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Thermodynamically Anomalous Regions as a Mixed Phase Signal

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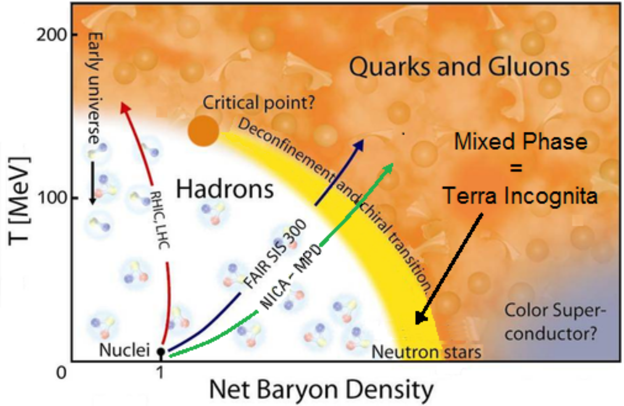
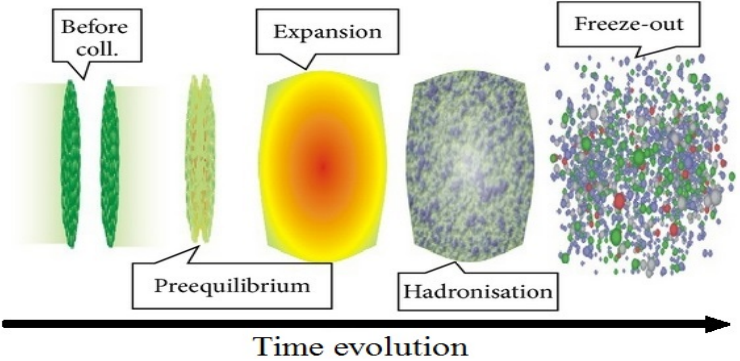
QCD phase diagram



Phase transitions from hadrons to QGP

- are predicted theoretically (**LQCD simulations, chiral limit calculations**)
  Z.Fodor, C.Guse, S.Katz, K.Szabo, PoS. LAT 2007
  R.D. Pisarski, F.Wilczek, PRD, 29 (1984)
- still are not observed directly in **Heavy Ion Collisions**

Chemical freeze-out in heavy ion collisions



Chemical freeze-out (CFO) :

- equilibrium stage of heavy ion collision
  P. Braun-Munzinger et al., Phys. Lett. B 344, 43, (1995)
  J. Cleymans et al., Z. Phys. C 74, 319 (1997)
- moment when all inelastic reactions excluding decays cease out to exist
- chemical composition of the hadronic system after CFO is frozen
- formation of many particle yields

Irregularities at CFO

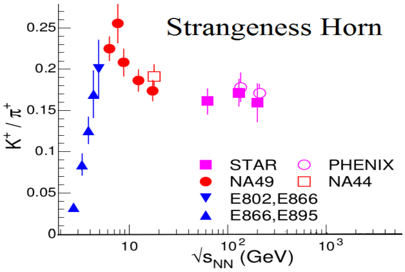
Possible phase transformations in heavy ion collisions

⇓

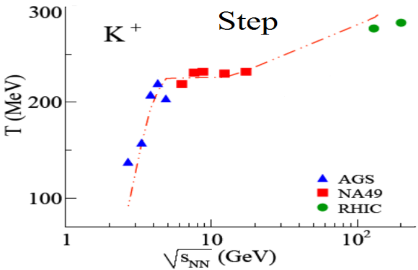
Qualitative changes in properties of strongly interacting system

⇓

Irregular behavior of different physical observables
Signals of phase transition in heavy ion collisions



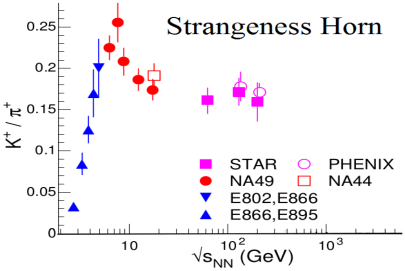
M. Gadzdzicki, M. Gorenstein, Acta Phys. Polon. B 30, 2705 (1999)



