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# Evidences of quark-gluon plasma formation in central nuclear collisions

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**Abstract.** Due to the absence of clear and unambiguous theoretical signals of the deconfinement transition from hadron matter to quark-gluon plasma (QGP) the experimental searches of QGP formation are based the analysis of various irregularities in the collision energy dependence of thermodynamic and hydrodynamic quantities. Here we present several remarkable irregularities at chemical freeze-out (CFO) of hadrons which are found using an advanced version of the hadron resonance gas model (HRGM). Among them are the sharp peaks of the trace anomaly and baryonic density which are seen at the center of mass energies  $\sqrt{s_{NN}}=4.9$  GeV and  $\sqrt{s_{NN}}=9.2$  GeV, and the two sets of highly correlated quasi-plateaus in the collision energy dependence of the entropy per baryon, total pion number per baryon, and thermal pion number per baryon which we found at the center of mass energies 3.8-4.9 GeV and 7.6-10 GeV. In addition we found a significant change of slope of the hadron yield ratios  $\frac{\Lambda}{p}$  and  $\frac{\Lambda-\bar{\Lambda}}{p-\bar{p}}$ , when the center of mass collision energy increases from 4.3 GeV to 4.9 GeV and from 7.6 GeV to 9.2 GeV [1]. The increase of slopes of these ratios at the collision energy interval 4.3-4.9 GeV is accompanied by a dramatic growth of resonance decays at CFO. We argue that such a strong correlation between the previously found irregularities and an enhancement of strangeness production can serve as the quark-gluon plasma formation signature. Hence, 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 may open entirely new possibilities for experimental studies of QGP properties at NICA JINR and FAIR GSI accelerators.

## 1. Introduction

Traditionally it is expected that the formation of quark-gluon-hadron mixed phase should be accompanied by the irregularities of different thermodynamic and hydrodynamic quantities [2]. Evidently, the success of experimental searches of the mixed phase formation can be achieved, if and only if there exist clear and unambiguous theoretical predictions for such signals. Here we report the new irregularities [1, 3] which are found using the advanced version of HRGM [4, 5, 6]. In contrast to previously developed versions of HRGM [7, 8] the present one accounts for the hard-core repulsion using the different hard-core radii for pions,  $R_\pi$ , kaons,  $R_K$ ,  $\Lambda$ -hyperons,  $R_\Lambda$ , other mesons,  $R_m$ , and other baryons,  $R_b$ .

The advanced version of HRGM [4, 5, 6] allows one not only to reach the highest quality of the data description, but also it allows us to extract various thermodynamic quantities at CFO with high confidence and, hence, to reveal a few novel irregularities. Among them are the sharp peak of the trace anomaly  $\delta = \frac{\epsilon-3p}{T^4}$  (here  $\epsilon$  is energy density) at  $\sqrt{s_{NN}} = 4.9$  GeV [1].



In Ref. [1] it was also shown that the trace anomaly peak at CFO exists almost at the same collision energy where the boundary between the QGP and quark-gluon-hadron mixed phase is reached. The latter was elucidated using the shock adiabat model which provides a reasonable description of hydrodynamic and thermodynamic parameters of the initial state formed in the central nucleus-nucleus collisions in the laboratory energy range  $1 \text{ GeV} \leq E_{lab} \leq 30 \text{ GeV}$  [1, 3, 8].

In addition to previously reported irregularities [1, 3] here we present a significant change of slope in the collision energy dependence of  $\frac{\Lambda}{p}$  and  $\frac{\Lambda-\Lambda}{p-p}$  hadron yield ratios observed at CFO for two intervals of the center of mass collision energy  $\sqrt{s_{NN}} = 4.3 - 4.9 \text{ GeV}$  (low energy interval) and  $\sqrt{s_{NN}} = 7.6 - 9.2 \text{ GeV}$  (high energy interval). Besides, we report about two sharp peaks of the baryonic density at CFO which are seen at  $\sqrt{s_{NN}} = 4.9 \text{ GeV}$  and  $\sqrt{s_{NN}} = 9.2 \text{ GeV}$ . The present work is devoted to elucidating the meaning of all these irregularities which are found in the low and high energy intervals and to revealing their relation to possible phase transformations in central nuclear collisions.

