From Heavy-Ion Collisions to Quark-Gluon matter

Constantin Loizides
(LBNL)

- Part I: Introduction and background
- Part II: Results mainly related to bulk properties
- Part III: Results mainly related to hard probes
What Physics Do You See?

The water droplets on the window demonstrate a principle: truly beautiful and complex physics emerges in systems whose underlying dynamics is given by QED.

H₂O

\[ \text{vapor} \]

\[ \text{critical point} \]

\[ \text{water} \]

\[ \text{ice} \]

\[ \text{0°C} \]

\[ \text{100°C} \]

\[ \text{760mm} \]

\[ \text{pressure} \]
Does QCD exhibit equally beautiful properties when looked at as bulk matter?

Of course, the answer is yes as we will see ...
Quantum Chromo Dynamics

(see e.g. arXiv:hep-ph/9505231)
The standard model and QCD

- **Strong interactions**
  - Binds quarks into hadrons
  - Binds nucleons into nuclei
- **Described by QCD**
  - Interactions between quarks and gluons carrying color charge
  - Mediated by gluons, the strong force carriers

### FERMIONS

<table>
<thead>
<tr>
<th>Leptons spin = 1/2</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1 \times 10^{-3}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>0.000511</td>
<td>−1</td>
</tr>
<tr>
<td>$\nu_\mu$ muon neutrino</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>−1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau neutrino</td>
<td>&lt;0.02</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>−1</td>
</tr>
</tbody>
</table>

### Quarks spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>−1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>−1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>−1/3</td>
</tr>
</tbody>
</table>

### BOSONS

<table>
<thead>
<tr>
<th>Unified Electroweak spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>$\gamma$ photon</td>
</tr>
<tr>
<td>$W^-$</td>
</tr>
<tr>
<td>$W^+$</td>
</tr>
<tr>
<td>$Z^0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong (color) spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>$g$ gluon</td>
</tr>
</tbody>
</table>
The standard model and QCD

- **Strong interactions**
  - Binds quarks into hadrons
  - Binds nucleons into nuclei

- **Described by QCD**
  - Interactions between quarks and gluons carrying color charge
  - Mediated by gluons, the strong force carriers

- **Very successful theory**
  - e.g. pQCD vs production of high energy jets

- **But with outstanding puzzles!**

Two puzzles in QCD:

i) hadron masses

- A proton is thought to be composed out of uud
- The proton mass is about 938.3 MeV/c
- Sum of bare quark masses is only about 12 MeV
- How is the extra mass generated?

ii) confinement

- Nobody ever succeeded in detecting an isolated quark
- Instead, quarks seem to be confined within hadrons
- It looks like one half of the fundamental fermions are not directly observable.
  Why?

Usually among the list of top most unsolved problems in physics
(List of unsolved problems on wikipedia)
Quantum Chromo Dynamics (QCD)

Same basic structure as QED (electro-magnetism) ... except that gluons (“photons” of strong force) carry color charge ...

\[
(q_\alpha)^a_f \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \alpha = 1, 2 \end{cases}
\]

\[
A_\mu^a \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}
\]

Dynamics: Generalized Maxwell (Yang-Mills)

\[
\mathcal{L} = \bar{q}_f (i\slashed{D} - m_f) q_f - \frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu}
\]

\[
G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c
\]

\[
i\slashed{D} q = \gamma^\mu \left( i\partial_\mu + g A_\mu^a t^a \right) q
\]

... so they interact also among themselves, generating much more complex structures
Consider the interaction of two elementary particles.

Momentum transfer $Q^2$:
- Small $Q^2 \Rightarrow$ large distance scales
- Large $Q^2 \Rightarrow$ small distance scales

Quantum mechanics:
Virtual pairs (loops) screen the bare interaction resulting in momentum dependent interaction strength.
"Running" of the coupling: QED vs QCD

\[ \alpha \equiv \frac{g^2}{4\pi} \]

QED: \( \alpha (Q^2) \approx \alpha (\mu^2) / \left( 1 - \frac{\alpha (\mu^2)}{3\pi} \log \frac{|Q^2|}{\mu^2} \right) \)

Smaller \( |Q^2| \) (larger distance) ⇒ weaker coupling
(similar to screening of charge in di-electric material)