M. I. Gorenstein et al., Phys. Lett. B 567, 175-178 (2003)

Irregularities at CFO

These irregularities cannot be reproduced within the same model



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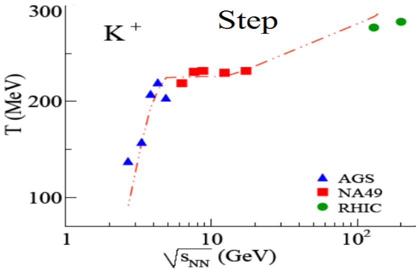

M. I. Gorenstein et al., Phys. Lett. B 567, 175-178 (2003)

Irregularities at CFO

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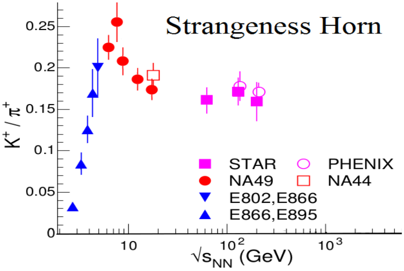
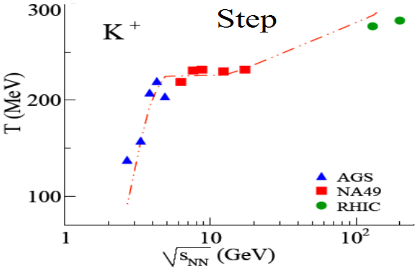
$\Downarrow$

We do not completely understand what they mean



M. Gadzdzicki, M. Gorenstein, Acta Phys. Polon. B 30, 2705 (1999)



M. I. Gorenstein et al., Phys. Lett. B 567, 175-178 (2003)

Irregularities at CFO

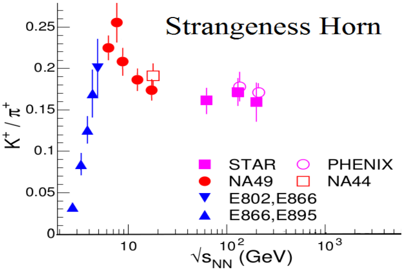
These irregularities cannot be reproduced within the same model

$\Downarrow$

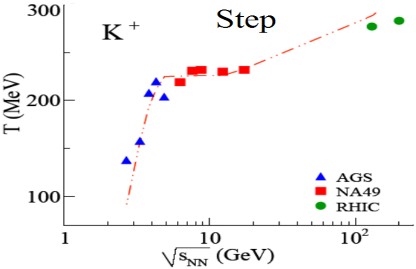
We do not completely understand what they mean

$\Downarrow$

New signals should be searched for



M. Gadzdzicki, M. Gorenstein, Acta Phys. Polon. B 30, 2705 (1999)



M. I. Gorenstein et al., Phys. Lett. B 567, 175-178 (2003)

Hadron resonance gas model (HRGM)

- Thermal/chemical equilibrium ⇒ parameters: $T, \mu_B, \mu_{I3}, \mu_S$

  P. Braun-Munzinger et al., Phys. Lett. B 344, 43, (1995)
  J. Cleymans et al., Z. Phys. C 74, 319 (1997)

- All hadrons from PDG tables with masses up to 3.2 GeV

  K.A. Bugaev et al., Eur. Phys. J. A 49, 30 (2013)

- Multicomponent hard-core repulsion ⇒ Van der Wals type equation of state

$$R_\pi = 0.1 \ \text{fm}, \quad R_K = 0.38 \ \text{fm}, \quad R_{meson} = 0.4 \ \text{fm}, \quad R_{baryon} = 0.2 \ \text{fm}$$

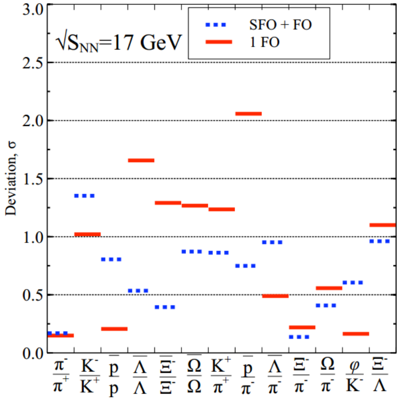
  K.A. Bugaev et al., Europhys. Lett. 104, 22002 (2013)

