Centrality dependence of chemical freeze-out parameters in beam energy scan at RHIC energies

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Abstract— The chemical freeze-out parameters (T_{ch} and μ_b) were extracted from the experimental particle ratios for Au+Au collisions at mid-rapidity using Hadron resonance gas (HRG) Model at different centralities. The centrality dependence of these parameters is studied for beam energy scan at 7.7, 11.5 and 39 GeV. We find that the chemical freeze-out temperature does not show any noticeable dependence on centrality, where the baryon chemical potential decreases as we go from peripheral to central collisions. Furthermore, the grand-canonical approach is no longer satisfied in peripheral collisions.

Index Terms— Centrality dependence, Chemical freeze-out, Fit with particle ratios, Hadron Resonance Gas.

1 Introduction

The heavy-ion experiments are carried out to understand the matter under extreme conditions. The exploration of phases and their creation conditions are summarized in Quantum Chromodynamic (QCD) phase-diagram [1]. The QCD phase-diagram structure is a two dimensional figure, temperature (T) versus baryon chemical potential (μ_b) where the latter indicates the system net baryonic density. In heavy ion collision experiments, there are two experimental control parameters tuned to explore QCD phase-diagram. These control parameters are the collision energy and the centrality of the collision. Centrality is an experimental quantity which reflects the impact parameter variation. Each Centrality theoretically has a corresponding range of impact parameter. In other words, it can be expressed as percentage of the geometrical cross section; or the number of participating nucleons which lie in the overlapping region of the two colliding nuclei [2]. To map this phase-diagram, thermodynamic properties of the system should be studied.

Hadron resonance gas (HRG) Model [3-6] is used to describe the system thermodynamics. The model deals with the fireball at chemical freeze-out, at which the inelastic collisions between hadrons cease. Consequently, the particle number become fixed till they reach the detector. The theoretical particle ratios are compared with the measured ratios in heavy-ion collision experiments in order to extract the chemical freeze-out parameters (T_{ch} , μ_b). With the help of extract parameters, QCD-phase diagram can be mapped (see for details Ref. [4-6]). The model's ability to fit the measured ratios over a wide range of energies [4-6], reflects the validity of applying this statistical view. Furthermore, the model results at low temperature (hadronic phase) coincide with the one from Lattice QCD [7]. At a certain centrality, a pair of parameters (T_{ch} , μ_b) is deduced. This pair is drawn as a point in the phase diagram. Doing that at different conditions will enable us to figure out how these parameters depend on these conditions of energy, centrality and rapidity.

In the most central collisions (small impact parameters) are more likely to produce quark gluon plasma (QGP) [8] where the peripheral collisions are a few numbers of nucleon-nucleon collision. The dependence of centrality, which is the goal of this paper, reveals how (T_{ch} , μ_b) changes and consequently all the thermodynamic quantities with system size. This paper is devoted to analyze the centrality dependence of the chemical freeze-out parameters through experimental particle ratios for Au+Au collisions at mid-rapidity at energy range $\sqrt{s_{NN}}$ = 7 - 39 e measured by STAR experiment [9-11]. The rest of the paper is organized as follows; Sec. 2 presents hadron resonance gas model. Section 3 is devoted to the results and discussion. The conclusions is summarized in the last section.

2 Hadron Resonance Gas Model

In Hadron resonance gas, the newly created multi-particle system at chemical freeze-out is controlled by the phase space and conservation laws. The phase space of each particle depends on the mass, energy, degeneracy and available volume. The conservation laws in grand canonical ensemble are satisfied on average through the chemical potentials. Three kinds of chemical potential are used in this analysis, which are ba-

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ryon chemical potential (μ_b), strange chemical potential (μ_s) and charge chemical potential (μ_q). In light of hadron resonances model, the hadronic phase can be treated as a free gas [12]. This ideal view is an excellent approximation since it has been shown that the thermodynamics of strongly interacting hadrons can also be approximated to an ideal gas composed of hadrons and all the possible resonances that can be appeared during the hadron interactions [12]. Consequently, the interactions were included implicitly by resonance formation. Eventually, the hadronic phase in heavy ion collisions, can be modeled as a non-interacting gas of all resonances. The grand canonical partition function of such a phase can be read

$$Z = Z_1 Z_2 Z_3 .... Z_j \tag{1}$$

where j is the total number of the hadrons and resonances in such phase. The partition function for the i[th] hadron can be written as

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

where $\varepsilon_i(p) = \sqrt{m^2 + p^2}$ is th dispersion relation, g_i is spin-isospin degeneracy factor and ± stands for fermions and bosons, respectively. The i[th] particle chemical potential is given as $\mu_i = \mu_b B_i + \mu_s S_i + \mu_q Q_i$, where B_i, S_i and Q_i are baryon, strange and charge quantum number, respectively.

