Hadronization from e+e- to AA collisions and from light to heavy quarks

- the statistical model baseline
- light quarks – e+e- to AA
- charm quarks and charmonia
- the statistical hadronization model
- results for SPS and RHIC energies
- plans for LHC energy

work based on collaboration with
A. Andronic, K. Redlich, and J. Stachel

ECT*/EMMI workshop
on chiral symmetry and confinement
in dense matter
Trento, July 2010
Evolution of the Early Universe

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed
Thermal model description of hadron yields

Grand Canonical Ensemble

\[ \ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T)) \]

\[ n_i = \frac{N}{V} = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu_i} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T)} \pm 1 \]

\[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{i_3}^3 \]

for every conserved quantum number there is a chemical potential \( \mu \) but can use conservation laws to constrain:

- **Baryon number:** \( V \sum_i n_i B_i = Z + N \rightarrow V \)
- **Strangeness:** \( V \sum_i n_i S_i = 0 \rightarrow \mu_S \)
- **Charge:** \( V \sum_i n_i I_{i_3}^3 = \frac{Z - N}{2} \rightarrow \mu_{I_3} \)

This leaves only \( \mu_b \) and \( T \) as free parameter when \( 4\pi \) considered for rapidity slice fix volume e.g. by \( dN_{ch}/dy \)
Hadro-chemistry at RHIC  -- weakly decaying particles

All data in excellent agreement with thermal model predictions

chemical freeze-out at: $T = 165 \pm 8$ MeV

fit uses vacuum masses

most recent analysis:
A. Andronic, pbm, J. Stachel,
nucl-th/0511071

pbm, d. magestro, j. stachel, k. redlich,
Parameterization of all freeze-out points

note: establishment of limiting temperature

\[ T_{\text{lim}} = 160 \text{ MeV} \]

get \( T \) and \( \mu_B \) for all energies

nucl-th/0511071
Combining the world's data

Is there a triple point in the phase diagram?

in AA collisions all hadrons are produced at the phase boundary

ArXiv:0911.4806

Hadron Production in Ultra-relativistic Nuclear Collisions: Quarkyonic Matter and a Triple Point in the Phase Diagram of QCD

A. Andronic a, D. Blaschke b,c, P. Braun-Munzinger a,d,e,f, J. Cleymans g, K. Fukushima h, L.D. McLerran i,j, H. Oeschler e, R.D. Pisarski i, K. Redlich a,b,k, C. Sasaki h, H. Satz k, and J. Stachel m

Peter Braun-Munzinger
Fit to STAR data alone

very good fit, even including strongly decaying resonances

no evidence for special role of wide states
Fit also works for 3He! constrains $\mu_b$ significantly.
Why vacuum masses?

Masses of particles should change in the hot, dense medium

See, e.g. J.-P Blaizot and R. Mendez Galain
for a very early reference on this

But fit needs vacuum masses:

Strong density change near T_c?
1\textsuperscript{st} oder phase transition?
??? this is an open issue
Hadron Production in elementary collisions

as first noticed by F. Becattini in 1996


thermal features observed for overall production pattern but:

recent results:


thermal fit is possible only
with several external, non-statistical parameters
(gamma\(_S\), production probability of c and b quarks, ...)

also: fit quality is rather poor
Thermal fit to e+e- data at 91 GeV


several non-thermal, external parameters

thermal production of strange quarks
poor fit quality despite additional free parameter gamma_s
no equilibration in strange quark sector
Remarks on production of open charm and charmonia

- charm quark mass $\gg \Lambda_{QCD}$ production described in QCD perturbation theory
- all calculations employ gluon fusion as starting point
- argument is energy independent until global energy conservation very close to threshold becomes important
- production of charm quark pairs takes place at timescale $1/2m_c$
  $m_c = 1.3$ GeV $\rightarrow t_c = 0.08$ fm
- to build up wave function of mesons including those with open charm needs about $t = 1$ fm $\rightarrow$ charm production and charmed hadron formation are decoupled
- overall cross section is due to production of charm quark pairs
- time scale is much too short to dress the charm quarks essential to take current quarks for production
Are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997) but: \((J/\psi)/\psi'\) ratio is far from thermal in pp collisions
see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the \((J/\psi)/\psi'\) ratio reaches a thermal value \((T=170 \text{ MeV})\) in central PbPb collisions at SPS energy

further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003 result: \((J/\psi)/\pi\) is approximately constant at SPS energy for PbPb

However, thermal production of charm quarks is appreciable only at very high temperatures (LHC) \((T > 800 \text{ MeV})\), pbm&Redlich, Eur. Phys. J. C16 (2000) 519.

solution: charm quarks produced in hard collisions, then statistical hadronization at the phase boundary.
The psi'/psi ratio in elementary and AA collisions
about 1 % of cc_bar
pairs end up in J/psi
variation reflects
uncertainty in open
ccharm cross section?
charm quark flow and large energy loss imply approach to thermal but not chemical equilibrium

PHENIX coll., PRL 98 (2007) 172301
nucl-ex/0611018
Elliptic flow of J/psi!!

\[ \nu_2 = 0.11 \pm 0.05 \]

28% < \sigma/\sigma_{geo} < 83%  
\[ p_t > 1 \text{ GeV/c} \]

In+In, SPS energy, NA60 collaboration

thermalization of charm quarks
no strong broadening observed as expected for initial state scattering
this is different from the situation at the SPS
Heavy quark and quarkonium production in e+e- collisions

