Evidence of the mixed phase formation in nucleus-nucleus collisions

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Abstract. Searchers for various irregularities in the behavior of thermodynamic quantities at chemical freeze-out (CFO) are rather important in a view of experimental studies of quark-gluon plasma (QGP). Using the multicomponent hadron resonance gas model (HRGM), developed in [Sagun, 2014; Bugaev et al.(1), 2015], we performed a high-quality fit of 111 hadronic ratios measured for 14 values of the center of mass collision energies between 2.7 GeV and 200 GeV with the overall fit quality $\chi^2/dof \simeq 0.95$. In addition to previously reported singularities [Bugaev et al.(1), 2015] at CFO we found that the hadron yield ratios $\Lambda/p$, $K^+/p$, $K^+/\Lambda$, $\bar{\Omega}/p$ and $\Xi^-/p$ measured in central nuclear collisions demonstrate a significant change of slope in the same range of center of mass collision energy $\sqrt{s_{NN}} = 4.3 - 4.9$ GeV [Bugaev et al.(2), 2015]. This change of slopes is accompanied by a dramatic increase of resonance decays at CFO. Also at CFO the trace anomaly and baryonic density demonstrate the pronounced peaks at the collision energy $\sqrt{s_{NN}} = 4.9$ GeV. We argue that all these and previously found irregularities provide an evidence for the QGP formation in nuclear collisions at about $\sqrt{s_{NN}} = 4.9$ GeV.

Keywords: irregularities, chemical freeze-out, QGP formation signatures

Introduction

Experimental searches for the QGP in heavy-ion collisions cannot be completed successfully without reliable and justified signals of its formation. Although some irregularities, known as the Kink [Gazdzicki, 1995], the Strangeness Horn [Gazdzicki et al., 1999] and the Step [Gorenstein et al., 2003], are widely considered as the signals of the onset of deconfinement [Gazdzicki et al., 2011], their relation to the QGP-hadron mixed phase is far from being clear. Therefore, the development of realistic models which are able to accurately describe the existing experimental data and to provide us with the reliable information about the late stages of the heavy-ion collision process is absolutely necessary.

The high quality description of data achieved recently for 111 independent hadron yield ratios measured at midrapidity in central nucleus-nucleus collisions for 14 values of the center of mass energies undoubtedly proves that the HRGM with the multicomponent hard-core repulsion is a precise and a sensitive tool of heavy ion collision phenomenology [Sagun, 2014]. In contrast to other existing versions of HRGM [Andronic et al., 2006; Bugaev et al., 2013] the present one accounts for the hard-core repulsion using different hard-core radii for pions, $R_\pi$, kaons, $R_K$, $\Lambda$-hyperons, $R_\Lambda$, other mesons, $R_m$, and other baryons, $R_b$. With such a model we are able to fit the experimental multiplicities measured at AGS for $\sqrt{s_{NN}} = 2.7, 3.3, 3.8, 4.3, 4.9$ GeV, the NA49 data measured at SPS energies $\sqrt{s_{NN}} = 6.3, 7.6, 8.8, 12.3, 17.3$ GeV and the STAR data measured at RHIC energies $\sqrt{s_{NN}} = 9.2, 62.4, 130, 200$ GeV with the highest quality $\chi^2/dof \simeq 0.95$ [Sagun, 2014; Bugaev et al.(1), 2015]. Therefore, using the HRGM with the multicomponent hard-core repulsion we can study thermodynamics of strongly interacting matter at CFO with very high confidence.

Using the multicomponent version of HRGM [Sagun, 2014; Bugaev et al.(1), 2015] we previously found the set of strongly correlated quasi-plateaus in the collision energy dependence of the entropy per baryon and of the pion number (both the thermal and total) per baryon at CFO [Bugaev et al.(1), 2015]. Such strongly correlated plateaus were predicted a long time ago as a signal of QGP-hadron mixed phase formation [Bugaev et al., 1989; Bugaev et al., 1990; Bugaev et al., 1991]. Hence, it was argued that the observed dramatic changes in the system properties seen in the narrow collision energy range $\sqrt{s_{NN}} = 4.3 - 4.9$ GeV evidence for the QGP formation in nuclear collisions [Bugaev et al.(1), 2015].
SAGUN ET AL.: MIXED PHASE FORMATION