Thermodynamic properties of the system can be obtained from the partition function. At finite temperature T and baryon chemical potential μ_b, the number density of all hadrons and resonance species can be read

$$n = \sum_i \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, dp}{\exp((\mu_i - \varepsilon_i(p))/T) \pm 1} \tag{3}$$

The conservations laws are enforced on average through the chemical potentials and temperature over the complete phase space. They include conservation of strangeness, , baryon and isospin respectively as follows

$$V \sum_i n_i(T, \mu_i) S_i = 0 \tag{4}$$

$$V \sum_i n_i(T, \mu_i) B_i = Z + N \tag{5}$$

$$V \sum_i n_i(T, \mu_i) Q_i = Z \tag{6}$$

where N and Z are the neutron and protons number in the colliding nuclei.

During the final expansion, the main process is unstable resonance decay. So, the final number density for i[th] particle will be equal to the thermally produced of i[th] particle plus all i[th] particle comes from the decay of the unstable ones as shown is this equation,

$$n_i^{final} = n_i + \sum_i Br_{i \to j} n_j \tag{7}$$

where $Br_{i \to j} n_j$ is the effective branching ratio [5] of j[th] hadron resonance into i[th] particle taking into consideration all multi-steps decay cascades.

It is worthy to mention that, we include contributions of the light flavor hadrons which listed in particle data group (PDG) [13]. This corresponds to 388 different isospin states and their branching ratios [13]. Zero-width approximation is utilized. The excluded-volume correction (EVC) [14] is not applied because it was proved that the EVC has almost no effect on the extracted chemical freeze-out parameters from particle ratios. The contributions of weak decays were implemented in order to match the experimental conditions in the full chemical equilibrium version [15].

3 Results and discussion.

3.1 Fitting with particle ratios.

Applying the model on the experiment data at 39, 11.5 and 7.7 GeV to deduce the chemical freeze-out point at QCD-phase diagram. We use yields of pions, kaons, protons, anti-proton [9,10], $\bar{\Lambda}$, Λ, $\bar{\Xi}$ and Ξ [11] measured at mid-rapidity by STAR experiment at different centralities. The measured pions spectra have been corrected for feed-down from weak decays, as well as $\Lambda(\bar{\Lambda})$ for the feed-down contributions from Ξ weak decay [9-11]. The analysis includes 9 independent ratios. The set of particle ratios is kept without change all energies and centralities.

The fit between the calculated particle ratios are preformed using the criterion of χ^2 which is calculated by the following equation

$$\chi^2 = \sum_i \frac{(R_i^{exp} - R_i^{model})^2}{\sigma_i^2} \tag{8}$$

where R_i^{exp} is the i-th ratio experimental value, where R_i^{model} is the calculated value of the same ratio and σ_i^2 is the experimental error of i-th ratio. The statistically-independent ratios used in estimating χ^2 are $\frac{\pi^-}{\pi^+}$, $\frac{k^-}{k^+}$, $\frac{\bar{p}}{p}$, $\frac{\bar{\Lambda}}{\Lambda}$, $\frac{\bar{\Xi}}{\Xi}$, $\frac{k^-}{\pi^-}$, $\frac{\bar{p}}{\pi^-}$, $\frac{\Lambda}{\pi^-}$ and $\frac{\Xi}{\pi^-}$.

Figures (1-3) represent the comparison between the experimental particle ratios and calculated ratios where the latter were performed using T_{ch} and μ_b parameters, which assure

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minimum χ^2. Figures (1-3) represent different energies and centralities. The quality of the fit is represented as χ^2 / Ndf where Ndf is the number degree of freedom that equals to number of used ratios minus the two fitting parameters (T_{ch}, μ_b).

