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Higher moments of net-proton multiplicity distributions in heavy ion collisions at chemical freeze-out

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ABSTRACT

The first four cumulants and ratios of cumulants of net-proton multiplicity distributions are calculated within the hadron resonance gas model. Quantum statistics, resonance decay contributions and the van der Waals excluded volume corrections are taken into account in the model calculations. The corrections due to quantum statistics are small even at the lower RHIC energies. The van der Waals excluded volume procedure leads to a larger suppression of the particle number fluctuations, especially for higher order cumulants. The STAR most central data on the various order cumulants and moment products at the higher RHIC energies are generally below the Poisson expectations and better described by the van der Waals gas with a hadron radius around $r = 0.3$ fm.

1. Introduction

One of the major goals of the heavy ion programs at CERN and BNL is to explore the QCD phase diagram related to deconfinement and chiral symmetry restoration. It was argued that, at high energies, the history of the system, in particular the transition from a system with quarks and gluons degrees of freedom to a system where the relevant degrees of freedom are hadrons, may be reflected in fluctuations of conserved charges, specially in their higher cumulants [1–3]. Large fluctuations of baryon number and electric charge as well as a nonmonotonic behavior of these fluctuations as a function of the collision energy in heavy ion collisions have been proposed as a signature for the QCD critical endpoint [1,4,5].

Particle yields of the physical system created at the time of freeze-out in heavy ion collisions from SIS up to LHC energies exhibit thermal characteristics and are well described by the hadron resonance gas (HRG) model [6,7]. Since the sensitivity to critical dynamics grows with the increasing order, the values of higher order cumulants of charge fluctuations can differ significantly from the results of HRG along the freeze-out curve even if lower-order cumulants agree [2]. The HRG model results on cumulants of charge fluctuations can serve as a theoretical baseline for the analysis of heavy ion collisions [8].

First data on cumulants of net-proton multiplicity distributions were recently obtained by the STAR Collaboration in Au + Au collisions at several collision energies [9–11]. Although the basic properties of the measured fluctuations and their ratios are consistent with HRG model expectations [2,12], a more detailed comparison reveals that deviations cannot be excluded [11,12]. Previous HRG model analyses on this topic are for the net-baryon number [2] or within the Boltzmann approximation [12].

In this Letter the first four cumulants of net-proton multiplicity distributions are calculated in the HRG model. The different cumulants and ratios of cumulants are evaluated on the phenomenologically determined freeze-out curve in the temperature, baryon chemical potential plane. Quantum statistics, resonance decay contributions and the van der Waals (VWD) excluded volume corrections are included in the model calculations. Energy dependence of ratios of cumulants of net-proton distributions and the centrality dependence of the first four cumulants are computed in the HRG model and compared to results obtained by the STAR Collaboration in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4,$ and 200 GeV.

2. Higher moments of net-proton multiplicity distributions in the HRG model

2.1. Ideal hadron gas

In the HRG model the partition function contains all relevant degrees of freedom of the confined, strongly interacting matter and implicitly includes interactions that result in resonance formation. For heavy ion collisions at high energies and a study of fluctuations within a narrow phase space acceptance window, the equilibrated

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medium at chemical freeze-out seems to be well described by a grand canonical (GC) ensemble. The logarithm of the GC partition function of a hadron resonance gas can be written as a sum of partition functions $\ln Z_i$ of all hadrons and resonances

$$\ln Z(T, V, \mu_1, \ldots, \mu_h) = \sum_{i=1}^{h} \ln Z_i(T, V, \mu_i), \tag{1}$$

where h is the number of different particle species, T is the temperature, V is the system volume, and

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

where g_i is the spin degeneracy factor, $E_i = \sqrt{p^2 + m_i^2}$ is the single particle energy, and m_i is the mass of a particle i. For a particle i of baryon number B_i, strangeness S_i, and electric charge Q_i, the chemical potential $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$. The upper and lower signs are for fermions and bosons, respectively.

The mean number of primary particles i is calculated according to [13]:

$$C_1 = M = \langle N_i \rangle = \left[\left(T\frac{\partial}{\partial \mu_i}\right) \ln Z_i\right]_{T,V} = \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp\, n_i, \tag{3}$$

where

$$n_i = \frac{1}{\exp[(E_i - \mu_i)/T] \pm 1}.$$

The variance and higher order cumulants of primary particles i are obtained from further derivatives of $\ln Z_i$ with respect to the corresponding chemical potential,

$$C_2 = \sigma^2 = \bigl\langle (\Delta N_i)^2 \bigr\rangle = \left[\left(T\frac{\partial}{\partial \mu_i}\right)^2 \ln Z_i\right]_{T,V} = \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp\, n_i(1 \mp n_i), \tag{4}$$

