Irregularities at chemical freeze-out of hadrons as an evidence of quark-gluon plasma formation

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Thessaloniki, August 28 - September 4, 2016
Hadron resonance gas model (HRGM)

- **Basic assumption** – thermal/chemical equilibrium \( \Rightarrow \) parameters: \( T, \mu_B, \mu_{I3} \)
  

- HRGM accounts for all hadrons from PDG tables with masses up to 3.2 GeV
  

- Hadronic gas – mixture with **multicomponent hard-core repulsion** \( \Rightarrow \)
  
  equation of state of the Van der Wals type

**Corrections:**

- Strange particle nonequilibrium
- Decaying of resonances
- Width correction

**Fit parameters:** \( T, \mu_B, \mu_{I3}, \gamma_s \)

\( R_{\text{pions}}, R_{\text{kaons}}, R_{\text{mesons}}, R_{\text{baryons}}, R_{\text{lambda}} \) – fixed hard-core radii.

\( \mu_S \) – is found from the net zero strangeness condition.

K. A. Bugaev et al., EPJ A 49, 30–1-8 (2013)

K. A. Bugaev et al., EPL 104, 22002, p.1 - 6 (2013)
Strangeness Horn and $\Lambda$ Horn

With new radii and $\gamma_s$ fit

Total fit of 121 hadron ratios is the best of existing!

$$\chi^2 / dof = 63.978/65 \approx 0.98$$
Temperature $T_{\text{CFO}}$ 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)

Jump of Entropy Density and Trace Anomaly Peak

These peaks are at same energy

K.A. Bugaev et al., arXiv:1412.0718 [nucl-th]

Are these trace anomaly peaks related to each other?

WupBud EOS arxive: lat 1007.2580
Baryonic density as functions of collision energy at CFO

Sharp peak of the baryonic charge density at $\sqrt{s_{NN}} = 4.9$ GeV
Irregularities in hadron production

In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement.


Narrow collision energy range $\sqrt{s_{NN}} = 4.3-4.9$ GeV
Conclusions

With our HRGM the high quality fit is achieved for 121 hadron ratios measured at 14 values of the center of mass energy \( \sqrt{s_{NN}} \) at the AGS, SPS and RHIC with the accuracy \( \chi^2 / \text{dof} = 63.978 / 65 \approx 0.98 \);

high quality description of the CFO data allowed us to find few novel irregularities in the collision energy range \( \sqrt{s_{NN}} = 4.3-4.9 \) GeV (pressure, energy density jumps and \( \frac{\Lambda}{p} \) yield ratio);

in addition, we found a sharp peak of the trace anomaly \( \delta = \frac{\varepsilon - 3p}{T^4} \) and baryonic charge density at \( \sqrt{s_{NN}} = 4.9 \) GeV;

we found two sets of strongly correlated quasi-plateaus in entropy per baryon and the pion number (thermal and total) per baryon at CFO which were predicted based on shock adiabat model as a signal of the quark-gluon-hadron mixed phase formation;

these irregularities are also accompanied by the total to thermal particle yields asymmetry, i.e.

\[
\begin{align*}
\frac{K^+_{\text{tot}} - K^+_{\text{th}}}{K^+_{\text{tot}} + K^+_{\text{th}}} & \quad \Lambda_{\text{tot}} - \Lambda_{\text{th}} & \quad \Xi^-_{\text{tot}} - \Xi^-_{\text{th}} & \quad \Xi^-_{\text{tot}} + \Xi^-_{\text{th}}
\end{align*}
\]

indicating a significant role of the particle decays at chemical freeze-out;

we conclude that a dramatic change in the system properties seen in the narrow collision energy range \( \sqrt{s_{NN}} = 4.3 - 4.9 \) GeV opens entirely new possibilities for experimental studies on FAIR and NICA.
thank you for your attention!
Hadron Resonance Gas Model

One component gas: \( p = p^{id.gas} \cdot \exp \left( -\frac{pV}{T} \right) \)

Multicomponent case: \( p = \sum_i p_i = \sum_i T \phi_i \exp \left[ \frac{\mu_i - 2 \sum_j p_j V_{ji} + \sum_{jl} p_j V_{jl} p_l}{T} \right] \)

All hadrons are in full chemical equilibrium

The number of particles of \( i \)-th sort:

\[
N_i = \phi_i(T, m_i, g_i) e^{\frac{\mu_i}{T}} \equiv \frac{g_i V}{(2\pi)^3} \int \exp \left( \frac{-\sqrt{k^2 + m_i^2 + \mu_i}}{T} \right) d^3 k
\]

\( \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I3} I_{3i}, \ i = 1..s \)

\( g_i \) - degeneracy factor
\( \phi_i \) - thermal particle density
\( V_{ij} = \frac{2\pi}{3} (R_i + R_j)^3 \) - excluded volume

Hadron Resonance Gas Model corrections

- **Strangeness corrections:**
  \[ \phi_i(T) \rightarrow \phi_i(T) \gamma^s_i \]
  
  \( s_i \) — number of strange valence quarks and anti-quarks.
  

- **Resonance decay:**
  \[ n^{\text{fin}}(X) = \sum_Y \text{BR}(Y \rightarrow X) n^{\text{th}}(Y), \]

  where \( \text{BR}(X \rightarrow X) = 1 \), \( \text{BR} \)=BRANCHING RATIO (taken from PDG);

- **Width correction:**
  \[
  \int \exp \left( -\frac{\sqrt{k^2 + m_i^2}}{T} \right) d^3 k \rightarrow \int_{M_0}^{\infty} \frac{dx_i}{(x-m_i)^2 + \Gamma^2/4} \int \exp \left( -\frac{\sqrt{k^2 + x^2}}{T} \right) d^3 k 
  \]

  Breit-Wigner distribution having a threshold \( M_0 \),
  \( m \) - resonance mass, \( \Gamma \) - resonance width.

- **Ratios:**
  \[ R_{ij} = \frac{N_i}{N_j} = \frac{\rho_i}{\rho_j} \Rightarrow \text{volume is excluded} \]

**Fit parameters:** \( T, \mu_B, \mu_{I_3}, \gamma_s \)

- \( R_{\text{pions}}, R_{\text{kaons}}, R_{\text{mesons}}, R_{\text{baryons}}, R_{\text{lambda}} \) - fixed hard-core radii.
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Correlated Quasi-Plateaus

Mixed phase has anomalous thermodynamic properties \implies\ plateau in collision energy dependence of entropy per baryon!


Since the main part of the system entropy is defined by thermal pions \implies\ thermal pions/baryon should have a plateau too!

Also the total number of pions per baryons should have a (quasi)plateau!

Entropy per baryon has wide plateaus due to large errors

Quasi-plateau in total pions per baryon?

Thermal pions demonstrate 2 plateaus