New Signals of Two QCD Phase Transitions in Heavy Ion Collisions

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Outline

1. Motivation

2. HRGM: Old and Novel Irregularities at chemical freeze out

3. Shock adiabat model of A+A collisions

4. Newest results and possible evidence for two phase transitions

5. Conclusions
Experiments on A+A Collisions

AGS (BNL) up to 4.9 GeV
SPS (CERN) 6.1 - 17.1 GeV
RHIC (BNL) 62, 130, 200 GeV

} Completed

Ongoing HIC experiments
LHC (CERN) > 1 TeV (high energy)
RHIC (BNL) low energy
SPS (CERN) low energy

Future HIC experiments
NICA (JINR, Dubna)
SIS300 = FAIR (GSI)
J-PARC
Present Status of A+A Collisions

In 2000 CERN claimed indirect evidence for a creation of new matter

In 2010 RHIC collaborations claimed to have created a quark-gluon plasma/liquid

However, up to now we do not know:

1. whether deconfinement and chiral symmetry restoration are the same phenomenon or not?
2. are they phase transitions (PT) or cross-overs?
3. what are the collision energy thresholds of their onset?

To answer these questions we need a very accurate tool to analyze data
HRG: a Multi-component Model

HRG model is a truncated Statistical Bootstrap Model with the excluded volume correction a la VdWaals for all hadrons and resonances known from Particle Data Group.

For given temperature $T$, baryonic chem. potential, strange charge chem. potential, chem. potential of isospin 3-rd projection $\Rightarrow$ thermodynamic quantities $\Rightarrow$ all charge densities, to fit data.

Chemical freeze-out - moment after which hadronic composition is fixed and only strong decays are possible. I.e. there are no inelastic reactions.
Why Van der Waals or Hard-core Repulsion EoS?

1. Hard-core repulsion EoS (= VdWaals without attraction) has the same energy per particle as an ideal gas => there is no problems to convert its energy into ideal gas energy

   Proof: if particles stay apart, they do not interact, if particles touch each other, potential energy is infinite and => such configurations do not contribute into partition

2. Hard-core repulsion does not create problems with QGP existence, since such repulsion suppresses pressure compared to ideal gas EoS
HRG: a Multi-component Model

Traditional HRG model: one hard-core radius $R=0.25-0.3$ fm

Overall description of data (mid-rapidity or $4\pi$ multiplicities) is good!

But there are problems with $K^+/\pi^+$ and $\Lambda/\pi^-$ ratios at SPS energies!!! $\Rightarrow$ Two component model was suggested
HRG: a Multi-component Model

Traditional HRG model: one hard-core radius $R=0.25-0.3$ fm

Overall description of data (mid-rapidity or $4\pi$ multiplicities) is good!

Two hard-core radii: $R_{\pi} = 0.62$ fm, $R_{\text{other}} = 0.8$ fm

Or: $R_{\text{mesons}} = 0.25$ fm, $R_{\text{baryons}} = 0.3$ fm

Two component models do not solve the problems!
Hence we need more sophisticated approach.
Recently Suggested Signals of QCD Phase Transitions 2014-2017

During 2013-2017 our group developed a very accurate tool to analyze data


KAB et al., Europhys. Lett. 104 (2013)


The high quality description of data allowed us to elucidate new irregularities at CFO from data and to formulate new signals of two QCD phase transitions


KAB et al., EPJ A 52 (2016) No 6

KAB et al., EPJ A 52 (2016) No 8

Strangeness Enhancement as Deconfinement Signal


which quantifies strange charge chemical oversaturation ($>1$) or strange charge chemical undersaturation ($<1$)

Idea: if s-(anti)quarks are created at QGP stage, then their number should not be changed during further evolution since s-(anti)quarks number is small and since density decreases => there is no chance for their annihilation!
Hence, we should observe chemical enhancement of strangeness with $\gamma_S > 1$

However, until 2013 the situation with strangeness was unclear:

P. Braun-Munzinger & Co found that $\gamma_S$ factor is about 1
F. Becattini & Co found that $\gamma_S$ factor is < 1
Include $\gamma_s$ factor $\phi_i(T) \rightarrow \phi_i(T)\gamma_s^{s_i}$, into thermal density

where $s_i$ is number of strange valence quarks plus number of strange valence anti-quarks.