The structure of the paper is as follows. The next Section is devoted to the HRGM formulation. In Section 3 we discuss the CFO irregularities and their relation to phase transformations. In Section 4 we summarize our conclusions.

## 2. Hadron Resonance Gas Model

The multicomponent HRGM developed in [4, 5, 6, 9] deals with the Boltzmann gas consisting of several sorts of hadrons having their own hard-core radius  $R_i$ . The multicomponent hard-core repulsion is introduced via the matrix of second virial coefficients  $b_{ij}$  which for the hadrons of hard-core radii  $R_i$  and  $R_j$  reads as  $b_{ij} = \frac{2\pi}{3}(R_i + R_j)^3$ . The hadrons of  $i$ -th sort are characterized by the spin-isospin degeneracy  $g_i$ , the mass  $m_i$  and the width  $\Gamma_i$ . The pressure  $p_i$  and the thermal density  $\varphi_i$  of  $i$ -th hadron sort are defined as

$$p_i = T\varphi_i \exp \left[ \frac{\mu_i - 2 \sum_j p_j b_{ji} + \sum_{jl} p_j b_{jl} p_l / p}{T} \right], \quad (1)$$

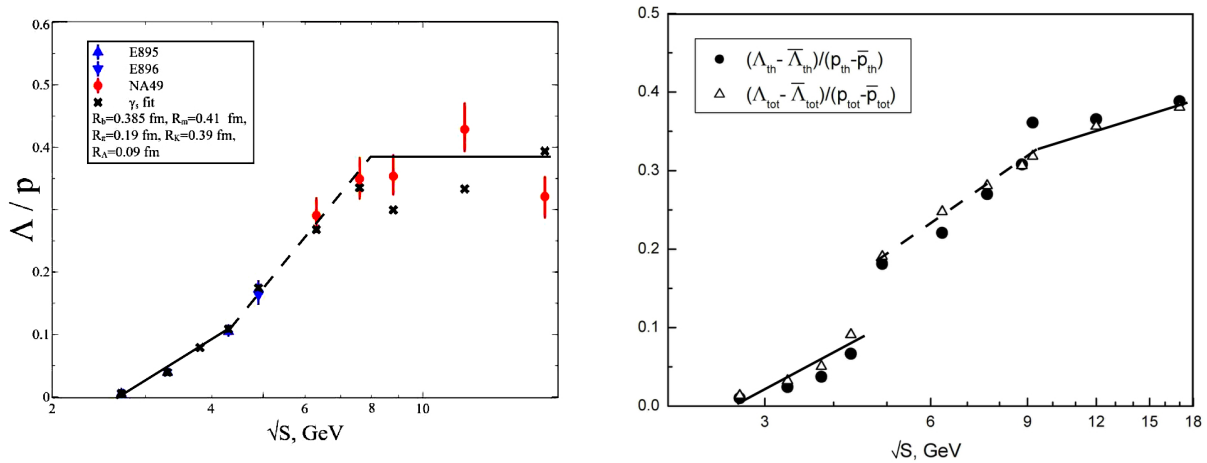
$$\varphi_i = \gamma_s^{S_i} g_i \int_{M_i}^{\infty} dm f(m, m_i, \Gamma_i) \int \frac{d\mathbf{k}}{(2\pi)^3} e^{-\frac{\sqrt{m^2 + \mathbf{k}^2}}{T}}, \quad (2)$$

where the total pressure  $p = \sum_i p_i$  is a sum of partial pressures  $p_i$  for each hadronic component. The full chemical potential of  $i$ -th sort of hadrons  $\mu_i = Q_i^B \mu_B + Q_i^{I3} \mu_{I3} + Q_i^S \mu_S$  is expressed via the charges  $\{Q_i^A\}$  of  $i$ -th hadron sort and the corresponding chemical potentials  $\{\mu_A\}$ . In Eq. (2) the strangeness suppression/enhancement factor is  $\gamma_s$ ,  $S_i$  denotes the total number of strange valence quarks and antiquarks in a hadron of sort  $i$ ,  $M_i$  is a threshold of its dominant decay channel and  $f$  is the normalized Breit-Wigner mass attenuation. The masses, the widths and the strong decay branching ratios of all experimentally known hadrons were taken from the particle tables of the thermodynamic code THERMUS [9]. The effect of resonance decay was taken into account in a standard way (for details see [7]).