QCD:
\[ \alpha (Q^2) \approx \alpha (\mu^2) / \left( 1 + \frac{\alpha (\mu^2)}{12\pi} \log \frac{|Q^2|}{\mu^2} \right) \]
\[ = \frac{33-12}{12\pi} = \text{positive!} \]

Smaller \( |Q^2| \) (larger distance) ⇒ stronger coupling
(so called anti-screening stronger than screening)

And that makes a huge difference!
“Running” of the coupling: QCD

Asymptotic freedom

2004 Nobel Prize

Confinement
QCD deconfinement phase transition
Confinement

- The increase of the interaction strength (for a \( qq \) pair) can be approximated by the Cornell potential

\[
V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + K r
\]

- \( K r \) parametrizes the effects of confinement
- When \( r \) increases, the color field can be seen as a tube
- At large \( r \), it becomes energetically favorable to convert the stored energy into a new \( qq \) pair
- Confinement cannot be described perturbatively, but with lattice QCD or bag models inspired by QCD

(Illustration from Fritzsch)
Deconfinement

- Since the interactions between quarks and gluons become weaker at small distances, it might be possible to create a deconfined phase of matter composed out of a large number of free quarks and gluons.

- First ideas in the mid 1970's
  Experimental hadronic spectrum and quark liberation
  Cabibbo and Parisi, PLB59 (1975) 67
  Superdense matter: Neutrons or asymptotically free quarks?
  Collins and Perry, PRL 34 (1975) 1353

We expect the same transition to be also present at low temperature but high pressure, for the same reason, i.e. we expect a phase diagram of the kind indicated in fig. 1.

Fig. 1. Schematic phase diagram of hadronic matter. $\rho_B$ is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.
Building intuition: The MIT Bag model

- The MIT bag model assumes that quarks are confined within bags of perturbative (empty) vacuum of radius $R$, in which they are free to move.
- The QCD (true) vacuum creates a confining bag pressure $B$.
- The bag pressure is obtained by balancing the vacuum with the kinetic pressure of the quarks.
- $B \approx (200 \text{ MeV})^4$ with $N=3$ quarks in $R=0.8\text{fm}$.

Chodos et al., PRD 10 (1974) 2599
Deconfinement: A toy model

- Heat matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

\[ p = \frac{\epsilon}{3} = \left( g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90} \]
Deconfinement: A toy model

- Heat or compress matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

\[ p = \frac{\epsilon}{3} = \left( g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90} + g_F \left( \frac{\mu_F^2 T^2}{12} + \frac{\mu_F^4}{24\pi^2} \right) \]

- Condition for QGP: Pressure \( \geq B \)

\[ p = \frac{\epsilon}{3} = B \Rightarrow T_c(\mu_F) \]

(see Reygers and Schweda)

\[ g_B = 0, \quad g_F = 2 \]

\[ g_B = 2 \times 8, \quad g_F = 2 \times 2 \times 2 \times 3 \]

\( B = \text{Boson} \quad F = \text{Fermion} \)
Phase diagram of non-interacting QGP

$T_c \approx 2 \cdot 10^{12} \text{K}$
($10^5$ times core of sun)

- **Condition for QGP:**
  - Pressure $\geq B$
  - $p = \frac{\epsilon}{3} = B \Rightarrow T_c(\mu_F)$

$(\text{see Reygers and Schweda})$
Lattice QCD
Lattice QCD

- As QCD is asymptotically free at small distances, cannot use perturbation theory to calculate properties of e.g. hadrons
- Instead solve QCD numerically by putting fields on a space-time lattice (lattice QCD)
- First principle non-perturbative calculation
- Computationally demanding as lattice needs to be big, e.g. $16^3 \times 32$

JUGENE in Jülich
(294,912 cores, ~ 1 PetaFLOPS)

Snapshot of fluctuating quark and gluon fields on a discrete space-time lattice
Lattice QCD: the approach

- Solve path integrals numerically in discretised Euclidean space-time
  \[ e^{iS} \rightarrow e^{-S_E} \]

- Physical results
  - Continuum limit \((a \rightarrow 0)\)
  - Infinite volume limit \((V \rightarrow \infty)\)
  - Set scale(s) using data e.g. hadron mass(es)

