Theoretical and experimental evidence for hadron formation above the QCD critical temperature

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The fundamental questions

- **How do hadrons form?**
  - Parton fragmentation or string fragmentation or recombination
  - An early color neutral object (pre-hadron) or a long-lived colored object (quasi-particle or constituent quark)

- **When do hadrons form?**
  - Inside the deconfined medium or in the vacuum?

**Why investigate it now?**

1.) more precise lattice QCD calculations for the case of formation out of equilibrium

2.) a better understanding of fragmentation (non-equilibrium formation)

3.) better data from RHIC and LHC to follow formation as a function of time, temperature and particle momentum
What happened to the QCD phase transition (in lattice QCD) over the past decades?

Main reasons: continuous improvements in lattice spacing (continuum limit) and realistic quark mass ratios (pion mass).

Are order parameters still order parameters?

Is an inflection point equivalent to a critical temperature? (and if so, what happens between the inflection point and the weak coupling limit)?
Is an order parameter still an order parameter?

The long list of QCD order parameters:
- Chiral condensate (chiral symmetry)
- Polyakov Loop (deconfinement)
- Trace Anomaly (interaction strength)
- Quark Correlators (interaction or binding)
- Susceptibilities (interaction strength)
- Energy Density
- Entropy
- Pressure

Lattice approach: the multitude of parameters tell (more or less) the same story
Evolution of the phase transition as a function of finer lattice spacing & realistic quark masses (the cross-over becomes smoother = a longer mixed phase?)

![Graph showing the evolution of the phase transition as a function of finer lattice spacing and realistic quark masses. The graph plots $c_2 \omega/T^2$ against $T/T_c$. Symbols represent different lattice spacings and quark mass configurations. The new and old data points are indicated.]
Are there bound states above $T_c$?

- Survival or formation – a question of perspective
- The deconfinement order parameter in lQCD: Polyakov loop

- Low energy collisions (AGS, SPS, RHIC scan, FAIR): survival of resonant states
- High energy collisions (RHIC, LHC): formation of pre-hadronic states

Bazavov et al., arXiv:1105.1131
Are there bound states above $T_c$?

A long standing question in the literature

- **Survival:** Rapp et al. (arXiv:0901.3289) – chiral symmetry restoration signatures in the transition region (mass shifts, width broadening, Brown-Rho scaling, etc. of surviving resonant states in particular of heavy quarks)

- **Formation:** Shuryak (PRD 70 (2004)054507) – colored bound states. Leads to phase diagram with differing quark condensates
Why distinguish between equilibrium and non-equilibrium?

- There is plenty of evidence for two components in the particle spectra at RHIC and LHC. Breakdown of hydrodynamics at high pT, power law at high pT

- Two component model:
  - soft (bulk, equil.) / hard (fragmentation, non-equil.)

- Kharzeev / Nardi scaling for yield:

$$\frac{dN}{d\eta} = (1 - x) n_{pp} \left( \frac{N_{part}}{2} \right) + x n_{pp} \langle N_{coll} \rangle$$

- Levi-Tsallis fit for spectra (exponential + power-law):

$$\frac{d^2 N}{dy dp_t} = \frac{(n - 1)(n - 2)}{nT[nT + m_0(n - 2)]} \times \frac{dN}{dy} \times p_t \times (1 + \frac{m_t - m_0}{nT})^{-n}$$
The non-equilibrium case – a high momentum probe in a deconfined medium
A question of formation time (RB & C. Markert, PLB 691, 208 (2010))

A parton traverses the medium and fragments outside

A parton fragments inside the medium

A parton converts into a pre-hadronic state or a quasi-particle which traverses the medium and fragments outside

The equilibrium case – particle formation out of the thermalized medium
A question for lattice QCD (C. Ratti, RB et al., PRD 85, 014004 (2012))
The non-equilibrium case
Schematic Modeling of Hadronization in medium

**Bjorken (1976):** The higher the energy and the lighter the final state, the later the hadron will form (inside-outside cascade) (Lorentz boost)

**Kopeliovich (1979):** A high z particle has to form early otherwise the initial parton loses too much energy (outside-inside cascade) (Energy conservation)

$$\tau_{\text{form}} = \tau_0 \frac{E}{m}$$

Inside-out cascade (boost)

$$\tau_0 \sim 1 \text{ fm/c} : \text{proper formation time in hadron rest frame}$$

$$E : \text{energy of hadron}$$

$$m: \text{mass of hadron} \quad E/m = \gamma$$

→ high energy particles are produced later

→ heavy mass particles are produced earlier

$$\Delta y^+ \simeq \frac{1}{\Delta p^-}$$

$$= \frac{z p^+}{m_h} \times 2 \left[ m_h + \frac{k^2}{(1 - z)m_h} - \frac{z m_q^2}{m_h} \right]^{-1}.$$  \hspace{1cm} (3)

