The formation of quark-gluon plasma in ultra-relativistic nucleus-nucleus collisions

Seminar

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Outline

1. QCD & QGP
2. Nucleus-nucleus collisions
3. Energy density and Bjorken formula
4. QGP signatures
1. QCD & QGP

2. Nucleus-nucleus collisions

3. Energy density and Bjorken formula

4. QGP signatures
Quantum chromodynamics

...the theory of strong interaction
Confinement
- quarks and gluons are confined in Hadrons
- color neutrality

Asymptotic freedom

Coupling is strong ...
- at large distances
- at low momenta

Coupling is weak ...
- at small distances
- at large momenta
QCD at high energy and density
QCD at high energy and density
QCD at high energy and density

Hadrons

QGP

Klaus Heckmann  QGP in AA-Collisions
QCD at high energy and density
The QCD phase diagram
The QCD phase diagram

- Critical end point?
- First order phase transition?
- Color superconductor?

- QGP
- Hadrons
Theoretical predictions


Energy density

Critical energy density

\[ \epsilon_c = 0.7 \pm 0.2 \text{GeV fm}^{-3} \approx 5\epsilon_{\text{nuclear}} \]

Temperature

\[ N_f = 2 : T_c = 173 \pm 8 \text{MeV} \]
\[ N_f = 3 : T_c = 154 \pm 8 \text{MeV} \]
The QCD phase diagram

- Critical end point?
- First order phase transition?
- Color superconductor?
The QCD phase diagram

- QGP
- critical end point
- first order phase transition
- color superconductor
- Hadrons
- neutron stars
- early universe
Theoretical predictions


Energy density

Critical energy density

\[ \epsilon_c = 0.7 \pm 0.2 \text{GeV fm}^{-3} \approx 5\epsilon_{\text{nuclear}} \]

Question:
How to attain these energy densities in laboratory?

Temperature

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Theoretical predictions


Energy density

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Temperature

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Question:

How to attain these energy densities in laboratory?

Answer:

relativistic nucleus-nucleus collisions
1. QCD & QGP

2. Nucleus-nucleus collisions

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4. QGP signatures
QGP in AA-Collisions

Nucleus-nucleus collisions

Nucleus

Heavy ion

- Au or Pb
- $A \approx 200$
QGP in AA-Collisions

Nucleus-nucleus collisions

Acceleration

Brookhaven
- 1986: AGS
- 2000: RHIC

CERN
- 1986: SPS
- future: LHC
QGP in AA-Collisions

Nucleus-nucleus collisions

Acceleration

Ultra relativistic velocities

- $E \approx 100$ GeV
- $\beta \approx 0.99996$
- $\gamma \approx 100$
- Lorentz-contraction

Rapidity $y$

$$y = \frac{1}{2} \ln \frac{E + p_{\parallel}}{E - p_{\parallel}}$$

$$(p_x, p_y, p_z) \sim (p_{\perp}, p_{\parallel}) \sim (p_{\perp}, y)$$
Collision
QGP in AA-Collisions

Nucleus-nucleus collisions

Collision

Centrality

\[ b = 0 \]

\[ b > 0 \]
Crossing
Crossing
Crossing

QGP in AA-Collisions

Nucleus-nucleus collisions
The Fireball
The fireball
Thermalization

Thermalization after $t \approx 1 \text{ fm/c}$?
Expansion

Expansion and cooling
Expansion and cooling
Freeze-out

Hadronization
at critical energy density
Detection

Example: The STAR detector at RHIC

figure from www.bnl.gov/rhic/STAR

- Silicon vertex tracker
- Time projection chamber
- Time of Flight
- E-M calorimeter
Detection

Example: The STAR detector at RHIC

figure from www.bnl.gov/rhic/STAR
1. QCD & QGP

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Energy density $\leftrightarrow$ Measured particles?