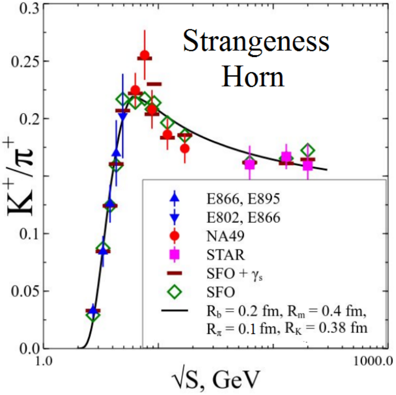
- Width of hadrons ⇒ modification of one particle thermal density by Gauss or Breit-Wigner mass attenuation

- Strong Decays ⇒ modification of particle densities from thermal to total ones according to values of branching ratios

HRGM and particle yields at CFO

- 111 independent hadron ratios measured at $\sqrt{S_{NN}} = 2.7 - 200$ GeV are fitted with $\chi^2/\text{dof} = 1.06$, even most problematic Strangeness Horn (K^+/π^+) is reproduced with $\chi^2/\text{dof} = 7.5/14$



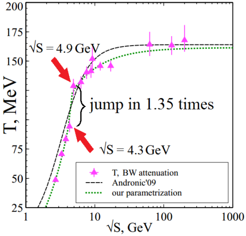


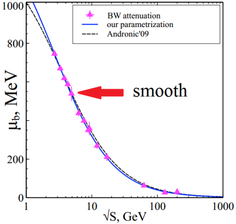
K.A. Bugaev et al., Europhys. Lett. 104 (2013) 22002
K.A. Bugaev et al., Eur. Phys. J. A, 49 (2013) 30

HRGM is a precise tool to investigate CFO

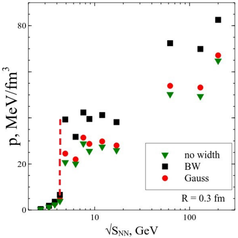
HRGM and non smooth CFO

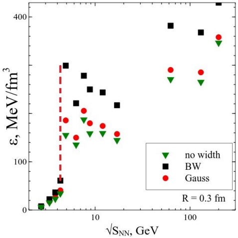
- Temperature T_{CFO} as a function of collision energy $\sqrt{s}$ is rather non smooth





- Significant jump of pressure ($\simeq 6$ times) and energy density ($\simeq 5$ times)

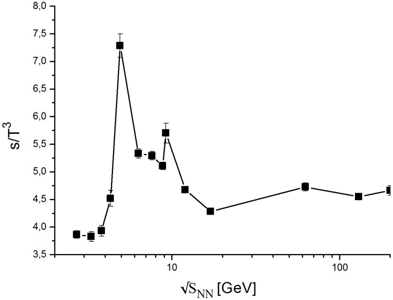


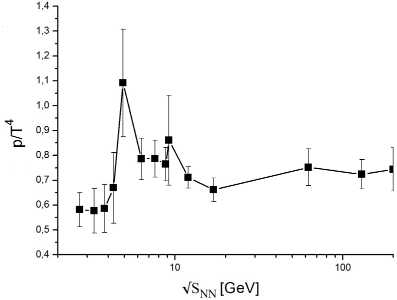


K.A. Bugaev et al., arXiv:1312.4367v2 [nucl-th]

HRGM and irregularities at CFO

- Narrow range of collision energy $\sqrt{S_{NN}} = 4.3 - 4.5$ GeV or $E_{lab} = 8.6 - 11.6$ GeV exhibits significant jumps of s/T^3 and p/T^4, which describe a number of effective degrees of freedom





K.A. Bugaev et al., arXiv:1405.3575[hep-ph]

What is the origin of these irregularities at CFO?

Phase transition?

