Chemical Freeze-out Irregularities and Quark Gluon Plasma Formation

A.I. Ivanytskyi[1], K.A. Bugaev[1], D.R. Oliinychenko[1,2], V.V. Sagun[1],
I.N. Mishustin[2], D.H. Rischke[3], L.M. Satarov[2] and G.M. Zinovjev[1]
[1] Bogolyubov Institute for Theoretical Physics, Ukraine
[2] Frankfurt Institute for Advanced Studies, Goethe-University, Germany
[3] Institute for Theoretical Physics, Goethe-University, Germany

Abstract

A high quality description of the hadronic ratios obtained by the realistic version of the hardon resonance gas model (HRGM) [1] allows us to reveal, at chemical freeze-out, remarkable irregularities such as an abrupt change of the effective number of degrees of freedom and plateaus in the collision-energy dependence of the entropy per baryon, total pion number per baryon, and thermal pion number per baryon at lab. energies 6.9-11.6 AGeV [2]. Using the generalized shock adiabat model we show that these plateaus give evidence for thermodynamic anomalous properties of the mixed phase at its boundary to the quark-gluon plasma (QGP).

Irregularities at chemical freeze-out

- HRGM accounts for all hadrons from PDG tables with masses up to **3.2** GeV [1].
- Equation of state:

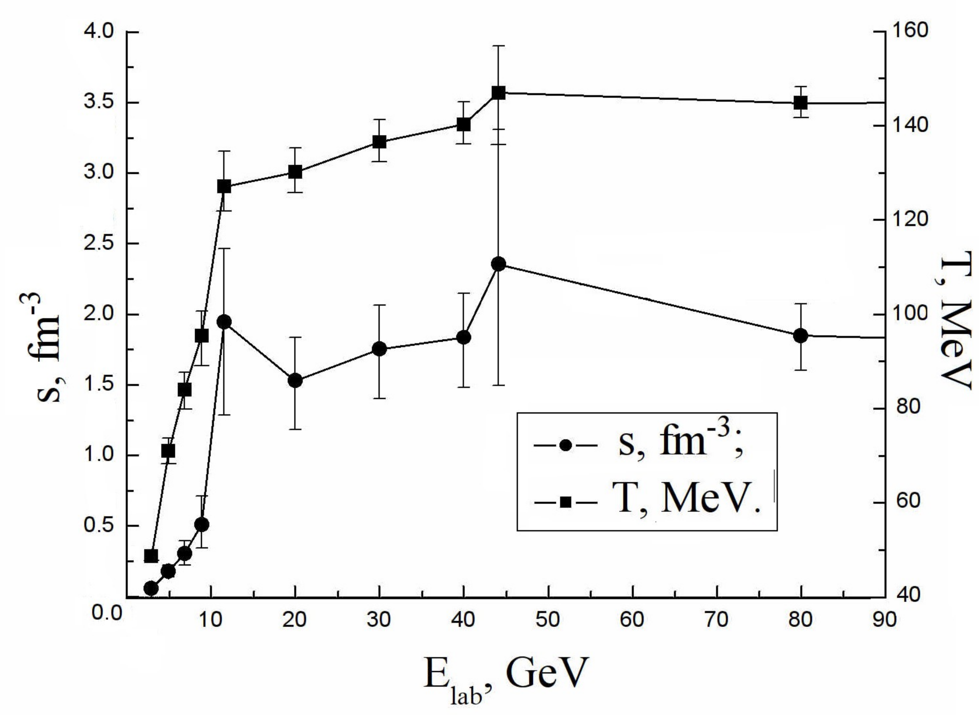
$$p = \sum_k p_k, \qquad \rho_k^{th} = \frac{\partial p}{\partial \mu_k}, \qquad \mu_k = Q_k^B \mu_B + Q_k^S \mu_S + Q_k^{I3} \mu_{I3}$$