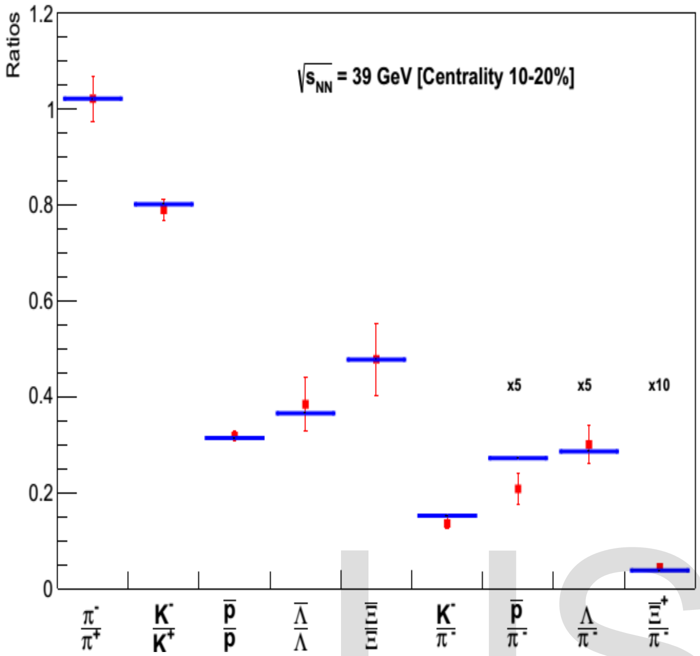

Fig. 1. The STAR particle ratios (symbols) [9-11] are compared to theoretical calculations using HRG model (horizontal lines) at 39 GeV for 10 – 20% centrality.

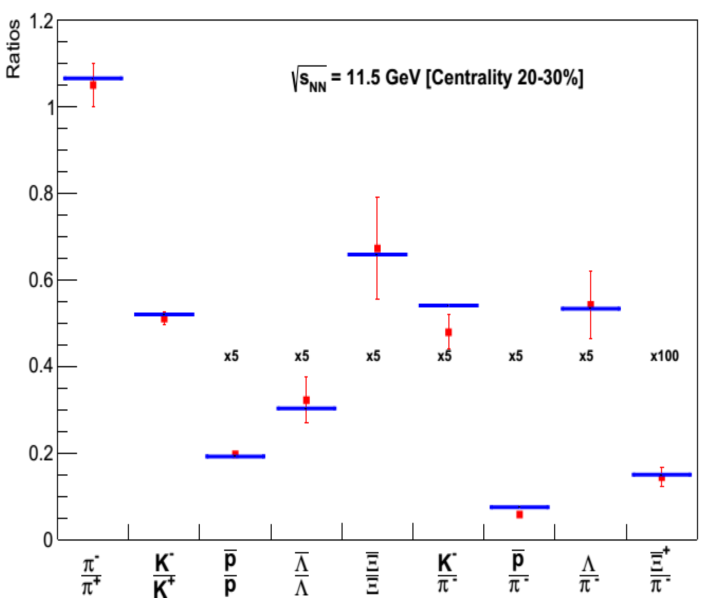

Fig. 2. The STAR particle ratios (symbols) [9-11] are compared to theoretical calculations using HRG model (horizontal lines) at 11.5 GeV for 20 – 30% centrality.

