particle multiplicity per event, and $\mu = \langle N_\mathrm{ch} \rangle$. A detailed study of the multiplicity fluctuations can be found in Ref. [3]. Following the above two equations, we obtain,

$$\omega_\mathrm{ch} = \frac{k_\mathrm{B} T \mu}{V} k_\mathrm{T}, \tag{3}$$

which makes a connection between multiplicity fluctuation and k_T. An estimation of the dynamical fluctuations from the experimental data has been made by subtracting the statistical fluctuations within the approximation of the participant model.

k_T can be estimated from Hadron Resonance Gas (HRG) model too, where the attempt has been to calculate in terms of species dependence (i), instead of total charged particles. k_T from HRG can be estimated using the equation,

$$k_T|_{T,\{\langle N_i \rangle\}} = \frac{1}{V} \frac{1}{\sum_i \left(\frac{\partial P}{\partial \mu_i}\right)^2 / \left(\frac{\partial N_i}{\partial \mu_i}\right)}. \tag{4}$$

On the other hand, heat capacity (C) of a system in thermal equilibrium to a bath at T can be computed from the event-by-event fluctuations of T. To reduce the fitting error in determining T in every event, a connection is made between $\langle p_\mathrm{T} \rangle$ of particles in every event with T. Thus, C can be measured following the equation,

$$\frac{1}{C} = \frac{(\langle T_\mathrm{eff}^2 \rangle - \langle T_\mathrm{eff} \rangle^2)}{\langle T_\mathrm{kin} \rangle^2}, \tag{5}$$

where, T_eff, is a combination of kinetic freeze-out temperature (T_kin) and transverse flow

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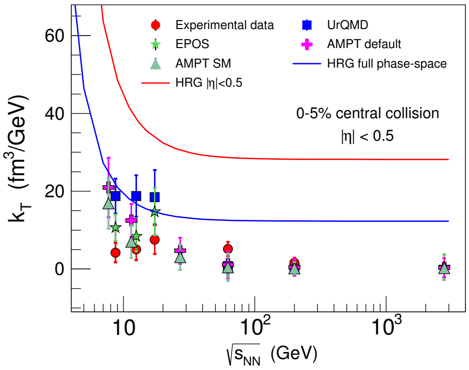

FIG. 1: Isothermal compressibility, k_{T}, as a function of $\sqrt{s_{\mathrm{NN}}}$ for available experimental data for central (0-5%) Au+Au (Pb+Pb) collisions. A uniform cut ($|\eta| < 0.5$) has been maintained for all cases. HRG estimations for full phase space and $|\eta| < 0.5$ are also superimposed.

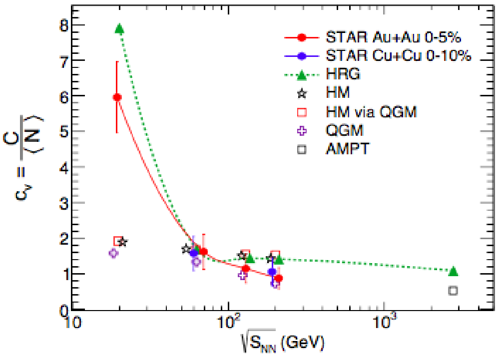

FIG. 2: c_{v} as a function of collision energy for central Au+Au and Cu+Cu collisions at RHIC energies. HRG calculations at T_{kin} are shown in the figure. Model calculations for three different scenarios are superimposed on the experimental results.

velocity (β_{T}) of the system. We measure, $c_{\mathrm{v}} = \frac{C}{\Delta}$, where Δ denotes phase space volume, which is equal to $\langle N \rangle$ for experimental measurements of c_{v}.

Results

We have made an estimation for the first time for k_{T} of the system formed in heavy-ion collisions for $\sqrt{s_{\mathrm{NN}}}$ from 7.7 GeV to 2.76 TeV. Since no new particles are produced after chemical freeze-out, k_{T} has been estimated at the chemical freeze-out temperature (T_{ch}). The results have been presented in Fig. 1. A higher value of k_{T} at low energies compared to higher energies indicates that the collision system is more compressible at the lower energies. The HRG calculations show a sharp transition in the value of k_{T} around $\sqrt{s_{\mathrm{NN}}}\sim$10 GeV. The results from event generators also confirm such a trend. The mild decreasing trend of k_{T} is observed in data as well for $\sqrt{s_{\mathrm{NN}}}>$10 GeV.

For the estimation of the specific heat, the event-by-event $\langle p_{\mathrm{T}} \rangle$ distributions are transformed to distributions of effective temperatures and the dynamical temperature fluctuations are obtained by subtracting the widths of the corresponding mixed event distributions. From Fig. 2, with increase of collision energy, c_{v} shows a sharp drop from low energy till $\sqrt{s_{\mathrm{NN}}}$= 62.4 GeV, beyond which the rate of decrease is very slow [5]. At the transition temperature and below, HRG results of $\frac{C}{VT^3}$ agree well with lattice calculations.

The estimation of k_{T} and c_v along with the EOS of matter provide deeper understanding of the speed of sound, and can be used for a clear understanding of the location of critical point.

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