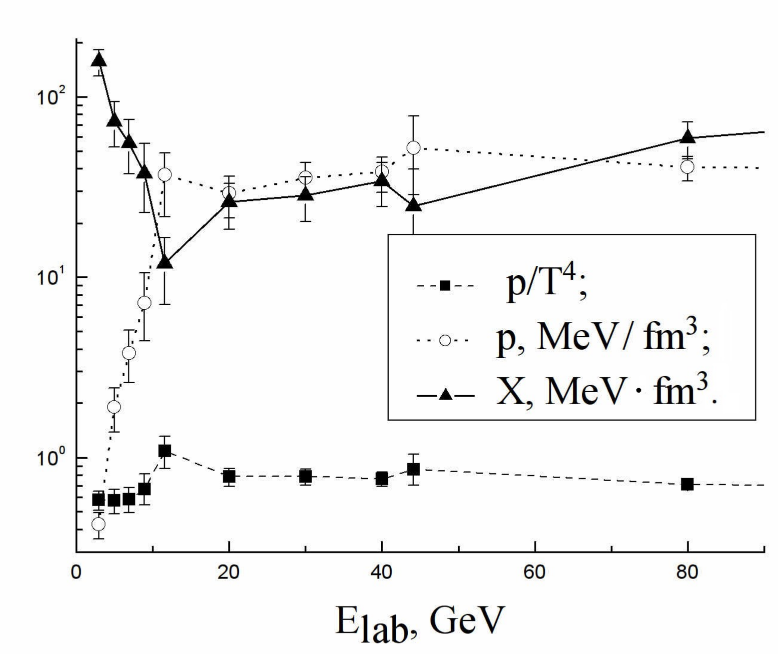
$$p_k = T\phi_k exp\left(\frac{\mu_k}{T} - 2\sum_j \frac{p_j V_{jk}}{T} + \sum_{jj'} \frac{p_j V_{jj'} p_{j'}}{T} \Big/ \sum_j p_j\right), \qquad V_{kj} = \frac{2\pi}{3}(R_k + R_j)^3,$$

$$\phi_k = g_k \int_{m^{Th}}^{\infty} dm\, f(m, m_k, \Gamma_k) \int \frac{d^3k}{(2\pi)^3} exp\left(-\frac{\sqrt{k^2+m^2}}{T}\right)$$

- The width effects are accounted by normalized mass distribution $f(m, m_k, \Gamma_k)$, either Gauss or Breit-Wigner.
- Strong decays are taken into account [1, 2].

111 independent hadron ratios measured at $\sqrt{S_{NN}} = 2.7 - 200$ GeV are fitted with $\chi^2/dof = 1.16$. Even the Strangeness Horn is described with $\chi^2/dof = 7.5/14$. Thus, the present model is a precise tool to investigate chemical freeze-out.





Narrow range of collision energy $E_{lab} = 6.9 - 11.6$ GeV exhibits significant jumps of s, p, T, p/T^4, s/T^3 and generalized specific volume $X = \frac{\epsilon + p}{\rho_B^2}$ has a deep minimum.

Observation of plateaus

It was predicted [3] that the anomalous properties of the mixed phase can generate the plateaus in energy dependence of s/ρ_B, ρ_π^{th}/ρ_B and ρ_π^{tot}/ρ_B. The chemical freeze-out data demonstrate such plateaus (see Fig. below). Let us find their parameters:

- The plateaus have heights R_A for $A \in \{s/\rho_B; \rho_\pi^{th}/\rho_B; \rho_\pi^{tot}/\rho_B\}$.
- The plateaus are generated by the same physical cause $\Rightarrow$ they have the same width $M > 1$, i_0 denotes its beginning.
- The plateaus are correlated to each other, if $\chi^2/dof < 1$.
- It is necessary to find the set of widest correlated plateaus.

For given M and i_0 the χ^2/dof is defined as

$$\chi^2/dof = \frac{1}{3M-3} \sum_A \sum_{i=i_0}^{i_0+M-1} \left(\frac{R_A - A_i}{\delta A_i}\right)^2,$$

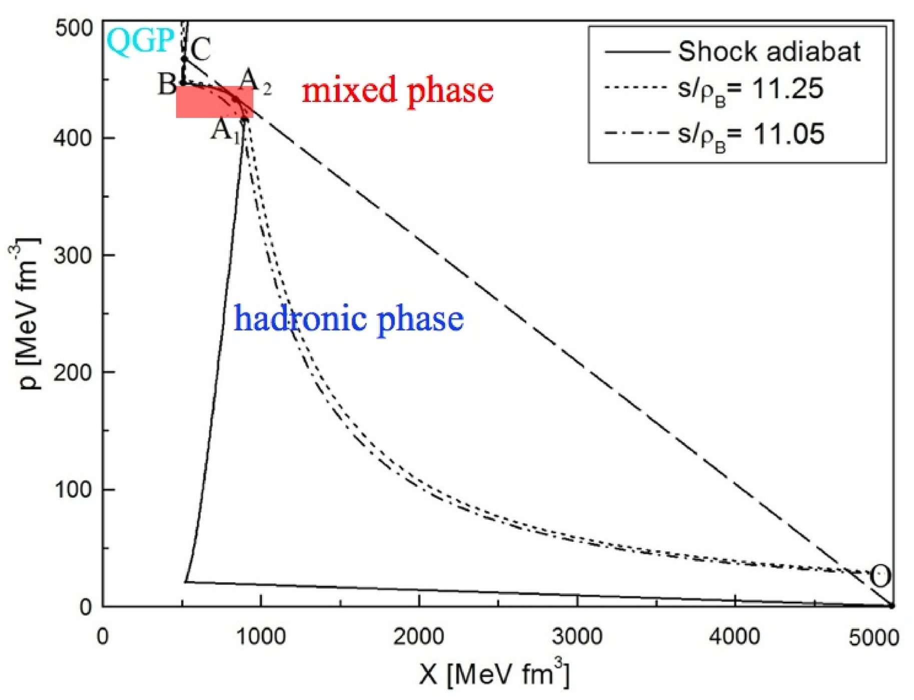
its minimization with respect to R_A gives