Comparison of stat. model calcs. with data


charmonium cannot be described at all in this approach
Ratios involving chi_c
Summary of this part

- in e+e- collisions strangeness is always undersaturated → no chemical equilibrium
- in AA collisions all hadrons are produced at the (a) phase boundary → full equilibrium
- charmonium production very different in elementary and AA collisions
- charm quark production mainly non-thermal
- at collider energies, charmonia are formed late, QGP is earlier
- no serious evidence for hadrons formed or surviving in the QGP
  → charmonia are formed at the phase boundary like all other hadrons

→ statistical hadronization model
Charmonium (re)generation models

- statistical hadronization model
  assumptions:
  - all charm quarks are produced in hard collisions, $N_c$ const. in QGP
  - all charmonia are dissolved in QGP or not produced before QGP
  - charmonium production takes place at the phase boundary with statistical weights
    $\rightarrow$ yield $\sim N_c^2$ -- quarkonium enhancement at high energies
    -- no feeding from higher charmonia

- charm quark coalescence model
  assumptions:
  - all charm quarks are produced in hard collisions
  - all charmonia are produced in the QGP via charm quark recombination
    $\rightarrow$ yield $\sim N_c^2$ -- quarkonium enhancement at high energies
Method and inputs

Thermal model calculation (grand canonical) $T, \mu_B: \rightarrow n_X^{th}$

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\Sigma_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\Sigma_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$$

$N_{c\bar{c}} \ll 1 \rightarrow \textbf{Canonical:}$ J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137

charm balance equation

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \rightarrow g_c$$

Outcome: $N_D = g_c V n_{D}^{th} I_1 / I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

Inputs: $T, \mu_B, \quad V = N_{ch}^{exp} / n_{ch}^{th}, \quad N_{c\bar{c}}^{dir}$ (pQCD)
Ingredients for prediction of quarkonium and open charm cross sections

- Energy dependence of temperature and baryochemical potential (from hadron production analysis)
- Open charm (open bottom) cross section in pp or better AA collisions
- Quarkonium production cross section in pp collisions (for corona part)

Result: Quarkonium and open charm cross sections as function of energy, centrality, rapidity, and transverse momentum

Important pre-requisite: All ratios among charmonia must be thermal
annihilation fraction is less than 0.2 %, even at LHC energy and with $\alpha_s = 1$. 
Recent publications:

Anton Andronic, F. Beutler, pbm, Krzysztof Redlich, Johanna Stachel

e-Print: arXiv:0805.4781 [nucl-th]

e-Print: arXiv:0710.1851 [nucl-th]

e-Print: nucl-th/0701079

e-Print: nucl-th/0611023

results for SPS energy

only moderately enhanced (2 x pQCD) cc_bar cross section needed

extrapolation to pp for $\psi'/\psi$ ratio still problematic in the model, although intuitively clear
RHIC result: nuclear modification factor

Data well described by our regeneration model without any new parameters.
Comparison of model predictions to RHIC data: rapidity dependence

Suppression is smallest at mid-rapidity (90 deg. emission) a clear indication for regeneration at the phase boundary
Calculations including shadowing

Assume PHENIX pA data reflect shadowing consistent with most recent PHENIX analysis by Frawley et al.
transverse momentum spectra

blast wave fit at $T = 160$ MeV

simultaneous fit of phi, Omega, and J/psi spectra at chemical freeze-out

strong support for production at the phase boundary
Quarkonium as a probe for deconfinement at the LHC

charmonium enhancement as fingerprint of deconfinement at LHC energy
Prediction for LHC energy: enhancement depends on charm cross section!

1. and 2: stat. hadronization

3: shadowing and regeneration in the hadronic phase only

A. Capella et al., arXiv:0712.4331 [hep-ph]
Summary

- charmonium production – a fingerprint for deconfined quarks and gluons
- evidence for energy loss and flow of charm quarks --> thermalization
- normalization to open charm in AA collisions – pA or dA
  normalization not easily applicable at LHC
- charmonium generation at the phase boundary – a new process
- first indications for this from RHIC data
- charmonium enhancement at LHC – deconfined QGP
Outlook

charm measurements in the LHC era:

ccbar cross section in pp and PbPb

charmonium production cross sections in pp and PbPb as function of pt, y, centrality, reaction plane …

charmonium from B-decay
hot news: first data from LHC pp collisions

November 23, 2009
First proton-proton collisions at $\sqrt{s}=900$ GeV

ALICE pseudo-rapidity density 
(Nov 28)

Dec 6, 2009 pp at $\sqrt{s}=2.36$ TeV
Mar 30, 2010 pp at $\sqrt{s}=7$ TeV
ALICE, the major nuclear physics experiment at LHC
ALICE has very good particle identification
dE/dx in TPC

few days of running: already antitritons visible – very clean
first observation of $D^0$, $D^+$ and $D^{0*}$ in 7 TeV pp data

for $10^9$ events, expect to measure open charm for $p_t = 0.5 - 15$ GeV/c

$1.25 \times 10^8$ events
first J/psi in ALICE central barrel from 110 million pp collisions at 7 TeV

expect about 500 J/ψ mesons by Sep. 2010 -> $p_t$ and $y$ distributions and production cross section
A first look at jets
rapidity dependence of nuclear modification factor


analysis of recent AuAu PENIX data, rapidity dependence of shadowing may also lead to maximum at mid-rapidity