Hadronic Signals of the QCD Phase Transition

R. Stock, Univ. of Frankfurt

1. Calorimetry, Rapidity density spectra $\rightarrow$ energy density $\epsilon$

2. QCD Debye screening and NA50 $\frac{1}{4}, \frac{1}{4}$ data $\rightarrow$ energy density $\epsilon$,
   $T = 1.3 T_c$ !!

3. Hadronization at $T = T_c$
   Becattini-analysis, hadronic yield ratios $T_c \approx 185$ MeV
   "Explosive Hadronization"

4. Strangeness Saturation
   NA49 obs. strangeness fits QGP-state
   at $T = 185$ MeV but not hadronic state at $T = 185$ MeV !! $\Rightarrow$ Explosive hadronization!

5. Bose-Einstein-Correlation and $\gamma_T$
   System arrives at freezeout at $T \approx 120$ MeV, after a FWHM life time of
   15 fm/$c$, with collective expansion velocity fields $\beta_T = 0.55$, $\beta_L = 0.9$
Historical origin of our interest in "Nuclear Matter under extreme Conditions":

Problem: Equation of State (EOS): $P(\rho)$

Structure of neutron stars

- Outer Crust
- Neutron-rich Nuclei, Electrons, Pinned Neutron Superfluid
- Superfluid Neutrons
- Superconducting Protons
- Electrons
- Pion Condensate?

Cross-section of a $1.4 \, M_\odot$ neutron star

Nuclear density $\rho_0 = 0.16 \, \text{baryons} / \text{fm}^3$

$\langle r_{12}^2 \rangle \approx 1.8 \, \text{fm}^2 \times 2 \, R_N$
The pion : baryon ratio as an example of a signal that gets established during the high density phase.

"chemical freeze-out" information preserved in expansion
Experiment NA49 at CERN Pb-Pb beam: p+p, T, K, Λ, Φ hadron analysis.
$E = (3.2 \pm 0.4) GeV/amu$

Barker - estimate

$E_T (TeV) = 2.9 (n < 3)$

Central Collisions

FRITIOF 1.6
VENUS 4.12
$S + Au$
$Pb + Pb$

$N_{49}$ Calorimeters

$\frac{d\sigma}{dE_T}$ (barn/GeV)
Bjorken-like estimate for length of cylinder in space:

\[ L = \Delta y \cdot \ell (\text{formation}) \]

Initial primordial volume:

\[ V_{\text{primordial}} = \pi R^2 (\text{Pb}) L = 340 \text{ fm}^3 \]

Contains:

\[ E_T = 1.0 \text{ GeV from calorim.} \]

Average:

\[ E = (2.95 \pm 0.30) \text{ GeV/fm}^3 \]

From \( 4\pi \) tracking:

\[ E = 2.7 \pm 0.3 \text{ GeV/fm}^3 \]
What is new in Pb+Pb, comp. to S+heavy

$\Rightarrow$ energy density $\varepsilon$ : profile

\[ \varepsilon \text{ [GeV/fm}^3\text{] } \]

\[ \Rightarrow \text{global averages similar: (NA49 data)} \]

but "hot cylinder" in central Pb+Pb

Blaizot, Karzeev at QM 96 (Glauber estimates)

The $p$ production rate in Pb+Pb (central)

NAS0

is consistent with zero $p$ production from "hot no. O nuclei" $\Rightarrow$ GP formation?!
CERN NA38/NA50 Data for $\Psi$ production in collisions of increasingly massive nuclear projectiles:
From pp, pd to $^{32}$S+U to $^{208}$Pb+$^{208}$Pb:

- $\Delta$ p(450 GeV/c)–A (A = p, d) (NA51)
- $\star$ p(200 GeV/c)–A (A = W, U) (NA38)
- ■ $^{32}$S(32 x 200 GeV/c) – U (NA38)
- ○ $^{208}$Pb(208 x 158 GeV/c) – Pb (NA50)

$B_{\mu\mu}(J/\Psi) / \sigma(drell-Yan)_{2.9-4.5}$

Please note: this signal is the only one to exhibit a "jump" in going to SPS Pb+Pb
Perhaps the only signal referring directly to the partonic state, before hadronization.
Debye Screening Radius in QCD
Matsui and Satz 1987

\[ r_D (\text{fm}) \]

- \( \chi_c \)
- \( \psi' \)
- \( J/\psi \)
- \( Y \)

<table>
<thead>
<tr>
<th>T / T_c</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>r_D (fm)</td>
<td>0.6</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- \( \Psi \) dissolves \( \varepsilon \approx 2.8 \varepsilon_{\text{crit}} \)
- \( Y \) dissolves \( \varepsilon \approx 39 \varepsilon_{\text{crit}} \)

\[ T \approx 1.3 T_c \approx 240 \text{ MeV} \text{ if } T_c \approx 185 \text{ MeV} \]
\[ \varepsilon \text{ (Pb + Pb, interior)} \approx 4 \text{ GeV/fm}^3 \Rightarrow T^4 \]
\[ \varepsilon_c \approx 1.5 \text{ GeV/fm}^3 \text{ at } T = T_c \times 185 \text{ MeV} \]

\( \varepsilon \) with lattice QCD
Statistical Model Fit gives:

Statistical Model Yields

NA49 Pb+Pb Hadron Multiplicities

\[ \gamma = 0.4 \text{ in } A + A \text{ vs. } 0.25 \text{ in } p + p, \quad e^+ e^- \text{ Strangequark Enhancement } \]

\[ \gamma = 0.6 \quad \text{Partial Strangequark Saturation in Hadron Gas} \]

\[ T_H = 190 \text{ MeV} \quad \text{Hadronization Temperature similar to } p + p, \quad e^+ e^- \]
Strangeness Production

