Physics Letters B 726 (2013) 691–696

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Conserved number fluctuations in a hadron resonance gas model

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ARTICLE INFO

Article history:
Received 2 May 2013
Received in revised form 11 September 2013
Accepted 11 September 2013
Available online 18 September 2013
Editor: D.F. Geesaman

Keywords:
Hadron resonance gas
Susceptibilities
Higher moments
Fluctuations
Heavy-ion collisions
Critical point

ABSTRACT

Net-baryon, net-charge and net-strangeness number fluctuations in high energy heavy-ion collisions are discussed within the framework of a hadron resonance gas (HRG) model. Ratios of the conserved number susceptibilities calculated in HRG are being compared to the corresponding experimental measurements to extract information about the freeze-out condition and the phase structure of systems with strong interactions. We emphasize the importance of considering the actual experimental acceptances in terms of kinematics (pseudorapidity (η) and transverse momentum (p_T)), the detected charge state, effect of collective motion of particles in the system and the resonance decay contributions before comparisons are made to the theoretical calculations. In this work, based on HRG model, we report that the net-baryon number fluctuations are least affected by experimental acceptances compared to the net-charge and net-strangeness number fluctuations.

1. Introduction

Measurement of the moments of distribution for conserved quantities like net-baryon, net-charge and net-strangeness number for systems undergoing strong interactions as in high energy heavy-ion collisions, have recently provided rich physics insights [1–10]. The most crucial realization is that, the product of moments of the conserved number distributions are measurable experimentally and can be linked to susceptibilities (χ) computed in Quantum Chromodynamic (QCD) based calculations [1,5]. For example, $S\sigma = \chi^{(3)}/\chi^{(2)}$ and $\kappa\sigma^2 = \chi^{(4)}/\chi^{(2)}$, where σ is the standard deviation, S is the skewness, κ is the kurtosis of the measured conserved number distribution, $\chi^{(n)}$ are the n-th order theoretically calculated susceptibilities associated with these conserved numbers. Such a connection between theory and high energy heavy-ion collision experiment has led to furthering our understanding about the freeze-out conditions [2,4], details of the quark–hadron transition [1,8] and plays a crucial role for the search of possible QCD critical point in the QCD phase diagram [5]. In all such physics cases there is a need to establish a reference point for the measurements. Computing these quantities within the framework of a hadron resonance gas (HRG) model [11] provides such a reference for both experimental data and QCD based calculations.

The experimental measurements have limitations, they are usually available for a fraction of the total kinematic phase space, due to the finite detector geometries and can detect only certain species of the produced particles. For example, measurements related to net-baryon number distribution is restricted by the kinematic range in p_T where their identification is possible. In addition, baryons like neutron are not commonly measured in most of the high energy heavy-ion collision experiments. While for the net-charge number distribution, the limitation is usually in kinematic range available in η and the details of how contribution from different charge states and resonances are dealt with in the measurements. The kinematic acceptance in a typical high energy heavy-ion collision experiment like STAR [12] and PHENIX [13] at the Relativistic Heavy-Ion Collider facility (RHIC) for net-charge multiplicity distributions are: $|\eta| < 0.5$, $0.2 < p_T < 2.0$ GeV/c and $|\eta| < 0.35$, $0.3 < p_T < 1.0$ GeV/c, respectively. While for net-baryon number and net-strangeness related studies carried out in the STAR experiment, within $|\eta| < 0.5$, is through the measurement of net-protons and net-kaons in the range of $0.4 < p_T < 0.8$ GeV/c and $0.2 < p_T < 2.0$ GeV/c, respectively [5,12].

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http://dx.doi.org/10.1016/j.physletb.2013.09.019

The main goal of this Letter is to demonstrate using the HRG model (discussed in the next section), the effect of the above experimental limitations on the physics observables $\chi^{(3)}/\chi^{(2)}$ and $\chi^{(4)}/\chi^{(2)}$. Our model based study clearly shows that the value of the observables related to net-charge and net-strangeness strongly depends on the experimental kinematic and charge state acceptances. Where charge state could be electric charge $(Q) = 1$ or higher for net-charge measurements and strangeness number $(S) = 1$ or higher for net-strangeness measurements. In contrast, the net-baryon number studies are found to be minimally affected by these experimental limitations. In this work, we have not considered the initial baryon distribution due to the participant number fluctuations in the heavy-ion collisions on the results for net-baryon fluctuations [14]. Another important effect that could influence the values of the higher moments of the net-charge, net-strangeness and net-baryon number distributions in limited acceptance, are the conservation laws related to charge, strangeness and baryon number.

The Letter is organized as follows. In Section 2, we will discuss the HRG model used in this study. In Section 3, the results for the observable $\chi^{(3)}/\chi^{(2)}$ and $\chi^{(4)}/\chi^{(2)}$ are presented for different kinematic acceptances, charge states, effect of collective flow of particle in the system and the resonance decay contributions. We also provide a table listing the values of these observable for typical experimental conditions as encountered in STAR and PHENIX experiments at RHIC and ALICE experiment at the Large Hadron Collider (LHC) Facility. Finally in Section 4, we summarize our findings and mention about the implications of this work to the current experimental measurements in high energy heavy-ion collisions.

2. Hadron resonance gas model

In the HRG model, we include all the relevant degrees of freedom of the confined, strongly interacting matter and also implicitly take into account the interactions that result in resonance formation [3]. It is well known that the fireball created in heavy-ion collision does not remain static, rather expands both in longitudinal and transverse directions until freeze out occurs. However, to keep the model simple, we first consider a static homogeneous fireball and flow effects are included subsequently.