The formation time then reads:

$$\tau_{\text{form}} = \frac{\Delta y^+}{1 + \beta_q}, \quad \beta_q = \frac{p_q}{E_q}. \hspace{1cm} (4)$$

Outside-in Cascade (pre-hadron formation)

large z (=ph / pq) = leading particle

→ shortens formation time

C. Markert, RB, I. Vitev
(PLB 669, 92 (2008))
Formation Time of Hadrons in RHIC / LHC QGP

**RHIC**

- $s^{1/2} = 200 \text{ GeV}$
- $\Lambda_{QCD} = 200 \text{ MeV}$

**LHC**

- $s^{1/2} = 5.5 \text{ TeV}$
- $\Lambda_{QCD} = 200 \text{ MeV}$

**Diagrams**

- RHIC QGP
- LHC QGP

- Pre-equilibrium
- pQCD estimates

**Axes**

- $p_T^{\text{hadron}}$ [GeV/c]
- Formation time [fm/c]
Predictions for energy loss
RB & C. Markert (PLB 691, 208, 2010)
Data can be described with differing formation time for baryons and mesons, if one assumes rather short existence of pre-hadron in mixed phase (late formation)

Alternative: recombination
The equilibrium case
C. Ratti, RB, M. Cristoforetti, M. Barbaro
Is Lattice QCD the right approach?

Greco et al., arXiv:1202.2262
No gluons near $T_c$

Ratti, Greco et al., arXiv:1103.5611
Evidence for massive states above $T_c$

Slight difference in temperature dependence of the quasi-particle masses for two lattice QCD actions
But could there be color-neutral bound states?

A re-interpretation of the Polyakov Loop in lattice QCD
(measure of deconfinement)
New lattice results: diagonal and non-diagonal correlators in limited T-range above $T_c$

( Seminar at C. Ratti talk on Wednesday)

\[ \text{Diagonal correlators} \]

\[ \text{Non-diagonal correlators} \]
How much of this is due to fluctuations in the deconfined medium rather than bound states?

Comparison of lattice to PNJL (*PRD 85, 014004 (2012*))

**PNJL variations**

- **PNJL-MF:** pure mean field calculation
- **PNJL-PL:** mean field plus Polyakov loop fluctuations
- **PNJL-MC:** mean field plus all fluctuations (incl. chiral and Kaon condensate fluctuations)

**Conclusion:** even the inclusion of *all possible fluctuations* is *not sufficient* to describe lattice data above $T_c$. *There has to be a contribution from bound states*.
Properties of bound states above $T_c$:
Flavor dependence even in the light sector

The heavier the quark the longer the mixed phase
More strange bound states than light bound states above $T_c$?
Potential evidence of flavor dependence in equilibrium freeze-out

**Data:** ALICE, SQM 2011

**Theory:** Ratti et al., QM 2011

Properties of bound states above $T_c$: Baryon-meson dependence in correlator

Upswing in lattice correlator shows that baryon contribution rises with $T$, but the correlator never turns positive $\rightarrow$ the contribution of bound states above $T_c$ must be predominantly of mesonic nature until final deconfinement

C. Ratti, Hadronic resonance gas (HRG) calculation:

Baryonic bound states dominate at $T>190$ MeV.

Confirmed by lQCD: S. Borsanyi et al., accepted at JHEP arXiv:1112.4416
Properties of bound states above $T_c$: Strange baryons form at higher $T$

S. Borsanyi et al., accepted at JHEP arXiv:1112.4416

Strange baryonic bound states should form at higher $T$
The effect of mass on the correlator inflection point ($T_c$ ?)

S. Borsanyi et al., arXiv:1204.0995

If not all heavy quark production is from initial gluon fusion but due to thermal production in the medium, then the heavy quark particle ratios will be sensitive to the transition temperature.

Let’s measure $D/\pi$ or $\Lambda_c/\pi$. 

The graph shows the quark number susceptibilities as a function of temperature ($T$). The curves represent different ratios of quark susceptibilities, such as $c_{2}^{uu}/T^2$, $c_{2}^{ss}/T^2$, and $c_{2}^{cc}/T^2$ with $N_t=12$. The data points indicate a transition behavior at a certain temperature.
Summary

- There is evidence for flavor and mass dependent color-neutral bound state formation in the medium above the QCD phase transition based on lattice QCD and fragmentation studies. *There is likely no common phase transition behavior (hadronization) for different flavor hadrons.*

- A comparison of lattice QCD to HRG and PNJL calculations allows us to quantify the relative abundance of the confined and deconfined states in the equilibrated mixed phase around the critical temperature as a function of $T$. SHM for different particle species might be sensitive to transition temperature.

- Experimental studies of $p_T$, width, mass broadening, nuclear suppression, yields and ratios of identified particles and resonances give us a unique tool to answer fundamental questions of hadron formation.