Observation of plateaus

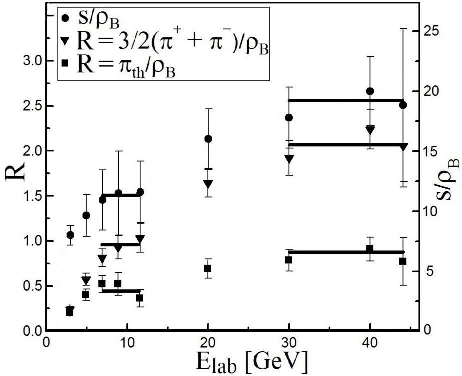
- Mixed phase formation $\Rightarrow$plateaus in $\{s/\rho_B,\ \rho_\pi^{th}/\rho_B,\ \rho_\pi^{tot}/\rho_B\}$ vs E_{lab}

  K.A.Bugaev,M.I.Gorenstein,D.H.Rischke,Phys.Lett.B 255,1,18(1991)
- Plateaus are correlated $\Rightarrow$ they have the same width M and location i_0
- Minimization of χ^2/dof $\Rightarrow$ heights of plateaus $A \in \{s/\rho_B,\ \rho_\pi^{th}/\rho_B,\ \rho_\pi^{tot}/\rho_B\}$

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

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

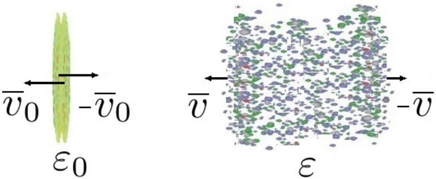
K.A. Bugaev et al., arXiv:1405.3575[hep-ph]



The low energy plateaus are located where irregularities do exist

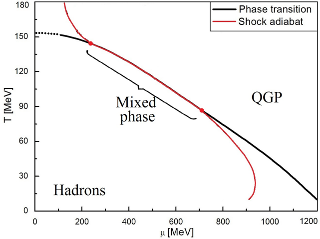
Generalized Shock Adiabat Model

- Hydrodynamic model of central nuclear collisions at 1 GeV $\leq E_{lab} \leq$ 30 GeV
  H. Stöcker, W. Greiner, Phys. Rep 137, 277 (1986)



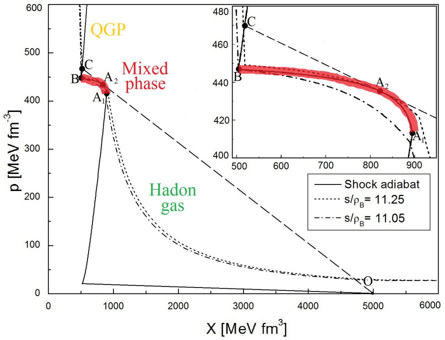
Solution of 1D Hydro $\Rightarrow$ evolution along generalized shock adiabat (GSA)
K.A. Bugaev, M.I. Gorenstein, B. Kampher, V.I. Zhdanov, Phys. Rev. D 40, 9, (1989)
K.A. Bugaev, M.I. Gorenstein, D.H. Rischke, Phys. Lett. B 255, 1, 18 (1991)

- Two phase equation of state $\Rightarrow$ mixed phase with anomalous properties

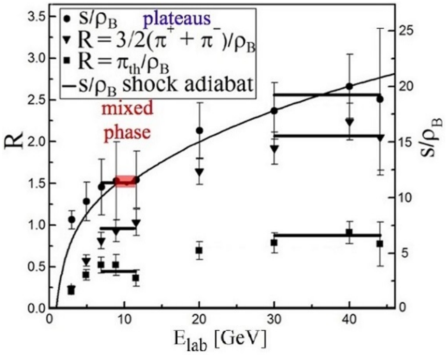


GSA Model and mixed phase formation

$X = \frac{\varepsilon + p}{\rho_B^2}$ – generalized specific volume



K.A. Bugaev et al., arXiv:1405.3575[hep-ph]



GSA Model explains irregularities at CFO as a signature of mixed phase

Conclusions

- On the basis of high quality experimental data fit it is shown that narrow range of collision energy $\sqrt{S_{NN}} = 4.3 - 4.5$ GeV contains remarkable irregularities in various thermodynamic quantities.
- Plateaus in dependence of s/ρ_B, π^{th}/ρ_B and π^{tot}/ρ_B on collision energy are found.
- Within Generalized Shock Adiabat Model the plateau-like behavior of s/ρ_B is explained as a signature of QGP formation.