$$C_3 = \bigl\langle (\Delta N_i)^3 \bigr\rangle = \left[\left(T\frac{\partial}{\partial \mu_i}\right)^3 \ln Z_i\right]_{T,V} = \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp\, n_i\bigl(1 \mp 3n_i + 2n_i^2\bigr), \tag{5}$$

and

$$C_4 = \bigl\langle (\Delta N_i)^4 \bigr\rangle - 3\bigl\langle (\Delta N_i)^2 \bigr\rangle^2 = \left[\left(T\frac{\partial}{\partial \mu_i}\right)^4 \ln Z_i\right]_{T,V} = \frac{V g_i}{2\pi^2} \int_0^\infty p^2\, dp\, n_i\bigl(1 \mp 7n_i + 12n_i^2 \mp 6n_i^3\bigr), \tag{6}$$

where $\Delta N_i = N_i - \langle N_i \rangle$. Skewness (S) and kurtosis (κ) are generally introduced to characterize the shape of statistical distributions,

$$S \equiv \frac{\langle (\Delta N)^3 \rangle}{\sigma^3}, \qquad \kappa \equiv \frac{\langle (\Delta N)^4 \rangle}{\sigma^4} - 3. \tag{7}$$

2.2. Effect of resonance decays

In the HRG model, after thermal "production", resonances and heavier particles are allowed to decay, therefore contributing to the final yields of lighter mesons and baryons. The ensemble averaged final particle yields, after resonance decays, equal to [14,15]

$$\langle N_i \rangle = \bigl\langle N_i^* \bigr\rangle + \sum_R \langle N_R \rangle \langle n_i \rangle_R, \tag{8}$$

where N_i^* and N_R denote the primordial yields of particles of species i and resonances R, the summation $\sum_R$ runs over all types of resonances, and $\langle n_i \rangle_R \equiv \sum_r b_r^R n_{i,r}^R$ is the average over resonance decay channels. The parameter b_r^R is the branching ratio of the r-th branch of resonance R decay, and $n_{i,r}^R$ is the number of particles of species i produced in the decay of resonance R via the decay mode r.

Resonance decay has a probabilistic character. This itself causes the particle number fluctuations in the final state. The two particle correlations after resonance decays can be calculated as [14–16]

$$\begin{aligned}\langle \Delta N_i \Delta N_j \rangle = {} & \bigl\langle \Delta N_i^* \Delta N_j^* \bigr\rangle + \sum_R \langle N_R \rangle \langle \Delta n_i \Delta n_j \rangle_R \\ & + \sum_R \bigl\langle \Delta N_i^* \Delta N_R \bigr\rangle \langle n_j \rangle_R + \sum_R \bigl\langle \Delta N_j^* \Delta N_R \bigr\rangle \langle n_i \rangle_R \\ & + \sum_{R,R'} \langle \Delta N_R \Delta N_{R'} \rangle \langle n_i \rangle_R \langle n_j \rangle_{R'}\end{aligned} \tag{9}$$

where $\langle \Delta n_i \Delta n_j \rangle_R \equiv \sum_r b_r^R n_{i,r}^R n_{j,r}^R - \langle n_i \rangle_R \langle n_j \rangle_R$. For the ideal hadron gas (HG), the correlations between different primary particle species are absent in the GCE. The three and four particle correlations after resonance decays can be obtained similarly from the following generating function [15]:

$$G \equiv \prod_R \left(\sum_r b_r^R \prod_i \lambda_i^{n_{i,r}^R}\right)^{N_R}, \tag{10}$$

where λ_i are auxiliary parameters that are set to one in the final formulas, and the results are listed in Appendix A.

2.3. Freeze-out conditions in heavy ion collisions

There is a phenomenological relation between the collision energy and the corresponding thermal parameters, which defines the so called chemical freeze-out line in the temperature and baryon chemical potential plane [17]. Following Ref. [17], the set of model parameters at different collision energies can be determined. With increasing colliding energy, the system temperature increases. This is accompanied by a drop in baryon chemical potential, which can be parameterized by the following function [17]:

$$\mu_B(\sqrt{s_{NN}}) = 1.308\ \text{GeV}/\bigl(1 + 0.273\ \text{GeV}^{-1}\sqrt{s_{NN}}\bigr), \tag{11}$$

where $\sqrt{s_{NN}}$ is the c.m. energy in units of GeV. The chemical freeze-out temperature is determined by $\langle E \rangle / \langle N \rangle \approx 1.08$ GeV [18]. Other model parameters, the chemical potentials related to strangeness and isospin, are determined by strangeness conservation and by total charge over total baryon $(Q/B = 0.4)$, respectively. The strangeness saturation factor γ_s has been set to 1.

The thermal model program THERMUS [19] is used in this analysis. Quantum statistics and the finite width of resonances have been taken into account. We first take hadrons in the model as an ideal HG of point-like particles, and include the repulsive interaction of hadrons and resonances by implementing a hard core repulsion of the VDW-type in the following subsection. The standard