Thus, it is a strangeness fugacity


Typical values of $\chi^2$/dof >2 at given energy!
Our Results on Strangeness Enhancement in 2013

High quality description of hadron multiplicities requires $T$, $\mu_B$, $\mu_{I3}$ and $\gamma_s$ factor

$\chi^2$/dof $= 1.15$ for 111 ratios measured for c.m. energies 2.7--200 GeV

Best global fit of all ratios gives $R_{pi} = 0.1$ fm, $R_K = 0.38$ fm,

for fixed: $R_{baryons} = 0.2$ fm, $R_{mesons} = 0.4$ fm


Strangeness enhancement exists where we do not expect deconfinement!
Strangeness Horn and $\Lambda$ Horn in 2014 within Multicomponent Van der Waals EoS

To avoid selective suppression of $\Lambda$-hyperons we added their hard-core radius

$$\chi^2/14 = 3.9/14$$  $$\chi^2/12 = 10.22/12$$  $$\chi^2/8 = 6.49/8$$

$R_{\pi} = 0.1$ fm,  $R_{\Lambda} = 0.1$ fm,  $R_{b} = 0.36$ fm,  $R_{K} = 0.38$ fm,  $R_{m} = 0.4$ fm

Total fit of 111 independent hadron ratios is the best of existing!

V. V. Sagun, **Ukr. J. Phys.** 59, No 8, 755-763 (2014)
V. V. Sagun et al., **Ukr. J. Phys.** 59, No 11, 1043-1050 (2014)
Induced Surface Tension EOS (2017)

EoS beyond the Van der Waals approximation (see my talk on July, 10)


Pressure

\[ \frac{p}{T} = \sum_i \phi_i \exp\left( \frac{\mu_i - pV_i - \sum S_i}{T} \right) \]

New term

Induced surface tension

\[ \frac{\Sigma}{T} = \sum_i R_i \phi_i \exp\left( \frac{\mu_i - pV_i - \sum S_i}{T} \right) \cdot \exp\left( \frac{(1 - \alpha)\Sigma S_i}{T} \right) \]

\( V_k \) and \( S_k \) are eigenvolume and eigensurface of hadron of sort \( k \)

\( \alpha \) switches excluded and eigen volume regimes

and accounts for 3-rd and 4-th virial coefficients of the gas of hard spheres!

Advantages

1. Allows to go beyond the Van der Waals approximation

2. Number of equations is 2 and it does not depend on the number different hard-core radii!
Most Problematic ratios at AGS, SPS and RHIC energies


Note: RHIC BES I data have very large error bars and hence, are not analyzed!

Our IST EOS has 3 or 4 more fitting parameters compared to usual HRGM!

Examples of Hadron Multiplicity Ratios for IST, Multicomponent and One component Van der Waals EoS (2018)


Blue bars    IST EoS
Red bars    Multicomponent Van der Waals EoS
Green bars  One-component Van der Waals EoS (a la P. Braun-Munzinger et al),

All EoS use $\gamma_s$ as a fitting parameter!

One-component Van der Waals EoS always gives the worst results!
Intermediate Conclusions

1. The multicomponent HRG model is a precise tool of HIC phenomenology.

2. HRG model gives us EOS at high baryonic densities where LQCD does not work.

3. Using multicomponent HRG model we can study thermodynamics at chemical freeze out.
Jump of ChFO Pressure at AGS Energies

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

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

Minimum of ChFO Volume at AGS Energies

All these irregularities occur at c.m. energies 4.3-4.9 GeV!