In heavy-ion collision, no fluctuation would be seen in measurements with full phase space coverage as B, Q and S are strictly conserved. However, since most of the experiments cover only limited phase space, the part of the fireball accessible to the measurements may resemble with the Grand Canonical Ensemble (GCE) where energy (momentum), charge and number are not conserved locally. In general, the magnitude of multiplicity fluctuations and correlations in limited phase space crucially depends on the choice of the statistical ensemble that imposes different conservation laws [15,16]. Since no extensive quantities like energy, momentum and charge are needed to be locally conserved in GCE, the particles following Maxwell–Boltzmann distribution are assumed to be uncorrelated and fluctuations are expected to follow Poisson statistics even in the limited phase space when quantum effects are ignored. In case of particles following Bose–Einstein or Fermi–Dirac distributions, within finite phase space, Poisson statistics is not expected to be obeyed and hence the deviations from Poisson limit can be studied.

In the ambit of GCE framework, the logarithm of the partition function (Z) in the HRG model is given as

$$\ln Z(T,V,\mu) = \sum_B \ln Z_i(T,V,\mu_i) + \sum_M \ln Z_i(T,V,\mu_i), \tag{1}$$

where

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

T is the temperature, V is the volume of the system, μ_i is the chemical potential, E is the energy and g_i is the degeneracy factor of the i-th particle. The total chemical potential $\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$, where B_i, Q_i and S_i are the baryon, electric charge and strangeness number of the i-th particle, with corresponding chemical potentials μ_B, μ_Q and μ_S, respectively. The '+' and '−' signs are for baryons and mesons, respectively. The thermodynamic pressure (P) can then be deduced for the limit of large volume as

$$\begin{aligned}\frac{P}{T^4} &= \frac{1}{VT^3}\ln Z_i \\ &= \pm\frac{g_i}{2\pi^2 T^3}\int d^3p \ln\{1 \pm \exp[(\mu_i - E)/T]\}.\end{aligned} \tag{3}$$

The n-th order generalized susceptibility for baryons can be expressed as [3]

$$\begin{aligned}\chi^{(n)}_{x,baryon} &= \frac{X^n}{VT^3}\int d^3p \sum_{k=0}^{\infty}(-1)^k(k+1)^{n-1} \\ &\quad \times \exp\left\{\frac{-(k+1)E}{T}\right\}\exp\left\{\frac{(k+1)\mu}{T}\right\},\end{aligned} \tag{4}$$

and for mesons,

$$\begin{aligned}\chi^{(n)}_{x,meson} &= \frac{X^n}{VT^3}\int d^3p \sum_{k=0}^{\infty}(k+1)^{n-1} \\ &\quad \times \exp\left\{\frac{-(k+1)E}{T}\right\}\exp\left\{\frac{(k+1)\mu}{T}\right\}.\end{aligned} \tag{5}$$

The factor X represents either B, Q or S of the i-th particle depending on whether the computed χ_x represents baryon or electric charge or strangeness susceptibility.

For a particle of mass m in static fireball with p_T, η and ϕ (azimuthal angle), the volume element (d^3p) and energy (E) can be written as $d^3p = p_T m_T \cosh\eta\, dp_T\, d\eta\, d\phi$ and $E = m_T\cosh\eta$, where $m_T = \sqrt{p_T^2 + m^2}$, respectively. The experimental acceptances can be incorporated by considering the appropriate integration ranges in η, p_T, ϕ and charge states by considering the values of $|X|$. The total generalized susceptibilities will then be the sum of the contribution from baryons and mesons as $\chi^{(n)}_x = \sum\chi^{(n)}_{x,baryon} + \sum\chi^{(n)}_{x,meson}$.

In order to make the connection with the experiments, the beam energy dependence of μ and T parameters of the HRG model needs to be provided. These are extracted from a statistical thermal model description of measured particle yields in the experiment at various $\sqrt{s_{NN}}$ [17–19]. This is followed by the parameterization of μ_B and T as a function of $\sqrt{s_{NN}}$ [17]. The μ_B dependence of the temperature is given as $T(\mu_B) = a - b\mu_B^2 - c\mu_B^4$ with $a = 0.166 \pm 0.002$ GeV, $b = 0.139 \pm 0.016$ GeV^{-1}, and $c = 0.053 \pm 0.021$ GeV^{-3}. The $\sqrt{s_{NN}}$ dependence of μ_B is given as $\mu_B(\sqrt{s_{NN}}) = \frac{d}{1+e\sqrt{s_{NN}}}$ with $d = (1.308 \pm 0.028)$ GeV and $e = (0.273 \pm 0.008)$ GeV^{-1}. Further the ratio of baryon to strangeness chemical potential is parameterized as $\frac{\mu_S}{\mu_B} \simeq 0.164 + 0.018\sqrt{s_{NN}}$. We have checked that the value of T and μ_B obtained using the yields extrapolated to 4π or from mid-rapidity measurements, have little impact on our study. However in order to study the rapidity (η) dependence, the μ_B parameterizations $\mu_B = 0.024 + 0.011\eta^2$ and $\mu_B = 0.237 + 0.011\eta^2$ at $\sqrt{s_{NN}} = 200$ GeV [20] and $\sqrt{s_{NN}} = 17.3$ GeV [21], respectively, are used in the calculations.