The Thermal Model

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DISCOVERY PHYSICS AT THE LHC

1 - 6 December 2014

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Outline

Basis of the Thermal Model

History of the Thermal Model

Beam Energy Scan at RHIC

The Thermal Model at the LHC

The Horn

Summary
Work done in collaboration with:
Francesco Becattini,
Antti Keränen,
Ingrid Kraus,
Helmut Oeschler,
Jörg Randrup,
Krzysztof Redlich,
Helmut Satz,
Natasha Sharma,
Esko Suhonen,
Spencer Wheaton.
Hadronic Gas

<table>
<thead>
<tr>
<th></th>
<th>Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>$\exp \left[ -\frac{E_\pi}{T} \right]$</td>
</tr>
<tr>
<td>$N$</td>
<td>$\exp \left[ -\frac{E_N}{T} + \frac{\mu_B}{T} \right]$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$\exp \left[ -\frac{E_\Lambda}{T} + \frac{\mu_B}{T} - \frac{\mu_S}{T} \right]$</td>
</tr>
<tr>
<td>$\bar{\Lambda}$</td>
<td>$\exp \left[ -\frac{E_\Lambda}{T} - \frac{\mu_B}{T} + \frac{\mu_S}{T} \right]$</td>
</tr>
<tr>
<td>$K$</td>
<td>$\exp \left[ -\frac{E_K}{T} + \frac{\mu_S}{T} \right]$</td>
</tr>
<tr>
<td>$\bar{K}$</td>
<td>$\exp \left[ -\frac{E_K}{T} - \frac{\mu_S}{T} \right]$</td>
</tr>
</tbody>
</table>
SPS data.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pb–Pb 158A GeV</th>
</tr>
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<tbody>
<tr>
<td>$(\pi^+ + \pi^-)/2.$</td>
<td>600±30</td>
</tr>
<tr>
<td>$K^+$</td>
<td>95 ±10</td>
</tr>
<tr>
<td>$K^-$</td>
<td>50 ±5</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>60 ±12</td>
</tr>
<tr>
<td>$p$</td>
<td>140±12</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>10 ±1.7</td>
</tr>
<tr>
<td>$\phi$</td>
<td>7.6±1.1</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>4.42±0.31</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>0.74±0.04</td>
</tr>
<tr>
<td>$\bar{\Lambda}/\Lambda$</td>
<td>0.2±0.04</td>
</tr>
</tbody>
</table>
SPS data.

SPS: Freeze-Out Parameters:

\[ T = 156.0 \pm 2.4 \text{MeV} \]
\[ \mu_B = 239 \pm 12 \text{MeV} \]

F. Becattini, J.C., A. Keränen, E. Suhonen and K. Redlich
E/N in 1999

E/N in 2000

\[ \frac{<E>}{<N>} = \begin{cases} 1.1 \text{ GeV} & \text{for RHIC Au-Au} \\ 1.0 \text{ GeV} & \text{for SPS Pb-Pb, AGS Au-Au, GSI Au-Au} \end{cases} \]
E/N in 2005

![Graph showing the relationship between temperature (GeV) and \( \mu_B \) (GeV) for different experiments including RHIC Au-Au, SPS Pb-Pb, GSI Au-Au, and AGS Au-Au. The graph includes two lines representing different values of \( <E>/<N> \): 1.1 GeV and 1.0 GeV. The data points for each experiment are plotted on the graph, indicating the temperature at various values of \( \mu_B \).]
E/N in 2006

**E/N in 2007**

![Graph showing the relationship between momentum density ($\mu_B$) and temperature for 2007 events at RHIC.](Image)

- **E/N = 1.1 GeV**
- **E/N = 1.0 GeV**

**Data Points:**
- RHIC Au-Au
- SPS Pb-Pb
- AGS Au-Au
- GSI Au-Au

Temperature (GeV) vs. $\mu_B$ (GeV) for 2007 events.
E/N in 2009

![Graph showing temperature vs. mu_B (GeV) for various experiments such as SPS Pb-Pb, AGS Au-Au, RHIC Au-Au, GSI Au-Au, HADES, FOPI. The graph includes lines showing <E>/<N> = 1.1 GeV and <E>/<N> = 1.0 GeV. The year 2009 is highlighted on the graph.]

- <E>/<N> = 1.1 GeV
- <E>/<N> = 1.0 GeV

The year 2009 is marked on the graph.
Beam Energy Scan at RHIC

Observables:

Phase boundary
Charge separation;
$v_2$ - NCQ scaling

1st order phase transition
Directed flow $v_1$

Critical point
Fluctuations

Chiral symmetry restoration
Di-lepton production

Study QCD Phase Structure!

Daniel McDonald: July 29 [FAIR workshop]

BES-I

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>7.7</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_B$ (MeV)</td>
<td>420</td>
<td>315</td>
<td>260</td>
<td>205</td>
<td>155</td>
<td>115</td>
</tr>
</tbody>
</table>

28 July – 6 August 2014, Kolymbari, Crete, Greece

Shusu Shi (for the STAR Collaboration) ICNFP2014

ALICE 2013

T = 154.75 ± 2.67 MeV
Radius = 10.47 ± 0.54 fm
**ALICE 2013**

![Graph showing particle multiplicities](image)

- **Data, ALICE, 0-10%**
- **Statistical model**
  
  Fit: $T=156$ MeV, $\mu_b=0$ MeV, $V=5380$ fm$^3$
  
  $T=164$ MeV, $\mu_b=1$ MeV

- P$^{-}$b-P$^{+}$b $\sqrt{s_{\text{NN}}}=2.76$ TeV

- Multiplicities of particles:
  - $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0_s$, $K^{*0}$, $\phi$, $p$, $\bar{p}$, $\Lambda$, $\Xi^-$, $\Xi^+$, $\Omega^-$, $\Omega^+$, $d$, $\Lambda$, $H$, $H$

Equilibrium SHM Fits

N.B. RHIC
\( \sqrt{s} = 200 \) STAR
\( \chi^2/\text{NDF} \sim 1 \)

Better fit in 60-80%,
(feel free to ask about it)

Petran et al, arXiv:1310.5108
Wheaton et al,
Comput.Phys.Commun, 180 84
Andronic et al, PLB 673 142
Chemical Freeze-Out Temperature

![Graph showing the relationship between √s_{NN} (GeV) and T (GeV)]
Chemical Freeze-Out $\mu_B$
Hadronic Freeze-Out

\[ \varepsilon^* = \varepsilon - m_N \rho \]

\( \sqrt{S}_{NN} \)

Excitation Energy Density \( \varepsilon^* \) (MeV/fm\(^3\))

Net Baryon Density (fm\(^{-3}\))

J. Randrup & J. Cleymans

S=0 & Q/B=0.4
Maxima in particle ratios: $K^+ / \pi^+$

![Diagram showing lines of constant $K^+ / \pi^+$ ratio and freeze-out curves.](image)
Maxima in particle ratios: $\Lambda/\pi^+$
Maxima in particle ratios

the roller-coaster seen in the particle ratios corresponds to a transition from a baryon-dominated to a meson-dominated hadronic gas. This transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

In the statistical model this transition leads to peaks in the $\Lambda/\langle \pi \rangle$, $K^+/\pi^+$, $\Xi^-/\pi^+$ and $\Omega^-/\pi^+$ ratios, each one at a different beam energy!
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