Are these minima related to deconfinement?

Trace Anomaly Peaks (Most Recent)

At chemical FO (large $\mu$)

Lattice QCD (vanishing $\mu$)


Are these trace anomaly peaks related to each other?
Shock Adiabat Model for A+A Collisions

A+A central collision at 1< $E_{\text{lab}}$<30

From hydrodynamic point of view this is a problem of arbitrary discontinuity decay: in normal media there appeared two shocks moving outwards.

Works reasonably well at these energies.

Medium with Normal and Anomalous Properties

Normal properties, if
\[
\Sigma \equiv \left(\frac{\partial^2 p}{\partial X^2}\right)^{-1}_{s/\rho_B} > 0 = \text{convex down:}
\]

Usually pure phases (Hadron Gas, QGP) have normal properties

\[X = \frac{\varepsilon + p}{\rho_B^2} - \text{generalized specific volume}\]
\[\varepsilon \text{ is energy density, } p \text{ is pressure,}\]
\[\rho_B \text{ is baryonic charge density}\]

Anomalous properties otherwise.

Almost in all substances with liquid-gas phase transition the mixed phase has anomalous properties!

Then shock transitions to mixed phase are unstable and more complicated flows are possible.
Highly Correlated Quasi-Plateaus

If anomalous properties exist => **entropy per baryons should have a plateau as a function of collision energy!**

=> **thermal pions/baryon should have a plateau!**

=> But 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

Details on Highly Correlated Quasi-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 \( \chi^2 / \text{dof} \) yields \( A \in \{s/\rho_B, \rho_{\pi}^{\text{th}}/\rho_B, \rho_{\pi}^{\text{tot}}/\rho_B\} \):

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

<table>
<thead>
<tr>
<th>M</th>
<th>( i_0 )</th>
<th>( s/\rho_B )</th>
<th>( \rho_{\pi}^{\text{th}}/\rho_B )</th>
<th>( \rho_{\pi}^{\text{tot}}/\rho_B )</th>
<th>( \chi^2 / \text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>11.12</td>
<td>0.52</td>
<td>0.85</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>11.31</td>
<td>0.46</td>
<td>0.89</td>
<td>0.53</td>
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<tr>
<td>4</td>
<td>2</td>
<td>10.55</td>
<td>0.43</td>
<td>0.72</td>
<td>1.64</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>11.53</td>
<td>0.47</td>
<td>0.84</td>
<td>4.45</td>
</tr>
</tbody>
</table>

Low energy plateau

<table>
<thead>
<tr>
<th>M</th>
<th>( i_0 )</th>
<th>( s/\rho_B )</th>
<th>( \rho_{\pi}^{\text{th}}/\rho_B )</th>
<th>( \rho_{\pi}^{\text{tot}}/\rho_B )</th>
<th>( \chi^2 / \text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>19.80</td>
<td>0.88</td>
<td>2.20</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>18.77</td>
<td>0.83</td>
<td>2.05</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>17.82</td>
<td>0.77</td>
<td>1.87</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>16.26</td>
<td>0.64</td>
<td>1.62</td>
<td>3.72</td>
</tr>
</tbody>
</table>

High energy plateau

Searching for WIDEST plateaus with SAME WIDTH and \( \chi^2 \times 2/\text{dof} \ll 1 \)!
Details on Highly Correlated Quasi-Plateaus II

Searching for WIDEST plateaus with SAME WIDTH and \( \chi^2/dof \ll 1 \Rightarrow \text{Very strong constraints!} \)
Unstable Transitions to Mixed Phase

\[ X = \frac{\varepsilon + p}{\rho_B^2} \] - generalized specific volume

QGP EOS is MIT bag model with coefficients been fitted with condition \( T_c = 150 \text{ MeV} \) at vanishing baryonic density!