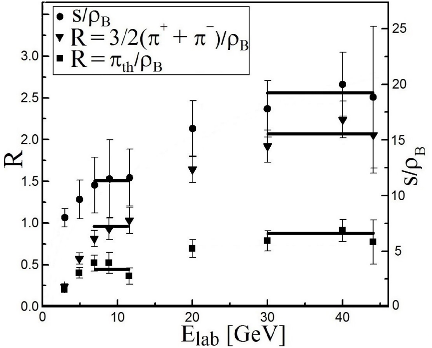
Thank you for your attention

Characteristics of correlated plateaus

- Common width M – number of points belonging to each plateau
- Common beginning i_0 – first point of each plateau
- For every M, i_0 minimization of χ^2/dof yields $A \in \{s/\rho_B,\ \rho_\pi^{th}/\rho_B,\ \rho_\pi^{tot}/\rho_B\}$:

$$\chi^2/\text{dof} = \frac{1}{3M-3}\sum_A \sum_{i=i_0}^{i_0+M-1}\left(\frac{A-A_i}{\delta A_i}\right)^2 \quad \Rightarrow \quad A = \sum_{i=i_0}^{i_0+M-1}\frac{A_i}{(\delta A_i)^2} \Big/ \sum_{i=i_0}^{i_0+M-1}\frac{1}{(\delta A_i)^2}$$

	Low energy plateau				
M	i_0	s/ρ_B	ρ_π^{th}/ρ_B	ρ_π^{tot}/ρ_B	χ^2/dof
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 plateau				
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



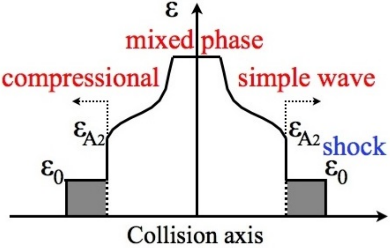
Generalized shock adiabat model

- GSAM describes central nuclear collisions at $E_{lab} \lesssim 30$ GeV
  K.A. Bugaev, M.I. Gorenstein, B. Kampher, V.I. Zhdanov, Phys. Rev. D 40,9, (1989)

- Hydrodynamic solution – compressional simple wave and shock $\Rightarrow$
  Rankine-Hugoniot-Taub abiabat

  $$(\rho_b X)^2 - (\rho_0 X_0)^2 - (p - p_0)(X + X_0) = 0$$

  $X = \frac{\epsilon + p}{\rho_b^2}$, initial state – ρ_0, X_0 and p_0



- Collision energy per nucleon

  $$E_{lab} = 2m_n \left(\frac{(p + \epsilon_0)(p_0 + \epsilon)}{(p + \epsilon)(p_0 + \epsilon_0)} - 1 \right)$$

- Thermodynamic properties of medium are defined by $\Sigma \equiv \left(\frac{\partial^2 p}{\partial X^2} \right)^{-1}_{s/\rho_B = const}$

  $\Sigma > 0$ – normal properties are typical for one phase regions

  $\Sigma < 0$ – anomalous properties are typical for mixed phase regions $\Rightarrow$ **plateaus**

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

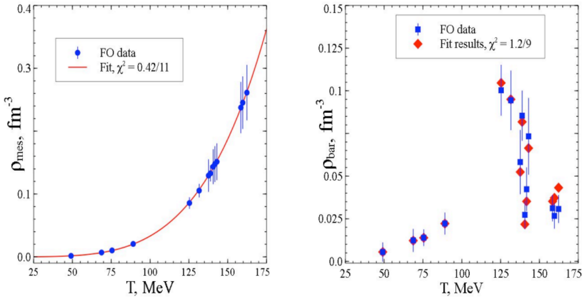
- Two phase equation of state
  Hadron gas – summation of hadronic spectrum $\Rightarrow$ (anti)baryonic and mesonic contributions
  QGP – MIT-Bag model Chodos A. et. al., Phys. Rev. D 9, 3471 (1974)

Effective hadronic equation of state

- Summation of hadronic spectrum ⇒ (anti)baryonic and mesonic contributions

$$p = \Big[\overbrace{2C_B T^{A_B} \mathrm{ch}\left(\frac{\mu}{T}\right) e^{-\frac{m_B}{T}}}^{\text{(anti)baryons}} + \overbrace{C_M T^{A_M} e^{-\frac{m_M}{T}}}^{\text{mesons}} \Big] e^{-\frac{pV_H}{T}}$$

- Effective EoS describes (anti)baryonic and mesonic densities at CFO



K.Bugaev et al. PoS Baldin ISHEPP XXI (2012) 017, arXiv:1212.0132 [hep-ph]