With such a model we are able to fit the experimental multiplicities measured at AGS energies  $\sqrt{s_{NN}} = 2.7, 3.3, 3.8, 4.3, 4.9 \text{ GeV}$ , the NA49 data measured at SPS energies  $\sqrt{s_{NN}} = 6.3, 7.6, 8.8, 12.3, 17.3 \text{ GeV}$  and the STAR data measured at RHIC energies  $\sqrt{s_{NN}} = 9.2, 62.4, 130, 200 \text{ GeV}$  with the highest quality  $\chi^2/dof \simeq 0.98$  [8]. The local fitting parameters for each collision energy ( $T$ ,  $\mu_B$ ,  $\mu_{I3}$  and  $\gamma_s$ ) and the global ones, i.e. the values of hard-core radii  $R_b = 0.355 \text{ fm}$ ,  $R_m = 0.4 \text{ fm}$ ,  $R_\pi = 0.1 \text{ fm}$ ,  $R_K = 0.38 \text{ fm}$  and  $R_\Lambda = 0.11 \text{ fm}$ , were determined by  $\chi^2$  minimization. Based on such a high quality fit we can study thermodynamics of strongly interacting matter at CFO with very high confidence.

### 3. Irregularities at chemical freeze-out of hadrons

Using the present formulation of the HRGM we found increase in the slope of the  $\Lambda/p$  ratio at  $\sqrt{s_{NN}} = 4.3$  GeV and its saturation above  $\sqrt{s_{NN}} = 7.6$  GeV which is clearly seen on the left panel of figure 3. According to the idea of strangeness enhancement [10] the change of slope at  $\sqrt{s_{NN}} = 4.3$  GeV can be naturally explained by a rapid increase in the number of strange quarks per light quarks.