HadronGas EOS is simplified HRGM discussed above.

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

**Other Minima at AGS Energies**

- **min V at ChFO**
  - SAME energy!

  - ![Graph](image1.png)

- **min X at ChFO**
  - X is generalized specific volume
  - Is second X peak due to other PT?

  - ![Graph](image2.png)

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K.A. Bugaev et al., EPJ A (2016)

**In this work we gave a proof that min X at boundary between QGP and mixed phase generates min X at ChFO which leads to min V of ChFO!**
We found one-to-one correspondence between these two peaks.

Thus, sharp peak of trace anomaly at c.m. energy 4.9 GeV evidences for mixed phase formation. But what is it?

Is second peak at c.m. energy 9.2 GeV due to another PT?
Trace anomaly peaks and baryonic density peaks are related to each other.

Can we relate them to $\gamma_s$ irregularities?

At c.m. energies above 8.8 GeV the strange hadrons are in chemical equilibrium due to formation of QG bags with Hagedorn mass spectrum!

Hagedorn mass spectrum is a perfect thermostat and a perfect particle reservoir! => Hadrons born from such bags will be in a full equilibrium!


At c.m. energy GeV strange particles are in chemical equilibrium due to formation of mixed phase, since under CONSTANT PRESSURE condition the mixed phase of 1-st order PT is explicit thermostat and explicit particle reservoir!
1. At limiting temperature the Hagedorn mass spectrum is a perfect thermostat and a perfect particle reservoir since it is a kind of mixed phase!


2. Under a constant external pressure ANY MIXED PHASE is a perfect thermostat and a perfect particle reservoir!

As long as two phases coexist

- Export/import of heat does not change T!

Pressure = const

\[ T = T_c = 273K \]

or

\[ 0 \leq T \leq 273K \]

- First take heat \( dQ = E \) from system with temperature \( T \):
- Then give it to thermostat

\[ \Rightarrow T = \text{const}, \mu = \text{const} \]

- Export/import of \textbf{finite amount} of phases \( \Rightarrow T = \text{const}, \mu = \text{const} \)
Additional Hints for 2 Phase Transitions

Our:


Each peak in trace anomaly \( \delta \) corresponds to a huge peak in baryonic charge density

Thermostatic properties of Hagedorn mass spectrum of QGP bags explain chemical equilibration of strangeness at \( \sqrt{s} > 8.8 \) GeV

Thermostatic properties of the 1-st order PT mixed phase explain strangeness equilibration at \( 4.3 \text{ GeV} < \sqrt{s} < 4.9 \) GeV

Other models predict deconfinement at \( \sqrt{s} = 8.7-9.2 \) GeV:
Onset of Deconfinement in Other Models

Che Ming Ko et al., arXiv 1702.07620 [nucl-th]

J. K. Nayak, S. Banik, Jan-e Alam, PRC 82, 024914 (2010)

Light nuclei fluctuations are enhanced at c.m. energy 8.8 GeV
=> CEP is located nearby!

Counting for thermodynamic, hydrodynamic and fluctuation signals we conclude that 3CEP may exist at 8.8-9.2 GeV

Strangeness Horn and other strange particles ratios can be explained, if the onset of deconfinement begins at c.m. energy 8.7 GeV!

If There Are 2 Phase Transitions, then

1. What kind of phase exists at $\sqrt{s} = 4.9-9.2$ GeV?

2. Can we get any info about its properties?
Effective Number of Degrees of Freedom I

One look at this EoS:

\[ p_{QGP} = \underbrace{A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B}_{\text{fitting}} = \underbrace{A_0^L T^4 + A_2^L T^2 \mu^2 + A_4^L \mu^4 - B_{eff}}_{\text{LQCD}} \]

\[ B_{eff}(T, \mu_B) = B - (A_0 - A_0^L)T^4 - (A_2 - A_2^L)T^2 \mu^2 - (A_4 - A_4^L)\mu^4 \]