With the help of this HRGM we also found the new irregularities related to deconfinement. The most spectacular of them is a sudden jump of the pressure $p$ at CFO in the narrow range of center of mass collision energies $\sqrt{s_{NN}} = 4.3$ - 4.9 GeV [Bugaev et al.(3), 2015, Bugaev et al.(4), 2015]. The observed pressure jump at CFO is so strong, that the effective number of degrees of freedom, $p/T^4$, increases by 70%, while the collision energy in the center of mass system changes by 15% and while the CFO temperature $T$ changes by 30%. Below we discuss other irregularities and possible signals of the mixed phase formation in nuclear collisions which are of great importance for the success of the planned heavy-ion collision experiments at JINR-NICA and GSI-FAIR.

HRGM with multicomponent hard-core repulsion

Let us consider the Boltzmann gas of $N$ hadron species in a volume $V$ that has the temperature $T$, the baryonic chemical potential $\mu_B$, the strange chemical potential $\mu_S$ and the chemical potential of the isospin third component $\mu_{I3}$. Such an approach is based on the assumption of local thermal and chemical equilibrium at CFO. Hence the hadron yields produced in the collisions of large atomic nuclei can be found using the grand canonical valuables. The system pressure $p$ and the $K$-th charge density $n^K_i$ $(K \in \{B,S,I3\})$ of the $i$-th hadron sort are given by the expressions

$$p = \sum_{i=1}^{N} p_i, \quad n^K_i = \frac{Q^K_i p_i}{T + \sum_{j=1}^{N} b_{ij} p_j/p},$$

(1)

where $b_{ij} = \frac{2\pi}{(R_i + R_j)^3}$ is a symmetric matrix of the second virial coefficients, and $R_j$ is the hard-core radius of hadron of sort $j$. The equation of state of the system is written in terms of partial pressures $p_i$

$$p_i = T \phi_i(T) \exp \left[ \frac{\mu_i - 2 \sum_j p_j b_{ij} + \sum_{ji} p_j b_{ji} p_i/p}{T} \right], \quad \phi_i(T) = \frac{g_i}{(2\pi)^3} \int \exp \left[ -\frac{\sqrt{k^2 + m_i^2}}{T} \right] d^3 k.$$  

(2)

Here the full chemical potential of the $i$-th hadron sort $\mu_i \equiv Q_i^B \mu_B + Q_i^S \mu_S + Q_i^{I3} \mu_{I3}$ is expressed in terms of the corresponding charges $Q^K_i$ and their chemical potentials, $\phi_i(T)$ denotes the thermal particle density of the $i$-th hadron sort of mass $m_i$ and degeneracy $g_i$, and $T$ denotes the row of variables $\xi_i$. For each collision energy the fitting parameters are the temperature $T$, the baryonic chemical potential $\mu_B$ and the chemical potential of the third projection of isospin $\mu_{I3}$, whereas the strange chemical potential $\mu_S$ is found from the condition of vanishing strangeness.

In order to account for the possible strangeness non-equilibrium we employ the $\gamma_s$ factor [Rafelski et al., 1982] by replacing $\phi_i$ in Eqs. (2) as $\phi_i(T) \rightarrow \phi_i(T)\gamma_s^i$. Here $s_i$ is a number of strange valence quarks plus number of strange valence anti-quarks. The width correction is taken into account by averaging the Boltzmann exponent with the Breit-Wigner distribution. As a result, the modified thermal particle density of $i$-th hadron sort acquires the form

$$\int \exp \left[ -\frac{\sqrt{k^2 + m_i^2}}{T} \right] d^3 k \rightarrow \int_{M_0}^{\infty} \frac{dx}{(x-m_i)^2+T^2/4} \int \exp \left[ -\frac{\sqrt{x^2+z^2}}{T} \right] d^3 k.$$  

(3)

Here $m_i$ denotes the mean mass of hadron and $M_0$ stands for the threshold in the dominant decay channel. The main advantages of this approximation are a simplicity of its realization and a clear way to account for the finite width of hadrons.