- Problems of approach
  - Fermion doubling
  - Sign problem for finite \(\mu\)
  - Small physical quark masses computationally demanding

\[
\begin{align*}
\text{Lattice spacing} & \quad a, \quad a^{-1} \sim \Lambda_{\text{UV}}, \quad x_\mu = n_\mu a \\
\text{Finite volume} & \quad L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a
\end{align*}
\]

\[
\begin{align*}
\text{(anti)quarks:} & \quad \psi(x), \quad \bar{\psi}(x) \\
\text{gluons:} & \quad U_\mu(x) = e^{aA_\mu(x)} \in \text{SU}(3) \\
\text{field tensor:} & \quad P_{\mu\nu}(x) = U_\mu(x)U_\nu(x + a\hat{\mu}) \\
& \quad U_\mu^+(x + a\hat{\nu})U_\nu^+(x)
\end{align*}
\]

\[
S[U, \bar{\psi}, \psi] = S_G[U] + S_F[U, \bar{\psi}, \psi]
\]

(see, e.g. Wittig)
Lattice QCD: hadron spectrum

Full calculation using 2 quark flavors in excellent agreement with experimental data
Lattice QCD: Static potential ($\mu=0$)


Lattice calculation (for a heavy quark pair) exhibits screening of long range confining potential with increasing temperature.
Lattice QCD: Energy density ($\mu=0$)

Fodor et al., JHEP 11 (2010) 077

Slow convergence to ideal gas (SB) limit

What carries the energy? Complex bound states of $q$ and $g$? Strongly coupled plasma?

Transition temperature region between 140 and 200 MeV, with wide range of energy density between 0.2 and 1.8 GeV/fm$^3$

Remember: $T_c \approx 170$ MeV and $\varepsilon_c \approx 1$ GeV/fm$^3$
Finite $\mu$ calculations complicated and computationally demanding

Some calculations suggest a critical endpoint at $T=162$ MeV, $\mu_B=340$ MeV with large theoretical uncertainties

Critical endpoint existence and exact location is an open question
Restoration of bare masses

- Up and down quarks have very small (<10 MeV) bare masses (generated from the coupling to the Higgs)

- Confined quarks however require about 300 MeV dynamically through the effect of the strong interactions

- Deconfinement should be accompanied by a restoration of the masses to the bare masses of the Lagrangian

- Usually called “Partial restoration of chiral symmetry”)

- Effective quark mass from $<\bar{\psi}\psi>$ computed on lattice confirms expected behavior
Natural appearance of QCD phase transition
In the beginning quark–gluon plasma ~10 μs after Big Bang hadron synthesis strong force binds quarks and gluons

~100 s after Big Bang nucleosynthesis strong force binds nucleons
QCD phase transition in the early universe

Effective degrees of freedom per relativistic particle

\[ g_*(T) = \frac{1}{\pi^2 T^4 / 30} \sum_{\text{species}} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3p}{(2\pi)^3} \]

The Early Universe, Kolb and Turner
Schwarz, astro-ph/0303574

Fig. 3.5: The evolution of \( g_*(T) \) as a function of temperature in the \( SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \) theory.
How to create the QGP?
In high energy physics we have concentrated on experiments, in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of “vacuum”, we must turn to a different direction; we should investigate some “bulk” phenomena by distributing high energy over a relatively large volume.

T.D. Lee,
Rev. Mod. Phys. 47 (1975) 267
Study QCD bulk matter at high temperature

- Bulk QCD matter at high temperature
  - Nebula M1-67 (see hubblesite.org)

Momentum transfer

- $>10$ GeV/c
- $0.2$ GeV/c

Transverse size of collision region

- $\sim 1$ fm
- $\sim 10$ fm
How can we create QCD matter?

Experimental study of QCD phase diagram by colliding nuclei head-on to convert cold nuclear matter into a fireball of partons.

- **QGP (quark-gluon plasma)**
- **color superconductor**
- **critical point**
In reality, strong dynamical evolution of the system
How to probe the QGP?
The first exploration of subatomic structure, by Rutherford, used Au atoms as targets and α particles as probes.