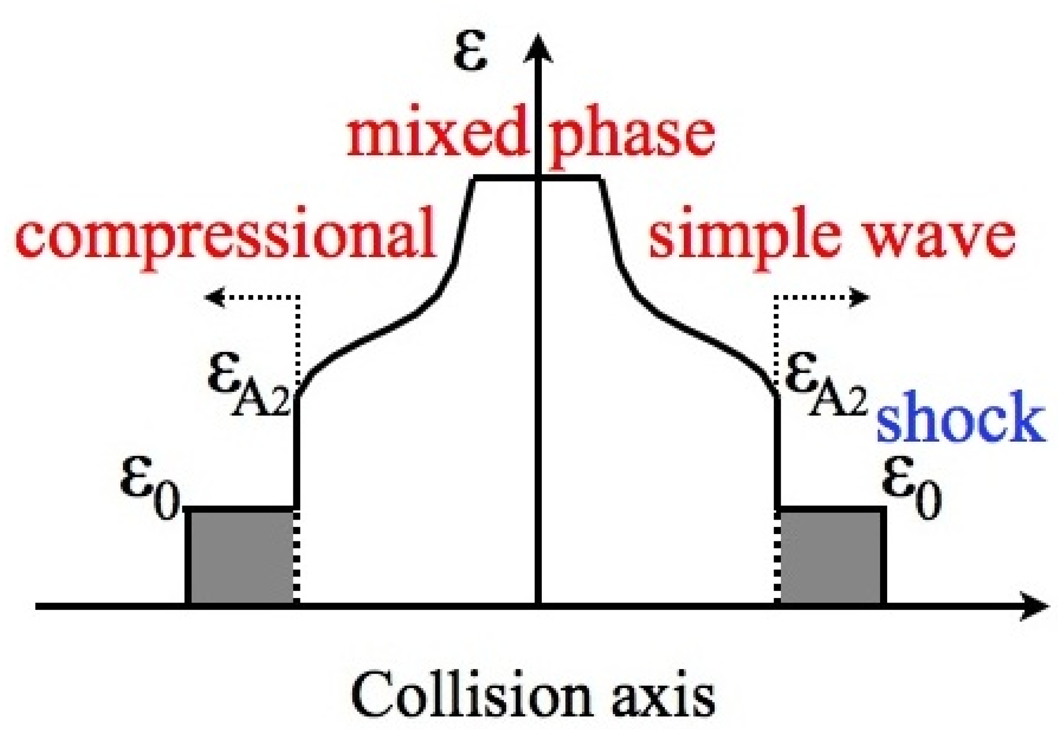
$$R_A = \sum_{i=i_0}^{i_0+M-1} \frac{A_i}{(\delta A_i)^2} \Big/ \sum_{i=i_0}^{i_0+M-1} \frac{1}{(\delta A_i)^2}.$$