In our fit of entropy per baryon along the shock adiabat we used the QGP EoS

\[ p_{QGP} = \underbrace{A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B}_{\text{fitting}} \]

\[ A_0 \simeq 2.53 \cdot 10^{-5} \text{ MeV}^{-3}\text{fm}^{-3} \]
\[ A_2 \simeq 1.51 \cdot 10^{-6} \text{ MeV}^{-3}\text{fm}^{-3} \]
\[ A_4 \simeq 1.001 \cdot 10^{-9} \text{ MeV}^{-3}\text{fm}^{-3} \]
\[ B \simeq 9488 \text{ MeV} \text{ fm}^{-3} \]

Effective Number of Degrees of Freedom II

One look at this EoS:

\[
p_{QGP} = A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B = A_0^L T^4 + A_2^L T^2 \mu^2 + A_4^L \mu^4 - B_{\text{eff}} \]

\[
B_{\text{eff}}(T, \mu_B) = B - (A_0 - A_0^L)T^4 - (A_2 - A_2^L)T^2 \mu^2 - (A_4 - A_4^L) \mu^4
\]

Another look at this EoS:

\[
p_{\text{New phase}} = A_0 T^4 + A_2 T^2 \mu^2 + A_4 \mu^4 - B
\]

It corresponds to massless particles with strong interaction

Then one can find an effective #dof from \( A_0 \)!

For massless particles

\[
A_0 = N_{\text{dof}} \frac{\pi^2}{90} \quad \text{with} \quad N_{\text{dof}} = N_{\text{Bosons}} + \frac{7}{8} \times 2 N_{\text{Fermions}}
\]

\[
\Rightarrow N_{\text{dof}} = A_0 \hbar^3 \frac{90}{\pi^2} \simeq 1800
\]

It's a huge number for QGP!

Other Possible Interpretations

1. The phase emerging at $\sqrt{s} = 4.9-9.2$ GeV has no Hagedorn mass spectrum, since strange hadrons are not in chemical equilibrium.

2. 1800 of massless dof may evidence either about new phenomena (i.e. unitary/chiral symmetry restoration) in hadronic sector.
   

3. Or 1800 of massless dof may evidence about tetra-quarks with massive strange quark!? 
   
   see Refs. in R.D. Pisarski, 1606.04111 [hep-ph]

4. Or 1800 of massless dof may evidence about quarkyonic phase!? 
   

5. 1800 of massless dof may evidence about something else…
Parton-Hadron-String-Dynamics Model

1-st order PT of Chiral Symmetry Restoration in hadronic phase occurs at about $\sqrt{s} \sim 4. \text{ GeV}$

and 2-nd order deconfinement PT exists at $\sqrt{s} \sim 9 \text{ GeV}$

Hard to locate them due to cross-over in A+A!

Evidence for Chiral Symmetry Restoration?

There are KINKs in apparent temperature of K+ and K- at 4.3-6.3 GeV

$$T^*_k(p_T \to 0) = \frac{T_{fo}}{1 - \frac{1}{2} \bar{v}_T^2 \left(\frac{m_k}{T_{fo}} - 1\right)} \approx T_{fo} + \frac{1}{2} \frac{m_k \bar{v}_T^2}{T_{fo}}$$

K.A. Bugaev et al., arXiv:1801.08605 [nucl-th]

apparent temperature = inverse slope of p_T spectra at p_T \to 0:
depends on FO temperature and mean transversal velocity

Simple (naive?) explanation:
1. FO temperature cannot decrease, if \sqrt{s} increases.
2. mean transversal velocity cannot decrease, if \sqrt{s} increases.
=> mass of Kaons gets lower due to ChSRestoration!?


