The Quark-Gluon Plasma
Four Lectures

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The Fundamental Problems of Physics

constituents
quarks
leptons
 gluons, photons
 vector bosons (Z, W\(^\pm\))
 Higgs

forces
 strong
e-m
 weak
 gravitation
 unification, TOE

elementary interactions
↓
complex systems

states of matter
 solid, liquid, gas
 glass, gelatine
 insulator, conductor
 superconductor, ferromagnet
 fluid, superfluid

transitions
 thermal phase transitions
 percolation transitions
 scaling and renormalization
 critical exponents
 universality classes
Complex Systems ⇒ **New Direction** in Physics

- Given constituents and dynamics of elementary systems, what is the behaviour of complex systems?
- What are the possible states of matter and how can they be specified?
- How do transitions from one state of matter to another occur?
- Is there a general pattern of critical phenomena, independent of specific dynamics?
- Conceptually new physics: renormalization, self-similarity, self-organization, emergence, sand piles, swarm intelligence, ...
Knowing all there is to know about the helium atom the ant tells you nothing about the behaviour of liquid helium a colony of ants

⇒ even a fully unified fundamental theory does not solve the issue of complex systems, of the states of matter
states of matter in antiquity - and in strong interaction physics?
Four Lectures

1. The Thermodynamics of Quarks and Gluons
2. Phase Diagram of Strongly Interacting Matter
   3. Quarkonia in Deconfined Matter
4. Statistical Hadronization and its Origin
Lecture 1
The Thermodynamics
of Quarks and Gluons
What is the **Quark-Gluon Plasma**?

A state of strongly interacting **matter**, in which the **constituents** of hadrons, quarks and gluons, are **not spatially confined** to form color-neutral **bound states**.

When many hadrons overlap, quarks cannot identify “their hadron”, the concepts of a hadron and of confinement become meaningless, color screening and high quark density (asymptotic freedom) forbid hadronic scales ⇒ transition to a new state of matter.
Confined Matter

• quark-antiquark pairs or three-quark states form color-neutral states of hadronic size $\sim$ 1 fm;

• quarks acquire a dynamically generated “effective” mass of about 300 MeV by gluon dressing $\rightarrow$ spontaneous chiral symmetry breaking;

• mesonic matter: constituents are mesons and baryons, the interaction is resonance-dominanted;

• baryonic matter: constituents are nucleons, the interaction is long-range attraction (1 fm) and short range repulsion (0.5 fm)

increasing the meson density (by increasing $T$), or increasing the nucleon density (by compressing nuclear matter) leads to hadron overlap and thus deconfinement.

what happens in the deconfinement transition?
Deconfined Matter

- at deconfinement, bound states are dissolved, constituents are colored quarks; ⇒ **insulator-conductor transition** of QCD
- the gluon dressing melts, the quark mass drops to Lagrangian mass; ⇒ **chiral symmetry restoration**.

Do the two phenomena coincide?

In general: either yes or first deconfinement, then chiral symmetry restoration

[Banks & Casher 1979]

- possible state of deconfined massive colored quarks: **quark plasma**; lattice studies: at low baryon density, deconfinement and chiral symmetry restoration coincide;
- deconfined quarks (whether massive or not) may still interact; QCD ⇒ quark-quark binding ⇒ **colored bosonic diquarks**;
- colored diquark bosons at low $T$ can form Bose condensate: **color superconductor**.
Speculative phase diagram for strongly interacting matter:

\[
\begin{align*}
\text{T} & \quad \text{quark–gluon plasma} \\
\text{T}_c & \quad \text{mesonic matter} \\
& \quad \text{nuclear matter} \\
& \quad \text{quark plasma} \\
& \quad \text{color superconductor}
\end{align*}
\]

NB: in all phases, \( \exists \) interactions!
2. From Hadrons to Quarks and Gluons

simplest confined matter: ideal pion gas \[ P_\pi = \frac{\pi^2}{90} \, 3 \, T^4 \approx \frac{1}{3} \, T^4 \]

simplest deconfined matter: ideal quark-gluon plasma

\[ P_{QGP} = \frac{\pi^2}{90} \left\{ 2 \times 8 + \frac{7}{8} \left[ 2 \times 2 \times 2 \times 3 \right] \right\} \, T^4 - B \approx 4 \, T^4 - B \]

with bag pressure \( B \) for outside/inside vacuum

given \( P_\pi(T) \) vs. \( P_{QGP}(T) \): nature chooses highest \( P \) (lowest \( F \))

phase transition from hadronic matter at low \( T \) to QGP at high \( T \)
critical temperature:

\[ P_\pi = P_{QGP} \rightarrow T_c^4 \simeq 0.3 \ B \simeq 150 \text{ MeV} \]

with \( B^{1/4} \simeq 200 \text{ MeV} \) from quarkonium spectroscopy

corresponding energy densities

\[ \epsilon_\pi \simeq T^4 \rightarrow \epsilon_{QGP} \simeq 12 \ T^4 + B \]

at \( T_c \), energy density changes abruptly by \textbf{latent heat of deconfinement}
compare energy density and pressure:
ideal gas $\epsilon = 3P$

here we obtain

and the interaction measure

$$\Delta \equiv \frac{\epsilon - 3P}{T^4} = \frac{4B}{T^4}$$

shows that for $T_c \leq T < 2 - 3 T_c$
the QGP is strongly interacting

so far, simplistic model; real world?
3. Finite Temperature Lattice QCD

given QCD as dynamics input, calculate resulting thermodynamics, based on QCD partition function

