Chemical equilibrium and chemical freeze-out

OUTLINE

- Introduction
- Chemical freeze-out in UrQMD
- Revisiting the data
- Conclusions
Chemical Freeze-Out vs QCD critical line

Colliding nuclei at different energies we obtain different chemical Freeze-out points.

Extrapolated $T-\mu$ critical line is flatter than the CFO curve.

A closer look


Is the agreement between SHM and data an indication of common freeze-out?
If yes, we should see a deterioration of fit quality to a simulation including post-hadronization inelastic rescattering

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**PROGRAMME**

- Employ hybrid transport model with hydro stage and subsequent hadronic cascade, e.g. UrQMD v3.3
- Terminate
  - directly after hydro phase → decay into vacuum
  - or use UrQMD cascade expansion as “afterburner”
- First impression: Bulk hadrons show little change, but effects on anti-baryons
Centrality dependence

Kinetic freeze-out (at RHIC energy) DOES vary significantly as a function of centrality, whereas chemical does not. Interpretation: if kinetic decoupling occurs in the expanding hadron gas stage, it MUST depend on the geometry, roughly on Surface/Volume ratio. On the other hand, chemical seems NOT to depend, which is an indication of it being very close to the critical line.

U. Heinz, G. Kestin, CPOD 2006
nucl-th: 0612105
Main effect of hadronic rescattering (afterburner): antibaryon loss
Second step: fitting to SHM ($\gamma_S$) - using exp. errors

(a) UrQMD 158 AGeV Pb+Pb central

T = $160 \pm 2$ MeV
$\mu_B = 246 \pm 6$ MeV
$\gamma_S = 0.90 \pm 0.03$
$\chi^2$/DOF = 4.7/8

(b) UrQMD 158 AGeV Pb+Pb central

T = $151 \pm 1$ MeV
$\mu_B = 277 \pm 7$ MeV
$\gamma_S = 1.00 \pm 0.04$
$\chi^2$/DOF = 28.2/8
Major effects of including afterburning:

- Lowering the output c.f.o. $T$ by $\sim 10$ MeV
- Sizeable worsening of fit quality
Third step: fitting to SHM ($\gamma_S$) removing antibaryons

(a) UrQMD 158 AGeV Pb+Pb central

(b) UrQMD 158 AGeV Pb+Pb central

Hydro

Hydro+UrQMD

T = 159 ± 3 MeV
$\mu_B$ = 251 ± 1 MeV
$\gamma_S = 0.92 ± 0.04$
$\chi^2$/DOF = 3.1/5

T = 165 ± 6 MeV
$\mu_B$ = 251 ± 22 MeV
$\gamma_S = 0.91 ± 0.05$
$\chi^2$/DOF = 13.0/5

(fit-model)/error
Major effects of excluding antibaryons:

- Essential recovery of “original” freeze-out point
- Much better fit quality
What does the data say?
A recently published $p$ yield by NA49 in Pb-Pb at 17.2 GeV turned out to be consistently lower than the predicted by SHM.

Measured: 4.23±0.35

New fit to Pb-Pb mult's at 17.2 GeV

Lower T, lower quality
Possible explanation: the effect of post-hadronization rescattering

Effect of UrQMD afterburning on initial statistical hadronic yields from a hydro code

See also S. Bass and A. Dumitru, Phys. Rev. C 61 (2000) 064909

Residual distribution of a fit to hadronic yields excluding anti-baryons: Similar pattern of deviations
LHC energy

The p (\bar{p})/\pi yield in PbPb at 2.76 TeV is lower than predicted by the statistical hadronization model by 40% (prediction by A. Andronic et al., J.Phys. G38 (2011) 124081)

Advocated as an effect of post-hadronization rescattering

Y. Pan and S. Pratt, Baryon Annihilation in Heavy Ion Collisions arXiv:1210.1577 [nucl-th]

Physical picture

**Elementary Collisions**

- Hadrons are born into equilibrium.
- They are few and escape the reaction volume immediately.

**Heavy Ion Collisions**

- Hadrons are born into equilibrium.
- They need more time to escape the reaction volume.
- They can undergo inelastic collisions.
Where did we start from?

How to reconstruct hadronization conditions?

Strictly speaking, the latest hadro chemical equilibrium point (LHCEP)

Estimating the effect of the afterburning with an analytical calculation (e.g. Pratt) or a Monte-Carlo (UrQMD)

“Corrected” fit to ALICE data
Higher T, much better quality

Critical line = Hadronization

Latest chemical equilibrium point

Chemical freeze-out

Kinetic freeze-out
Comparing reconstructed LCHP's with lattice QCD

F. Karsch, J. Phys. G 38, 124098 (2011); S. Borsanyi et al., ibidem 124101

See also: The critical line of two-flavor QCD at finite isospin or baryon densities from imaginary chemical potentials. P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys.Rev. D85 (2012) 094512
We now start to see the details...
Conclusions and outlook

It has been believed that
Chemical freeze-out = chemical equilibrium ≈ hadronization ≠
QCD critical line at higher $\mu_B$

In fact, there is strong evidence that:
Chemical freeze-out ≠ chemical equilibrium ≈ hadronization = critical line

There should be some (slight) dependence of C.F.O. on centrality:
we are going to repeat the analysis with data taken in different
centrality bins.

A special thank to Reinhard Stock
S. Das, talk at Quark Matter 2012
Core-corona model

- $\gamma_s = 1$ for the core
- $\gamma_s < 1$ in heavy ion collisions is the effect of peripheral single NN collisions, for which $\gamma_s \sim 0.5$
- Calculates $N_c$ from Glauber

This approach reproduces very well the centrality dependence of strangeness enhancement (F.B., J. Manninen QM 2008 and J. Aichelin, K. Werner)
At $\mu_B = 0$ the transition is continuous (crossover) $T_c \sim 160$ MeV
Relativistic heavy ion collisions

How to produce “matter” with $\varepsilon \gg 1$ GeV/fm$^3$ lasting for $\tau > 1$ fm/c in a volume much larger than a hadron?

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Lab</th>
<th>$\sqrt{s_{NN}}$</th>
<th>Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS (90's)</td>
<td>CERN</td>
<td>6-18</td>
<td>Pb-Pb</td>
</tr>
<tr>
<td>RHIC (00-..)</td>
<td>RHIC</td>
<td>7.7-200</td>
<td>Au-Au</td>
</tr>
<tr>
<td>LHC (09-..)</td>
<td>CERN</td>
<td>2750</td>
<td>Pb-Pb</td>
</tr>
</tbody>
</table>
Sketch of the nuclear collision process

- Freeze-Out
- Pre-equil. phase
- Hadron Gas
- QGP
- $\tau_{eq}$
- $T_c$
Hadron radiation and freeze-out

Hadron radiation provides direct information about the thermodynamical state of the system at the stage when hadrons cease interactions and decouple.

FREEZE-OUT:
Chemical = when inelastic interactions cease
Kinetic = when also elastic interactions cease

QGP → Critical line = Hadronization → Chemical freeze-out → Kinetic freeze-out

Does the system stay in chemical equilibrium up to chemical freeze-out?

For many years the answer has been YES