The effect of resonance decay $Y \rightarrow X$ on the final hadronic multiplicity is taken into account as $n^{fin}(X) = \sum_{Y} BR(Y \rightarrow X) n^{th}(Y)$, where $BR(Y \rightarrow X) = 1$ for the sake of convenience. The masses, the widths and the strong decay branchings $BR(Y \rightarrow X)$ of all experimentally known hadrons were taken from the particle tables used by the thermodynamic code THERMUS [Wheaton et al., 2009]. The detailed description of the analyzed data sets together with the fit procedure can be found in [Sagun, 2014].

Table 1. The quality of data description achieved for the center of mass collision energy $\sqrt{s_{NN}}$.

| $\sqrt{s_{NN}}$ (GeV) | 2.7 | 3.3 | 3.8 | 4.3 | 4.9 | 6.3 | 7.6 | 8.8 | 9.2 | 12 | 17.0 | 62.4 | 130.0 | 200.0 |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|------|------|-------|-------|
| $\chi^2$            | 0.428 | 0.052 | 0.048 | 0.306 | 0.149 | 5.936 | 1.201 | 3.735 | 0.002 | 11.992 | 13.633 | 0.2807 | 4.337 | 6.898 |
| ratios number       | 4 | 5 | 5 | 5 | 8 | 9 | 10 | 11 | 5 | 10 | 13 | 5 | 11 | 10 |
The best global fit of all hadronic multiplicities corresponds to \( R_b = 0.355 \, \text{fm}, R_{\text{em}} = 0.4 \, \text{fm}, R_\pi = 0.1 \, \text{fm}, R_K = 0.38 \, \text{fm} \) and \( R_\Lambda = 0.11 \, \text{fm} \) with the quality \( \chi^2/\text{dof} \approx 0.95 \) [Sagun, 2014]. These hard-core radii were chosen, since the most abundant particle which are measured for all collision energies are pions, kaons, protons and (anti)Λ hyperons. As a result, this set of hard-core radii allowed us for the first time to simultaneously describe the peaks in \( K^+/\pi^+ \) and \( \Lambda/\pi^- \) ratios [Sagun, 2014, Bugaev et al.(1), 2015] without spoiling the high quality description of all other ratios. Note that for more than a decade these particle yield ratios, known as the Strangeness Horn \( K^+/\pi^+ \) and the Lambda hyperon horn \( \Lambda/\pi^- \), were the most problematic ones for the traditional thermal models [Andronic et al., 2006]. In Figure 1 we compare these experimental ratios and their fits achieved by the multicomponent HRGM. The obtained quality of fit of independent particle ratios for each center of mass collision energy point is presented in Table 1.

Irregularities at chemical freeze-out

It is necessary to stress that with the help of the present formulation of HRGM a plateau in the collision energy dependence of the thermal pion number per baryon and the quasi-plateaus in the entropy per baryon and in the total pion number per baryon were found recently in [Bugaev et al.(1), 2015]. A simultaneous appearance of these quasi-plateaus was predicted a long time ago in [Bugaev et al., 1989; Bugaev et al., 1990; Bugaev et al., 1991] to be a signal of the QGP-hadron mixed phase formation. Their appearance is a manifestation of anomalous thermodynamic properties of the mixed phase.

The validity of this signal is strongly supported by an existence of the sharp peak of the trace anomaly at \( \sqrt{s_{NN}} = 4.9 \, \text{GeV} \) (see the right panel of Figure 2). Note that the inflection point/maximum of the trace anomaly is traditionally used in lattice QCD to determine the pseudocritical temperature of the cross-over transition Borsanyi et al., 2012]. Furthermore, our simulations of the generalized shock adiabat show that this peak of \( \delta \) at CFO is a consequence of the peak of trace anomaly on the shock adiabat located exactly at the boundary of the mixed phase and QGP. From the expression for trace anomaly

\[
\delta = \frac{\varepsilon - 3p}{T^4} \approx \frac{s}{T^3} \left( 1 + \frac{\mu_B \rho_B}{s} \right) - 4 \frac{p}{T^4},
\]

one can show [Bugaev et al.(4), 2015] that the strong increase of \( \delta \) when the collision energy changes from \( \sqrt{s_{NN}} = 4.3 \, \text{GeV} \) to \( \sqrt{s_{NN}} = 4.9 \, \text{GeV} \) is provided by a strong jump of the effective number of degrees of freedom \( \frac{\varepsilon}{s} \) on this interval. Here \( \varepsilon \) is the energy density and \( s \) is the entropy density.