Suggestions for RHIC BESII, NICA and FAIR:
measure p_T spectra and apparent temperature of Kaons and (anti)\Lambda hyperons at 4.3-6.3 GeV with high accuracy and small collision energy steps!
Conclusions

1. High quality description of the chemical FO data allowed us to find few novel irregularities at c.m. energies 4.3-4.9 GeV (pressure, entropy density jumps e.t.c.)

2. HRG model with multicomponent repulsion allowed us to find the correlated (quasi)plateaus at c.m. energies 3.8-4.9 GeV which were predicted about 30 years ago. The second set of plateaus and irregularities may be a signal of another phase transition!

3. Probably, for the first time we have an evidence of (partial) Chiral Symmetry Restoration in hadronic phase at 3.8-4.9 GeV, deconfinement and 3CEP at 8.8-9.2 GeV.

4. Hopefully, RHIC, NICA, FAIR and J-PARC experiments will allow us to make more definite conclusions
Table 1. The summary of possible PT signals. The column II gives short description of the signal, while the columns III and IV indicate its location, status and references.

<table>
<thead>
<tr>
<th>No and Type</th>
<th>Signal</th>
<th>C.-m. energy $\sqrt{s}$ (GeV) Status</th>
<th>C.-m. energy $\sqrt{s}$ (GeV) Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Thermodynamic</td>
<td>Minimum of the chemical freeze-out volume $V_{CFO}$. In the one component HRGM it is seen at 4.3-4.9 GeV [13]. In the multicomponent HRGM it is seen at 4.9 GeV [14]. Explained by the shock adiabat model [4, 5].</td>
<td>Not seen.</td>
<td></td>
</tr>
<tr>
<td>4. Thermodynamic</td>
<td>Peak of the trace anomaly $\delta = \frac{\mu}{T^3}$.</td>
<td>Strong peak is seen at 4.9 GeV [5]. Is generated by the $\delta$ peak on the shock adiabat at high density end of the mixed phase [5].</td>
<td>Small peak is seen at 9.2 GeV [5]. Require an explanation</td>
</tr>
<tr>
<td>5. Thermodynamic</td>
<td>Peak of the baryonic density $\rho_b$.</td>
<td>Strong peak is seen at 4.9 GeV [10]. Is explained by min${V_{CFO}}$ [14].</td>
<td>Strong peak is seen at 9.2 GeV [10]. Require an explanation</td>
</tr>
<tr>
<td>6. Thermodynamic</td>
<td>Apparent chemical equilibrium of strange charge. $\gamma_s = 1$ is seen at 4.9 GeV [10]. Explained by thermostat properties of mixed phase at $p = const$ [10].</td>
<td>$\gamma_s = 1$ is seen at $\sqrt{s} \geq 8.8$ GeV [10, 13]. Explained by thermostat properties of QG bags with Hagedorn mass spectrum [10].</td>
<td></td>
</tr>
<tr>
<td>7. Fluctuational</td>
<td>Enhancement of fluctuations (statistical mechanics)</td>
<td>N/A</td>
<td>Seen at 8.8 GeV [9]. Can be explained by CEP [9] or 3CEP formation [10].</td>
</tr>
<tr>
<td>8. Microscopic</td>
<td>Strangeness Horn ($K^+/\pi^+$ ratio)</td>
<td>N/A</td>
<td>Seen at 7.6 GeV. Can be explained by the onset of deconfinement at $\sqrt{s}$. Can be explained by the onset of deconfinement at [15]/above [8] 8.7 GeV.</td>
</tr>
</tbody>
</table>
Possible Interpretation

Evolution of possible «initial» states with collision energy

Appearance of 2-nd intersection at c.m. energies ~9-12.5 GeV probably means that trajectory goes near 3 critical (right) endpoint.
Back Up Slides
Main Results for AGS, SPS and RHIC energies

IST EOS (without ALICE): \( \chi^2 / dof = 57.099/55 \approx 1.04 \)