**Interpretation:**
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions.

\[ \frac{d\sigma}{d\Omega} \propto \left( \frac{Z_1 Z_2}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)} \]

Hoppenau and Eggers, Eur.J.Phys. 6 (1985) 86
Deep inelastic scattering experiments at SLAC in the 1960s established the quark-parton model:

The angular distribution of the scattered electrons reflects the distribution of charge inside the proton.

Approximately constant form factor \( \Rightarrow \) scattering on point-like constituents \( \Rightarrow \) quarks

1990 Nobel Prize in Physics
In analogy, we study the QCD matter produced in HI collisions by measuring how it affects well understood probes, as a function of the temperature of the system.
Good probes of QCD matter

Jets and heavy quarkonia \((J/\psi, \chi_c, Y, Y', \text{etc})\) should be good QCD matter probes!
Heavy-ion experiments
Two main laboratories for heavy-ion collisions

**AGS** : 1986 – 2000
- Si and Au beams; $\sqrt{s} \sim 5$ GeV
- only hadronic variables

**RHIC** : 2000 – ?
- He3, Cu, Au beams; up to $\sqrt{s} = 200$ GeV
- 4 experiments (only two remain)

- O, S, In, Pb beams; $\sqrt{s} \sim 20$ GeV
- Various experiments in North Area

**LHC** : 2009 – ?
- Pb beams; up to $\sqrt{s} = 5500$ GeV
- ALICE, CMS and ATLAS
Between 1986 and 2004, many experiments studied high-energy nuclear collisions at the CERN SPS, to probe hot QCD matter.
One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

Up to ~2500 hadrons are produced (comp. to ~8 in pp collisions)
The Relativistic Heavy Ion Collider (RHIC)
STAR and PHENIX at RHIC  
(PHOBOS, BRAHMS more specialized)

**STAR**

- 2π coverage, -1<η<1 TPC for tracking + (coarse) EMCal
- PID by TOF, dE/dx
- Optimized for acceptance (correlations, jet-finding)

**PHENIX**

- 2π coverage 2x0.5π, -0.35<η<0.35
- Finely segmented calorimeter + forward muon arm, PID by RICH
- Optimized for high-pt π⁰, γ, e, J/ψ (EMCal, high trigger rates)
LHC: The Large Hadron Heavy-ion Collider
(Heavy-)Ion data-taking experiments at the LHC

- ALICE dedicated HI experiment
  - Low-\(p_T\) tracking, PID, mid-rapidity
  - Forward-muon spectrometer
- ATLAS/CMS large HEP experiments
  - Large acceptance, full calorimetry
- LHCb (recorded pPb data)
  - Forward tracking, PID, calorimetry
Summary

- QCD is a quantum field theory with rich dynamical content, complex phase structure, and important open questions
- Heavy-ion collisions attempt to create and probe QCD matter at high temperature and energy density
- The scientific approach is conceptually similar to conventional scattering experiments, and relies on a series of well calibrated probes and a variety of collision systems

In the next two lectures we will look at a set of important results obtained from heavy-ion collisions at RHIC and LHC

If you have questions about today's lecture please send them to “cloizides at lbl dot gov”
References

- **QCD**
  - QCD and jets: CTEQ web page and summer school lectures
  - Handbook of perturbative QCD, Rev. Mod. Phys. 67 (1995) 157
  - QCD and collider physics,
    Ellis, Sterling, Webber, Cambridge University Press (1996)

- **Heavy-ion physics**
  - Results from the Relativistic Heavy Ion Collider,
  - First results from Pb+Pb collisions at the LHC,
  - New developments in relativistic viscous hydrodynamics,
    Romatschke, Int. J. Mod. Phys E 19 (2010) 1
  - The theory and phenomenology of QCD-based jet quenching,
    Majumber and van Leeuwen, arXiv:1002.2206
  - Gauge/string duality, hot QCD and heavy ion collisions,
    Casalderrey-Solana et al., arXiv:1101.0618
  - Relativistic Heavy Ions, Stock et al., Springer (2010)
Acknowledgments

Lots of input (slides, graphics, discussion) from

Federico Antinori
Tom Hemmick
Peter Jacobs
Jamie Nagle
Carlos Lourenco
Klaus Reygers
Enrico Scomparin
Kai Schweda
Peter Steinberg