Also at \( \sqrt{s_{NN}} = 4.9 \, \text{GeV} \) we observe a sharp peak of the baryonic density at CFO (see the left panel of Figure 1. Collision energy dependence of \( K^+/\pi^+ \) (left panel, \( \chi^2/\text{dof} = 3.9/14 \)) and \( \Lambda/\pi^- \) (right panel, \( \chi^2/\text{dof} = 10.2/12 \)) hadron yield ratios.
Figure 2. Baryonic charge density (left panel) and trace anomaly (right panel) as functions of collision energy at CFO.

panel of Figure 2), which is a consequence of the baryonic density peak at the generalized shock adiabat existing at the boundary between the mixed phase and QGP.

Figure 3. The center of mass collision energy dependence of the $\frac{\Lambda}{p}$ ratio obtained within the present HRGM. The lines are given to guide the eye.

The other evidence of a possible deconfinement transition between the collision energies $\sqrt{s_{NN}} = 4.3$ and 4.9 GeV is provided by the sudden increase of $\frac{\Lambda}{p}$ slope at $\sqrt{s_{NN}} = 4.3$ GeV (see Figure 3). The same behavior was found for $\frac{K^+}{p}$, $\frac{\Omega^-}{p}$ and $\frac{\Xi^-}{p}$ ratios. This behavior can be naturally explained [Bugaev et al.(4), 2015] by the idea suggested in [Rafelski et al., 1982] that the mixed phase formation can be detected by a rapid increase in the number of strange quarks per number of light quarks. Evidently, the $\Lambda/p$ ratio is a convenient indicator because at low collision energies the $\Lambda$-hyperons are generated in collisions of nucleons. Moreover, such a ratio does not depend on baryonic chemical potential, since both the protons and $\Lambda$-hyperons have the same baryonic charge. As it is seen from the Figure 3, this mechanism works up to $\sqrt{s_{NN}} = 4.3$ GeV, while an appearance of the mixed phase leads to an increase of the number of strange quarks and antiquarks due to the annihilation of light quark-antiquark and gluon pairs.

A similar behavior with a clear jump at the energies $\sqrt{s_{NN}} = 4.3 - 4.9$ GeV we predict for the
collision energy dependence of the ratio $\Delta \Lambda p / \Delta p$ which is shown in the left panel of Figure 4. Since the observed jump of this ratio is located in the collision energy region of the mixed phase formation (i.e. with a first order phase transition), then a change of its slope at $\sqrt{s_{NN}} = 9.2$ GeV can be naturally associated with a weak first order or a second order phase transition \cite{Bugaev et al.(4), 2015}. Note that this hypothesis is well supported by the second peak of the trace anomaly existing at $\sqrt{s_{NN}} = 9.2$ GeV (see the right panel of Figure 2) and by the second set of quasi-plateaus found for $\sqrt{s_{NN}} \in [7.6; 9.2]$ GeV \cite{Bugaev et al.(1), 2015}.

The observed irregularities are also accompanied by a sudden increase of the strange particle decays at CFO which is also seen in the same collision energy range $\sqrt{s_{NN}} \in [4.3; 4.9]$ GeV. The asymmetries between the total and the thermal particle yields $K^+_\text{tot} - K^+_\text{th}$, $\Lambda_{\text{tot}} - \Lambda_{\text{th}}$, $\Xi^-_{\text{tot}} - \Xi^-_{\text{th}}$, indicating a significant role of the strange particle decays at CFO. In addition, we found the strong sharp peaks in the trace anomaly $\delta = \frac{\varepsilon - 3p}{T}$ and in the baryonic charge density at $\sqrt{s_{NN}} = 4.9$ GeV, which are related to the peaks of corresponding quantities on the generalized shock adiabat located at the boundary between the mixed phase and QGP.

Therefore, we conclude that a dramatic change of the system properties seen in the narrow collision energy range $\sqrt{s_{NN}} = 4.3 - 4.9$ GeV opens entirely new possibilities for the FAIR and NICA experiments. We guess that the second set of peaks of these quantities which we observe at the collision energy $\sqrt{s_{NN}} = 9.2$ GeV may evidence for another phase transformation in heavy ion collisions, but to get more definite conclusions about them we need more experimental data measured with essentially higher precision. We hope that the future experiments at NICA and FAIR will provide us with such data.

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