\( R_\pi = 0.15 \text{ fm}, \quad R_K = 0.395 \text{ fm}, \quad R_\Lambda = 0.085 \text{ fm}, \quad R_p = 0.365 \text{ fm}, \quad R_m = 0.42 \text{ fm} \)

Only pion and \( \Lambda \) hyperon radii are changed, but no effect on \( T \) and \( \mu_B \)

1. We confirm that there is a jump of \( T_{\text{CFO}} \) between \( \sqrt{s} = 4.3 \text{ GeV} \) and \( \sqrt{s} = 4.9 \text{ GeV} \)

2. We confirm that there is a strangeness enhancement peak at \( \sqrt{s} = 3.8 \text{ GeV} \)

Generalized Shock Adiabat Model

In case of unstable shock transitions more complicated flows appear:

Remarkably

Z model has stable RHT adiabat, which leads to quasi plateau!


If during expansion entropy conserves, then unstable parts lead to entropy plateau!

FIG. 9. The entropy per baryon as a function of the bombarding energy per nucleon of the colliding nuclei for models W and Z. The points 1, 2, 3, 4 on curve W correspond to those on the generalized adiabatic as displayed in Fig. 7. The point 1 on curve Z marks the boundary to the mixed phase.

Claim that onset of deconfinement is at c.m. energy 7.6 GeV


F is Fermi variable $\sim s^{1/4}$

NA49 “Signals” = Irregularities

I. There is NO a single model which can simultaneously describe these «signals»!

II. As long as these «signals» cannot be reproduced by existing hydrodynamic and hydro-cascade models with deconfinement phase transition.

Therefore, their relation to deconfinement is unclear!

Hence, these «signals» are irregularities which require an explanation!

Furthermore, it seems that there is also something wrong with our EOS!
In 1982 J. Rafelski and B. Müller predicted that enhancement of strangeness production is a signal of deconfinement.

We observe 3 regimes: at c.m. energies 4.3 GeV and ~9 GeV slope of experimental data drastically changes!

Combining Rafelsky & Muller idea with our result that mixed phase appears at 4.3 GeV we explain this finding:

Below 4.3 GeV Lambdas appear in N+N collisions

Above ~9 GeV formation of QGP produces additional s (anti)s quark pairs => saturation due to CSR

Between ~4.3-9 GeV there is fast growth=> decrease of strange particle masses
What To Measure at FAIR & NICA?

We predicted JUMPS of these ratios at 4.3 GeV due to 1-st order PT and

CHANGE OF their SLOPES at ~ 9-12 GeV due to 2-nd order PT
(or weak 1-st order PT?)

To locate the energy of SLOPE CHANGE we need MORE data at 7-13 GeV
Consequent Problem and Its Possible Solution

If 1800 of massless dof exist then at high T and same μ_B the QGP cannot exist, since its pressure is too low to dominate!

⇒ Contradiction with Lattice QCD!

The only possibility to avoid the contradiction with LQCD is to assume hard-core repulsion for 1800 of massless dof!

Since they are almost massless (m << T), then the hard-core repulsion should be formulated for ultra-relativistic particles and include the effect of Lorentz contraction.


In the limit μ_B /T << 1 and mass/T << 1 the pressure of such system is

\[ p \sim \frac{T^2}{V_0^3} N_{dof}^{\frac{1}{3}} C \quad \text{with} \quad C = Const \sim 1 \quad \text{here } V_0 \text{ is eigenvolume of hadron} \]

No mass dependence and very weak dependences on T and on #dof: \( N_{dof}^{\frac{1}{3}} \sim 12 \)
Most Problematic ratios at AGS, SPS and RHIC energies

IST EOS results are very similar to previous ones:

\[ \chi^2 / \text{dof} \simeq 3.29/14 \]

\[ \chi^2 / \text{dof} \simeq 11.62/12 \]

\[ \chi^2 / \text{dof} \simeq 8.89/8 \]

Only few points for \( \Lambda \) (anti)hyperon are improved