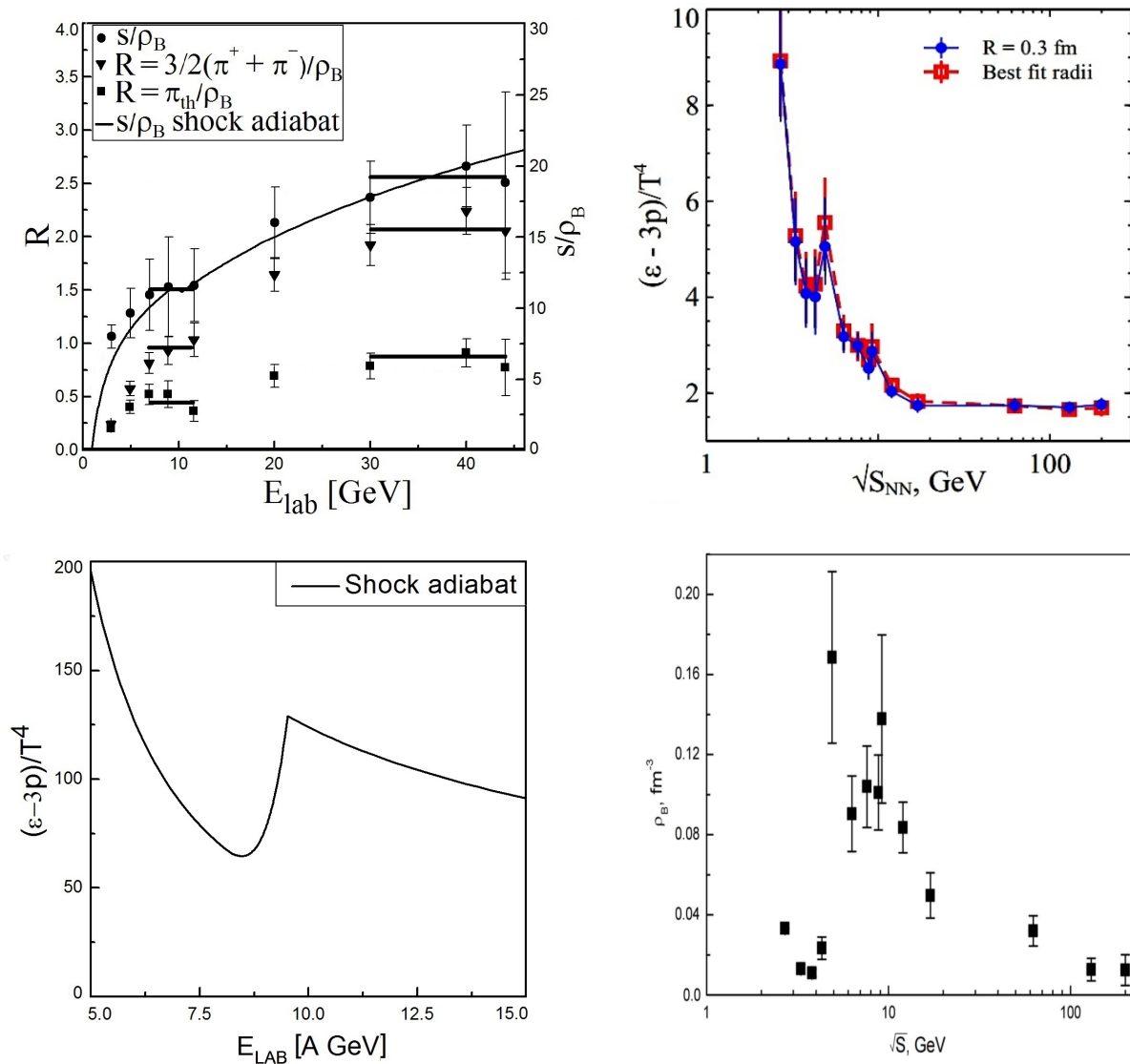


**Figure 1.** The center of mass collision energy dependence of the  $\frac{\Lambda}{p}$  ratio (left panel) and  $\frac{\Delta\Lambda}{\Delta p}$  ratio (right panel). The data and their description is shown in the left panel. In the right panel we compare the total (triangles) and thermal (circles) multiplicities. The lines are given to guide the eye.

Since at low collision energies the  $\Lambda$  hyperons are generated in collisions of nucleons, the  $\Lambda/p$  ratio is a convenient indicator of the onset of deconfinement. If the mixed phase is formed at about  $\sqrt{s_{NN}} = 4.3$  GeV, then its appearance should lead to an increase in the number of strange quarks and antiquarks due to the annihilation of light quark-antiquark and gluon pairs [11]. Note that this simple picture is in line with our previous conclusions that the mixed phase can be reached at  $\sqrt{s_{NN}} = 4.3$  GeV [1, 3].

From the right panel of figure 3 one can see a remarkable jump in the collision energy dependence of the  $\frac{\Delta\Lambda}{\Delta p} = \frac{\Lambda - \bar{\Lambda}}{p - \bar{p}}$  ratio which is located in the collision energy region of the mixed phase formation (i.e. with a first order phase transition), while the change of its slope at  $\sqrt{s_{NN}} \simeq 9.2$  GeV can be, probably, associated with a weak first order or a second order phase transition. As one can see from the figure 3 the behavior of thermal multiplicities of the  $\frac{\Delta\Lambda}{\Delta p}$  ratio (right panel) is very similar to the one of total multiplicities at CFO (left panel) and, therefore, such a ratio can be used to directly access the moment of CFO by other models which, in contrast to HRGM, do not account for the resonance decays.

Based on the multicomponent 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 at laboratory energies 6.9–11.6 GeV (i.e.  $\sqrt{s_{NN}} = 3.8 - 4.9$  GeV) were found recently in [1, 3] (see the upper left panel of figure 3). A simultaneous appearance of these quasi-plateaus was predicted in [12, 13, 14] as a signal of the QGP-hadron mixed phase formation. Their existence is a signal of forming a matter with the anomalous thermodynamic properties. In comparison to the pure phases in which at high densities the adiabatic compressibility of matter decreases for increasing pressure in the systems with anomalous thermodynamic properties there appears another possibility to compress matter:



**Figure 2. Left panels:** Laboratory energy dependence of the correlated quasi-plateaus at CFO are taken from [3] (upper panel) and trace anomaly along the generalized shock adiabat (lower panel). For more details see the text. **Right panels:** Center of mass energy dependence of the trace anomaly (upper panel) and the baryonic charge density (lower panel) found at CFO [8].

by converting the less dense phase into the more dense one. Within the shock adiabat model [1, 3, 13] it is possible to successfully describe the collision energy dependence of the entropy per baryon found at CFO (see the solid curve in the upper left panel of figure 3).