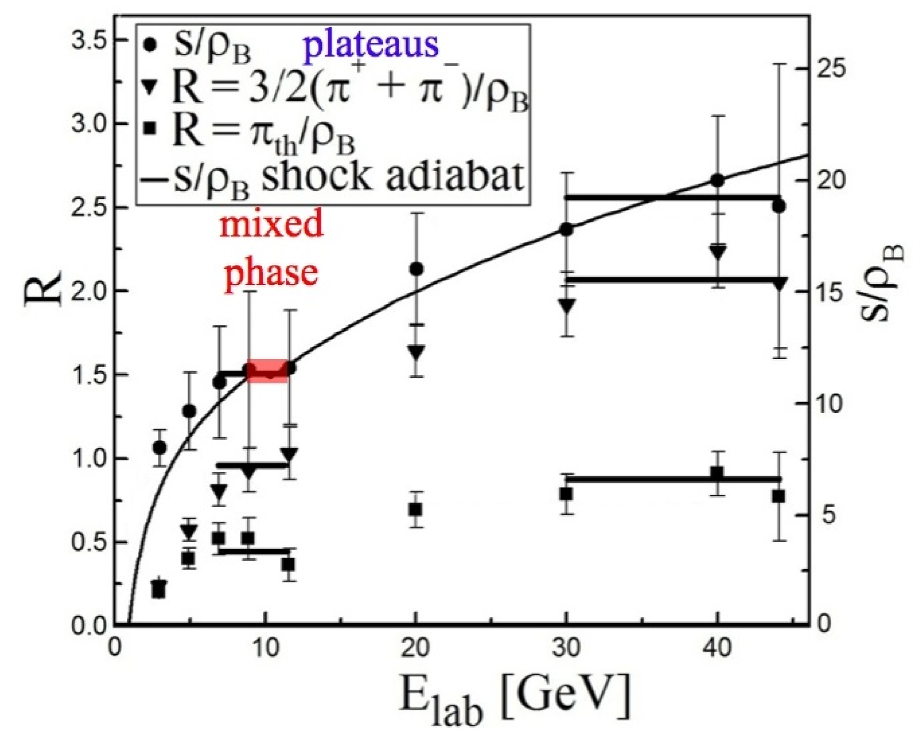
M	i_0	R_{s/ρ_B}	$R_{\rho_\pi^{th}/\rho_B}$	$R_{\rho_\pi^{tot}/\rho_B}$	χ^2/dof
		Low energy minimum			
2	3	11.12	0.52	0.85	0.17
3	3	11.31	0.46	0.89	0.53
4	2	10.55	0.43	0.72	1.64
5	2	11.53	0.47	0.84	4.45
		High energy minimum			
2	8	19.80	0.88	2.20	0.12
3	7	18.77	0.83	2.05	0.34
4	6	17.82	0.77	1.87	0.87
5	5	16.26	0.64	1.62	3.72

There are two different sets of plateaus. The low energy one is located at $E_{lab} = 6.9 - 11.6$ GeV, where irregularities do exist.

Generalized shock adiabat model (GSAM)







- GSAM of central nuclear collisions defines thermodynamic parameters of the compressed matter by the Rankine-Hugoniot-Taub abiabat [3]

$$(\rho_b X)^2 - (\rho_0 x_0)^2 - (p - p_0)(X + X_0) = 0,$$ where ρ_0, p_0, ϵ_0 and $X_0 = \frac{p_0 + \epsilon_0}{\rho_0^2}$ corresponds to initial state.

- Collision energy per nucleon of mass m_n is defined as $E_{lab} = 2m_n\left(\frac{(p+\epsilon_0)(p_0+\epsilon)}{(p+\epsilon)(p_0+\epsilon_0)} - 1\right)$.
- The EOS is necessary to complete the shock adiabat equation. The used QGP EOS is of the MIT Bag model kind, while the hadronic EOS is an effective one, which successfully describes the the chemical freeze-out data [1, 2].
- Thermodynamically normal ($\Sigma > 0$) and anomalous ($\Sigma > 0$) properties are typical for onephase and twophase regions, respectively $\Sigma = \left(\frac{\partial^2 p}{\partial X^2}\right)^{-1}_{s/\rho_B = const}$.

The anomalous properties of mixed phase (A_1 A_2B) lead to instabilities of shock transitions into the region A_2BC (see fig. $p(X)$). In this case a single shock to the region A_2B should be replace by the shock from O to A_2 (Chapman-Jouguet point) and by a compressional simple wave starting at point A_2 (see collision sketch). For such a solution the entropy is conserved, i.e., the ratio $s/\rho_B = const$, because the whole entropy production is generated by a shock OA_2 to the point A_2. This means that by increasing E_{lab} one generates more compressed states which have the same value of s/ρ_B. Thus, one gets the plateau in E_{lab} dependence of s/ρ_B. The important physical consequence of such an instability is also a plateau in the collison-energy dependence of the total number of pions per baryon produced in a nuclear collision, i.e., $\rho_\pi^{tot}/\rho_B(E_{lab}) \simeq const$ [3], provided by the entropy conservation during the subsequent expansion of the hydrodynamic flow formed by the GSA.

Conclusions

- On the basis of high quality experimental data fit it is shown that narrow range of collision energy $E_{lab} = 6.9 - 11.6$ GeV contains remarkable irregularities in various thermodynamic quantities.
- Within GSAM the plateau-like behavior of s/ρ_B is explained as a signature of QGP formation.
- New signal of QGP formation, i.e. minimum of generalized specific volume X, is suggested and justified.

References

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3. K.A. Bugaev, M.I. Gorenstein and D.H. Rischke, Phys. Lett. B **255**, 1, 18 (1991).