- Kaon/Pion ratio in $4\pi$
  
  $\Rightarrow$ 'Strangeness enhancement' in central heavy ion collisions

Pb+Pb, NA49 Preliminary

![Graph showing strangeness production in heavy ion collisions]
The ratio strangeness to entropy.

\[ \frac{\text{hadron gas}}{(n_{K^-} + n_{\Lambda})/S} \]

\[ \frac{n_s}{S} \]

Kapusta, Meissner
P.R. C33(86)

\[
T_c \approx 185 \text{ MeV}
\]

From hyperon abundances and "flow" model applied to spectra/bose correlation.
NA49 Pb+Pb $2\pi$ – Bose Einstein Correlations

in small bins of pair rapidity and $K_\perp$

$3.4 < Y_{\pi\pi} < 3.9 \quad 0.1 < K_\perp < 0.2 \text{ GeV/c}$

$C_2$ vs $Q_\perp$ (MeV/c) $Q_\parallel$ (MeV/c) $Q_\perp$ (MeV/c)

from the $Y_{\pi\pi}$ and $K_\perp$ dependence of the correlation parameters:

$R_\perp$ geometrical radius

$\beta^2_\perp$ trans. expansion vel$^2$

$T$ freeze-out Temperature

$R_\parallel$

$\beta_\parallel$ long. expansion velocity

$\Delta\tau$ duration of emission

Conditions at freeze-out

- source size 2.5 x larger than primordial size
- lifetime $\tau = 8 \text{ fm/c}$
- $\beta^2_\perp / T = 3.7 \pm 1.6 \text{ GeV}^{-1}$ $\beta_\parallel = 0.9$
- duration of emission $\Delta\tau = 3.5 \text{ fm/c}$
Temporal pattern of hadron source

Data: Pb+Pb central 158 GeV/A
NA49 H. Appelshauser, T. Schönfeldt
2.9 < y < 3.4: at midrapidity
Sinyokov - Heinz - analysis

Pion emission strength: time profile

Hadronic expansion takes about 15 fm/c until all hadrons decouple or is it rather the total expansion time?!! tentatively: yes
NA49 central Pb+Pb at 158 GeV/Nucleon

Hadronic Expansion Dynamics

- Bose Einstein correlation of negative pions \( (2\pi - \text{BE}) \)
- and transverse mass spectra of negative hadrons \((h^-)\) and deuterons \((d)\)

\[ \text{determine the conditions at hadronic decoupling} \]

**Results**

From initial hadronization stage at \( T = 190 \text{ MeV} \) to final hadronic decoupling (freeze - out)

- Source expanding radially and longitudinally
- Duration of expansion \( \langle \tau \rangle = 8 \text{ fm/c} \)
- Local thermal equilibrium
  \[ T_{\text{freeze - out}} = 120 \pm 10 \text{ MeV} \]
  \[ \beta_{\perp \text{freeze - out}} = 0.55 \pm 0.12 \]
  \[ \beta_{L \text{freeze - out}} = 0.90 \]
NA49 Pb+Pb Event-by-Event Fluctuations

Non-statistical Event-by-Event Fluctuations:

- <1% in \( p_T \)
- <15% in \( K/\pi \)
Hadronic Signals

In the last 2 years we have learned to pin down the entire hadronic expansion phase from hadronization to decoupling from strong interaction.

\[ \text{hadron ratios} \quad \text{"hadrochemistry"} \]

\[ \text{Bose - Einstein correlation spectra} \]

But note:

reaction time

Chemistry can pick up quark abundances in plasma phase \( <s+\bar{s} > \text{u+\bar{u}+d+\bar{d}+\bar{s}+c+\bar{c}> \text{etc.} \)

Bose - Einstein measures source dynamics including conditions at hadronization and prior to it!

\( \Rightarrow \text{Observables point into the "plasma phase"!} \)

This is completely contrary to common belief!
Time history of a central Pb+Pb collision

1. Calorimetry, dN/dy, \( T/\pi \) suppression:
   - Primordial system
   \[ V = 340 \text{ fm}^3; \bar{\epsilon} (\text{interior}) = 4 \text{ GeV/fm}^3; T = 240 \text{ MeV} \]
   - Recall \( T \leq 250 \) from \( T/\pi \leq 0.05 \)
   - The system must expand in a partonic state to reach \( \epsilon_{\text{crit}} \approx 1.5 \text{ GeV/fm}^3; T_c \approx 185 \text{ MeV} \)
   - This takes about 3 fm/c ?!

2. Hadron multiplicities, ratios:
   - The hadronization phase is reached at \( T \approx 185 \pm 10 \text{ MeV} \)
   - It takes about 2-3 fm/c ?!
   - **Explosive hadronization**:
     - System in full expansion as it enters hadronization!
   - That is why the hadronic population "freezes out" almost immediately \( \rightarrow \) "explosively"

3. Strange hadron multiplicity to partonic, to pions, entropy...
   \( \rightarrow \) "quark counting"
   - Strangeness out of global equilibrium in hadronic \( T = 185 \text{ MeV} \) population but in flavour equilibrium in a partonic \( T = 185 \text{ MeV} \) population

4. Bose - Einstein correlation and \( m_T \)-spectra:
   - Freezeout \( \approx 120 \text{ MeV} \), overall life-time 8 fm/c,
   - Decoupling period 4 fm/c,
   - \( \beta_1 \approx 0.55 \) at mid-momentum. \( \Lambda \approx 0.7 \text{ fm} \quad (\nu = 5) \)