In Ref. [1] it was established the one-to-one correspondence between the peak of the trace anomaly  $\delta$  along the shock adiabat model (see the lower left panel of figure 3) and the peak of  $\delta$  at CFO shown in the upper right of figure 3. Note that a strong increase of  $\delta = \frac{\epsilon - 3p}{T^4} \simeq \frac{s}{T^3} (1 + \frac{\mu_B}{T} \frac{\rho_B}{s}) - 4 \frac{p}{T^4}$  between  $\sqrt{s_{NN}} = 4.3$  GeV to  $\sqrt{s_{NN}} = 4.9$  GeV is provided by a strong jump of the effective number of degrees of freedom  $\frac{s}{T^3}$  on this interval [14]. Here  $\epsilon$  is the energy density and  $s$  is the entropy density. Besides this peak in the upper right of

figure 3 one can see a weaker peak of  $\delta$  at  $\sqrt{s_{NN}} = 9.2$  GeV. At the same time from the lower right panel of figure 3 one can clearly see two sharp peaks of the baryonic density at CFO at collision energies  $\sqrt{s_{NN}} = 4.9$  GeV and  $\sqrt{s_{NN}} = 9.2$  GeV. It is remarkable that the energies of these two pairs of peaks are very well correlated with the maximal energies of low and high energy sets of quasi-plateaus discussed above (see also the upper left panel of figure 3). Since the low energy quasi-plateaus and, hence, other irregularities can be attributed to the mixed phase formation [1, 3] we can guess that the set of high energy quasi-plateaus and the accompanied irregularities of the  $\frac{\Lambda}{p}$  and  $\frac{\Delta\Lambda}{\Delta p}$  ratios, and peaks of trace anomaly and baryonic density may also evidence for another phase transformation which should be studied further.

#### 4. Conclusions

Here we present several irregularities found at the CFO of hadrons. We found that the strong peaks in the trace anomaly  $\delta = \frac{\epsilon - 3p}{T^4}$  and in the baryonic charge density at  $\sqrt{s_{NN}} = 4.9$  GeV are related to the peaks of corresponding quantities on the generalized shock adiabat which are located at the boundary between the mixed phase and QGP. Furthermore, the low energy 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 ends exactly at  $\sqrt{s_{NN}} = 4.9$  GeV. These quasi-plateaus were predicted as the signal of mixed phase formation in [11, 12, 13]. Also in the narrow collision energy region  $\sqrt{s_{NN}} = 4.3 - 4.9$  GeV we observe a strong increase of slope of the  $\frac{\Lambda}{p}$  ratio and a jump of the  $\frac{\Delta\Lambda}{\Delta p}$  ratio which can be naturally explained by an old idea of strangeness enhancement [10] at the deconfinement transition. Therefore, all these irregularities can be considered as the strongest signals of the onset of deconfinement.

At the collision energies  $\sqrt{s_{NN}} = 7.6 - 10$  GeV we found the second set of quasi-plateaus of the same quantities as for the low energy set. Moreover, at  $\sqrt{s_{NN}} = 9.2$  GeV there are the peaks in the trace anomaly and baryonic density at CFO, and one can see that the  $\frac{\Lambda}{p}$  and  $\frac{\Delta\Lambda}{\Delta p}$  ratios change their slopes again at about  $\sqrt{s_{NN}} = 7.6 - 9.2$  GeV. This set of irregularities requires further clarifications, but it is possible that it could be either the weak first order or the second order phase transition, if QCD has a tricritical endpoint. We hope that the nature of all these irregularities can be clarified in the future experiments at NICA and FAIR.

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