⇒ lattice regularization, computer simulation

• energy density

⇒ latent heat of deconfinement

For $N_f = 2, 2 + 1$:

$$T_c \simeq 175 \text{ MeV}$$
$$\epsilon(T_c) \simeq 0.5 - 1.0 \text{ GeV/fm}^3$$

explicit relation to deconfinement, chiral symmetry restoration?

⇒ order parameters
• deconfinement \[ \Rightarrow m_q \to \infty \]

Polyakov loop \[ L(T) \sim \exp\{-F_{Q\bar{Q}}/T\} \]

\( F_{Q\bar{Q}} \): free energy of \( Q\bar{Q} \) pair for \( r \to \infty \)

\[
L(T) \begin{cases} 
= 0 & T < T_L \text{ confinement} \\
\neq 0 & T > T_L \text{ deconfinement} 
\end{cases}
\]

variation defines deconfinement temperature \( T_L \)

• chiral symmetry restoration \[ \Rightarrow m_q \to 0 \]

chiral condensate \( \chi(T) \equiv \langle \bar{\psi}\psi \rangle \sim M_q \)

measures dynamically generated (‘constituent’) quark mass

\[
\chi(T) \begin{cases} 
\neq 0 & T < T_\chi \text{ chiral symmetry broken} \\
= 0 & T > T_\chi \text{ chiral symmetry restored} 
\end{cases}
\]

variation defines chiral symmetry temperature \( T_\chi \)
• how are $T_L$ and $T_\chi$ related?

$SU(N)$ gauge theory: $\sim$ spontaneous $Z_N$ breaking at $T_L$

QCD, chiral limit: $\sim$ explicit $Z_N$ breaking by $\chi(T) \to 0$ at $T_\chi$

chiral symmetry restoration $\Rightarrow$ deconfinement

lattice results

at $\mu = 0$, $\exists$ one transition hadronic matter $\to$ QGP

for $N_f = 2, m_q \to 0$ at $T_c = T_L = T_\chi \simeq 175$ MeV
Finite temperature lattice QCD shows:

- ∃ transition at $T \sim 0.175 \pm \text{?} \text{ GeV}$, where deconfinement & chiral symmetry restoration coincide
- at transition, $\epsilon$ increases suddenly by latent heat of deconfinement

What about interactions in QGP?

**interaction measure** (trace of energy-momentum tensor)

$$\Delta = \frac{\epsilon - 3P}{T^4}$$

vanishes for non-interacting massless constituents
quarks and gluons are (ideally) massless; what $\Delta(T > T_c)$?
4. The Strongly Interacting QGP

Expect that for high enough $T$, asymptotic freedom $\rightarrow$ ideal QGP (perturbation theory)
how high is enough? – consider best known case $SU(3)$ gauge theory
$\exists$ perturbative calculations up to $O(g^5)$
perturbation theory oscillates strongly
does not converge for $T \leq 10 \, T_c$

non-pert. extension [Kajantie et al. 2003]:
still qualitatively wrong for $T \leq 5 \, T_c$

re-organize perturbation theory
("re-summed" theory, HTL)
[Andersen, Strickland & Su 2010]

– weak coupling approaches cannot account for QGP at

$T \leq T_c \leq 5 \, T_c$: no dip at $T_c$, wrong (log) $T$-dependence
Non-perturbative approach: bag model
non-interacting quarks & gluons in “medium” gluon condensate

\[ \Delta = \frac{4B}{T^4} = \frac{G_0^2}{T^4} \]

bag pressure \( \sim \) gluon condensate at \( T = 0 \)

numerical estimate \( G_0^2 \approx 0.012 \text{ GeV}^4 \)

[Shifman, Vainshtein & Zakharov 1979]

Conclude:

• weak coupling: \( T \)-dependence too weak, no dip at \( T_c \)

• bag model: \( T \)-dependence too strong, no dip at \( T_c \)

what is QGP for \( T_c \leq T \leq 4 \ T_c \)?