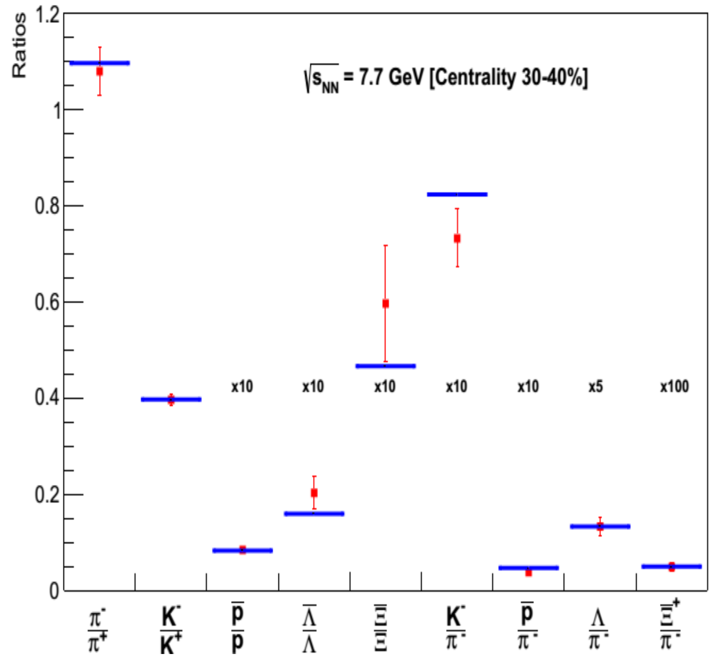

Fig. 3. The STAR particle ratios (symbols) [9-11] are compared to theoretical calculations using HRG model (horizontal lines) at 7.7 GeV for 30 – 40% centrality.

3.2 Centrality Dependance

	39 GeV		
centrality	T_{ch}	μ_b	χ^2_{min}/Ndf
5-10%	160.5	108.5	7.44/7
10-20%	160	106	7.78/7
20-30%	161	100	7.36/7
30-40%	159	94.5	7.51/7
40-60%	157.5	89.5	14.36/7
60-80%	147.5	75	36.64/7

Table 1: The freeze-out parameters, T_{ch} and μ_b, are estimated from χ^2 fitting approaches using HRG at different centralities for $\sqrt{s_{NN}}$ = 39 GeV

	11.5 GeV		
centrality	T_{ch}	μ_b	χ^2_{min}/Ndf
5-10%	154	309.5	8.37/7
10-20%	154	297	7.65/7
20-30%	154	288.5	7.45/7
30-40%	155	286.0	15.95/7
40-60%	154.5	272.5	46.28/7
60-80%	150.5	247.5	160.8/7

Table 2: The freeze-out parameters, T_{ch} and μ_b, are estimated from χ^2 fitting approaches using HRG at different centralities for $\sqrt{s_{NN}}$ = 11.5 GeV.

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	7.7 GeV		
centrality	T_{ch}	μ_b	χ^2_{min}/Ndf
5-10%	144	409	14.64/7
10-20%	145.5	405	7.71/7
20-30%	146	399	6.69/7
30-40%	142.5	387	7.69/7
40-60%	145.5	376	27.68/7
60-80%	151.5	397.5	140.8/7

Table 3: The freeze-out parameters, T_{ch} and μ_b, are estimated from χ^2 fitting approaches using HRG at different centralities for $\sqrt{s_{NN}}$ = 7.7 GeV.

Tables (1-3) have summerized the results of the analysis at different energies as well as centralities. The small $\chi^2_{\min}/Ndf$ represent the validity of this model reproducing the experimental ratios, especially at small impact parameters. However, as the impact parameter increases, the agreement disappears. This means that the grand-canonical approach is no longer satisfied in peripheral collisions. It was expected because grand-canonical approach is convinced when a large number of particles are produced. The centralities, namely 40-60% and 60-80%, need canonical ensemble approach [16].

Thermal parameters values deduced in this analysis at 5-10% are consistent with the most central collisions [5]. At a fixed energy, the chemical freeze-out temperature stays fairly constant for all centralities.

It was found in Ref.[17] that baryon chemical potential for proton-proton collisions is less than the one of heavy ion collision at the same energy. This represents the high transparency of proton-proton collision in comparison with heavy ion collsion [17]. This analysis shows that the baryon chemical potential, μb , decreases as we go from peripheral to central collisions which means that at large impact parameter the collision can be seen as few separetly nucleon-nucleon interactions. In other words, nucleon-nucleon collision features appear in peripheral collisions.

4 Conclusion

In this paper, we present the centrality dependence of the chemical freeze-out parameters (T_{ch} , μ_b) with hadron resonance gas model for Au+Au collision at $\sqrt{s_{NN}}$ = 39-7.7 GeV. Furthermore, a check of the validity of grand canonical ensemble approach have been preformed. As seen in figures (1-3), an agreement represented by the small values of the minimum χ^2 at centralities (5-10% , 10-20%, 20-30% and 30-40%) where grand-canonical approach is no longer satisfied in peripheral collisions. We found that the chemical freeze-out temperature does not show any noticeable dependence on centrality where the baryon chemical potential decreases as we go from peripheral to central collisions.

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