Scaling behaviour of μ_B/T in the STAR experiment

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Introduction

Heavy Ion collisions (HIC) are investigated both theoretically and experimentally to understand the properties of nuclear matter at extreme conditions. One of the most important issues addressed in HIC is the possibility for nuclear matter to undergo a phase transitions to quark matter. At low baryon density and high temperature nuclear matter is expected to smoothly cross over to a quark gluon plasma (QGP) phase. Whereas, at high baryon density and low temperature the system is expected to have a first order phase transition. Therefore, the first-order phase transition at high baryonic chemical potential and low temperature should end at a critical end-point (CEP) as one moves towards a high temperature and low baryonic chemical potential region in the phase diagram of strongly interacting matter. The main goal of experiments of heavy ion collisions is to map the quantum chromodynamics (QCD) phase diagram in terms of temperatures and baryonic chemical potential. The beam energy scan programme at RHIC is currently investigating the location of CEP. In the near future, experiments at the FAIR (GSI) and at NICA (JINR) will also involve in such an investigation.

Event-by-event fluctuations of conserved charges like baryon, strangeness, and electric charge are sensitive indicators of the transition from hadronic matter to QGP. Not only that, the existence of the CEP can be signalled by the divergent fluctuations. Therefore, a non-monotonic variation of observables related to the cumulants of the distributions of the above mentioned conserved charges with the centre of mass energy ($\sqrt{s_{NN}}$) are believed to be good signatures of a phase transition and a CEP. Similar behaviour is expected with a variation of centrality as well at a fixed $\sqrt{s_{NN}}$. Several experimental results of conserved charge fluctuations (or cumulants) have recently been reported at various energies and centralities [1, 2] in this regard. However, cumulants are volume dependent. Therefore, ratios of cumulants are constructed to cancel volume term and they are related to the ratios of the different order of susceptibilities. In principle, it is possible to calculate chemical freeze-out parameters by comparing experimentally measured ratios of cumulants with ratios of susceptibilities calculated in a model. In an experiment cumulants are measured within certain acceptances which can be incorporated in the hadron resonance gas (HRG) model which is not only successful in describing the hadron yields in central heavy ion collisions from AGS up to RHIC energies but also in describing the bulk properties of hadronic matter in thermal and chemical equilibrium. Therefore, this model can be used to extract freeze-out parameters using experimental information of the ratios of cumulants of conserved charges.

HRG model

The system of thermal fireball consists of all the hadrons and resonances given in the particle data book. We assume that the hadronic matter is in thermal and chemical equilibrium. The grand canonical partition function of a hadron resonance gas can be written as $\ln Z^{id} = \sum_i \ln Z_i^{id}$, where the sum is over all the hadrons. *id* refers to ideal *i.e.*, non-interacting HRG. For particle species i,

$$\ln Z_i^{id} = \pm \frac{V g_i}{(2\pi)^3} \int d^3p \ln[1 \pm \exp(-(E_i - \mu_i)/T)],$$

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where V is the volume of the system, g_i is the degeneracy factor, T is the temperature, E_i 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. In the last expression, B_i, S_i, Q_i are respectively the baryon number, strangeness and charge of the particle, $\mu's$ are corresponding chemical potentials. The upper and lower sign corresponds to baryons and mesons respectively. We assume that the hadronic matter is in thermal and chemical equilibrium therefore we have ignored non-equilibrium phenomena like decays of particles. In case of heavy-ion collision experiments, the parameters T and $\mu's$ of HRG model corresponds to those at chemical freeze-out which depend on initial conditions of the collision. The chemical potentials μ_B, μ_S and μ_Q are not independent, but related to each other as well as to T via the relations $\sum_i n_i\ S_i = 0$, and $\sum_i n_i\ Q_i = r\sum_i n_i\ B_i$, where r is the ratio of net-charge to net-baryon number of the colliding nuclei. For Au + Au collisions $r = N_p/(N_p + N_n) = 0.4$, where N_p and N_n are respectively proton numbers and neutron numbers of the colliding nuclei. In terms of transverse momentum (p_T) and pseudo-rapidity (η), the volume element d^3p and the single particle energy E_i can be written as $d^3p = 2\pi\ p_T^2\ cosh\ \eta\ dp_T\ d\eta$ and $E_i = \sqrt{(p_T\ cosh\ \eta)^2 + m_i^2}$, respectively. Instead of pseudo-rapidity, one can use rapidity (y) as well. The experimental acceptances can be incorporated by considering the appropriate integration ranges. Now, the n th order susceptibility is defined as $\chi_q^n = \frac{1}{VT^3}\frac{\partial^n(\ln Z)}{\partial(\frac{\mu_q}{T})^n}$, where μ_q is the chemical potential for conserved charge q. Experimentally measured quantities like $\sigma^2/M, S\sigma$ and $\kappa\sigma^2$ are related to the ratios of susceptibilities by the following relations $\sigma_q^2/M_q = \chi_q^2/\chi_q^1$, $S_q\sigma_q = \chi_q^3/\chi_q^2$, and $\kappa_q\sigma_q^2 = \chi_q^4/\chi_q^2$, where C_n is the n th order cumulants of the charge distribution. The STAR collaboration has reported results of the above-mentioned observables of net-proton and net-charge at different energies ranging from 7.7 GeV to 200 GeV and at various centralities [1, 2].

Results and discussions

In this work chemical freeze-out parameters have been extracted analysing experimental information of σ^2/M of net-proton and net-charge. Experimental data of net-proton fluctuation was measured in the mid rapidity ($|y| < 0.5$) and within transverse momentum $0.4 < p_T < 0.8$ GeV. Whereas net-charge fluctuation was measured in pseudo-rapidity range $|\eta| < 0.5$ and within transverse momentum range $0.2 < p_T < 2.0$ GeV (removing net-proton of $p_T < 0.4$ GeV) [2]. Same acceptances have been used in the HRG model in the present study.

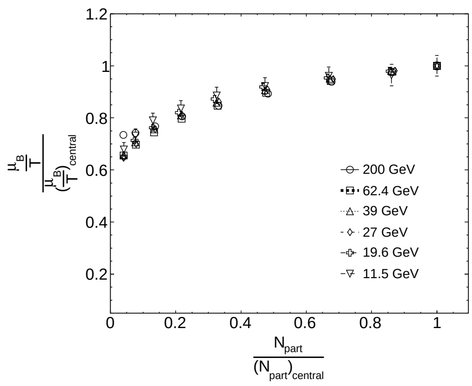

FIG. 1: Scaling behaviour of μ_B/T with centrality.

In the Fig. 1, we have shown an approximate behaviour of $(\mu_B/T)/(\mu_B/T)_{central}$ with $N_{part}/(N_{part})_{central}$. This scaling behaviour indicate that μ_B/T can be separated into two parts $\mu_B/T(\sqrt{s_{NN}}, N_{part}) = f(N_{part})g(\sqrt{s_{NN}})$, so that $(\mu_B/T)/(\mu_B/T)_{central}$ becomes independent of $\sqrt{s_{NN}}$.

References

[1] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **112**, 032302 (2014).
[2] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. Lett. **113**, 092301 (2014).