\( \Rightarrow \) Quasi-Particle Model
∃ two regions

- critical region as $T \to T_c$, “singular” behavior
- screening region in hot QGP

consider gluons in deconfined medium:
polarization $\to$ dressing, effective gluon mass

- as $T \to T_c$ from above, correlation length increases/diverges,
  so gluon polarizes more & more of medium

- as $T > T_c$ increases, correlation length decreases, so gluon
  sees less and less of medium

- as $T > T_c$ increases, energy density of medium increases

two competing effects:

consider $SU(2)$ gauge theory

$\Rightarrow$ continuous transition, critical exponents

[Goloviznin & HS 1993]
for $T \rightarrow T_c$, with $t \equiv (T/T_c)$,

- energy density $\epsilon \sim (t - 1)^{1-\alpha}$
- correlation volume $V_{\text{cor}} \sim (t - 1)^{-2\nu-\eta}$

with ($Z_2$ universality class) $\alpha = 0.11$, $\nu = 0.69$, $\eta = 0.04$, so that

$$m_{\text{crit}}(T) \sim \epsilon \, V_{\text{cor}} \sim (t - 1)^{1-\alpha-2\nu-\eta} \sim (t - 1)^{-0.41}$$

effective gluon mass diverges for $T \rightarrow T_c$ in hot QGP, screening length $r_D \sim 1/T$, hence

- $\epsilon \sim T^4$
- $V_{\text{cor}} \sim T^{-3}$
- $m_{\text{crit}}(T) \sim \epsilon \, V_{\text{cor}} \sim T$

overall behavior of effective gluon mass

$$m(T) = a(t - 1)^{-c} + bt$$

with constants $a, b, c$; here $c = 0.41$
retain this form in general
apply to $SU(3)$ gauge theory
[Castorina, Miller & HS 2010]

excellent description of all thermodynamic quantities, including $\Delta(T)$
NB: speed of sound in QGP “vanishes” at $T_c$, heavy gluons...
5. Probing the Quark-Gluon Plasma

At high temperatures and/or densities, strongly interacting matter becomes a QGP;
how can we probe its properties and its behaviour as function of temperature and density?

Given a volume of strongly interacting matter and an energy source, how can we determine its state at different temperatures?

NB: equilibrium thermodynamics, no collision effects, time dependence, equilibration, etc.
Possible probes:  • hadron radiation  
• electromagnetic radiation  
• dissociation of quarkonium states  
• energy loss of parton beams

Here, just a brief first look....

The medium is hotter than its environment (vacuum) and hence emits

• **Hadron Radiation**

  emission of light hadrons  
  (made of $u, d, s$ quarks)  
  scale $\sim 1$ fm $\simeq 1/(200$ MeV$)$

  cannot exist in hot interior  
  emission at surface of $T \simeq T_c$

  information about hadronization stage

$\Rightarrow$ same relative abundances for different initial energy densities
In the interior of the medium, quark-gluon interactions or quark-antiquark annihilation leads to

- **Electromagnetic Radiation**

  produced photons and dileptons
  leave medium without further interaction
  provide information about the medium at the time of their production:
  probe of hot QGP

  problem:
  they can be formed anywhere & at any time
  even at the surface or by the emitted hadrons
  task: identify hot thermal radiation

  hadronic and e-m radiation: emitted by the medium itself
  provide information about the medium at the time of production
  other possibility: “outside” probes
Quarkonium Suppression

quarkonia: bound states of heavy quarks ($c\bar{c}, b\bar{b}$)
smaller than usual hadrons ($r_Q \ll r_h \simeq 1$ fm),
binding energies $0.5 - 1.0$ GeV

$\Rightarrow$ can survive in QGP
in some temperature range $T > T_c$

Example: charmonium states

$J/\psi(1S) - r_{J/\psi} \simeq 0.2$ fm
$\chi_c(1P) - r_\chi \simeq 0.3$ fm
$\psi'(2S) - r_{\psi'} \simeq 0.4$ fm

different charmonia “melt” in QGP at different temperatures

potential & lattice studies: $T_{\psi'} \simeq T_\chi \simeq 1 - 1.1$, $T_{J/\psi} \simeq 1.5 - 2 T_c$
$\epsilon_{\psi'} \simeq \epsilon_\chi \simeq 1 - 1.5$, $\epsilon_{J/\psi} \simeq 8 - 12$ GeV/fm$^3$
⇒ “sequential charmonium melting” as quantitatively predicted property of QGP

similar to solar spectra as thermometer of sun
● **Jet Quenching**

shoot an energetic parton beam (quarks or gluons) into QGP, measure energy of outgoing beam attenuation ("quenching") determined by density of medium increases with temperature

NB: how to get “external” probes in nuclear collision experiments?

● **Hard Probes:**

quarkonia, open charm/beauty, jets, energetic photons & dileptons
– formed very early in the collision, are present when QGP appears
– can be predicted (to large extent) by perturbative QCD
– can be “gauged” in *pp* and *pA* collisions
Summary

In strong interaction thermodynamics \( \exists \) a well-defined transition at which

- deconfinement sets in & chiral symmetry is restored
- latent heat increases energy density
- transition temperature \( T_c \approx 160 - 190 \text{ MeV} \).

For \( T > T_c \), the state of matter is a plasma of deconfined quarks and gluons which can be probed by

- electromagnetic radiation
- quarkonium spectra
- jet quenching

In addition, decisive information on confinement transition from

- hadron production