[Figure: AGS proton spectrum]

entropy $S \leftrightarrow N$

$$\frac{dS}{dy} \propto \frac{dN}{dy}$$
Energy density ↔ Measured particles?

adiabatic expansion → entropy conservation

Energy density:

$$\epsilon = \frac{E}{V} = \langle m_\perp \rangle \frac{dN}{dy} \times \frac{1}{V}$$

with $$m_\perp = \sqrt{p_\perp^2 + m^2}$$ — But what is $$V$$?
Energy density $\leftrightarrow$ Measured particles?

adiabatic expansion $\rightarrow$ entropy conservation

Energy density:

$$
\epsilon = \frac{E}{V} = \langle m_\perp \rangle \frac{dN}{dy} \times \frac{1}{V}
$$

with $m_\perp = \sqrt{p_\perp^2 + m^2}$ — But what is $V$?

$$
\epsilon = \langle m_\perp \rangle \frac{dN}{dy} \times \frac{1}{A_\perp} \frac{dy}{dz}
$$

Surface $A_\perp$

$A_\perp = \pi r^2$, $r_{Pb} \approx 14\text{fm}$

Length $\left(\frac{dy}{dz}\right)^{-1}$

$$
y = \frac{1}{2} \ln \frac{1 + v_\parallel}{1 - v_\parallel}
$$

Klaus Heckmann | QGP in AA-Collisions
a heavy ion collision in a Minkowski diagram
a heavy ion collision in a Minkowski diagram

Collision event at $z = 0$ and $t = 0$.
a heavy ion collision in a Minkowski diagram
a heavy ion collision in a Minkowski diagram
a heavy ion collision in a Minkowski diagram

Created particles in the allowed cone
Thermalized region

Hydrodynamics
After thermalization: description in local thermal equilibrium
Particle creation in thermalized QGP

... but what ist $v_\parallel$ for given $t, z$?
Bjorken’s ansatz

\[ v_\parallel = \frac{z}{t} \]
Bjorken formula

It turns out that

\[ \frac{d y}{d z} = \frac{1}{\tau} \]

with the thermalization time \( \tau \approx 1 \text{ fm/c} \).
Alternating Gradient Synchrotron
BNL, Brookhaven

figure from http://www.bnl.gov/bnlweb/facilities/AGS.asp

- Heavy ion experiments started 1986
- fixed target
- Au+Au 4.84 GeV/A c.m.
Super Proton Synchrotron
CERN, Genève

### Accelerator
- Heavy ion experiments
  1986–2003
- fixed target
- Pb+Pb
- 17.2 GeV/A c.m.

### Collision
- $T_0 = 205–245$ MeV
- $\epsilon = 1.2–2.6$ GeV/fm$^3$
- $\frac{dN^g}{dy} = 200–350$

Data from Vitev, hep-ph/0403089
Relativistic Heavy Ion Collider
BNL, Brookhaven

Accelerator
- Since 2000
- collider
- $\text{Au+Au}$
- $\sqrt{s_{NN}} = 200$ GeV

Collision
- $T_0 = 360–410$ MeV
- $\epsilon = 12–20$ GeV/fm$^3$
- $\frac{dN_g}{dy} = 800–1200$

Data from Vitev, hep-ph/0403089
### Large Hadron Collider

CERN, Genève

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**Accelerator**
- heavy ion start 2009 (?)
- collider
- Pb+Pb
- $\sqrt{s_{NN}} = 5.5$ TeV

**Collision**
- $T_0 = 710-850$ MeV
- $\epsilon = 170-350$ GeV/fm$^3$
- $\frac{dN^g}{dy} = 2000-3500$

Data from Vitev, hep-ph/0403089

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Figure from www.cern.ch
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Collective flow

figure from STAR, www.bnl.org/rhic

Event
Collect data from all measured particles
Collective flow

Collective Flow
Reconstruct the flow of the particles
Collective flow

Azimuthal angle $\phi$

Fourier modes
- directed flow: $v_1$
- elliptic flow: $v_2$
Relativistic Hydrodynamics

Relation between energy momentum tensor, spacetime evolution and equation of state for fluids in local thermal equilibrium

**Relativistic Hydrodynamic**

Description of
- White Dwarfs
- Neutron stars
- Super nova explosions
- ... and fireballs!

**Ideal fluids**

\[ T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu}p \]

\[ J^\mu = u^\mu n \]

- No dissipation
- No entropy growth

Klaus Heckmann
figure from P. Braun-Munzinger, heavy ion collisions and hydrodynamics (talk given at Bad Honnef 2006), based on STAR (PRL 92 (2004)052302,PRL87(2001)182301) and Huovinen et. al.(PRLB503(2001)58)
An ideal fluid

Good agreement of measured data with predictions from ideal relativistic hydrodynamics!

Confirmation

- local thermal equilibrium is attained
- thermalization takes place
- equation of state is confirmed
An ideal fluid

Good agreement of measured data with predictions from ideal relativistic hydrodynamics!

**Confirmation**
- Local thermal equilibrium is attained
- Thermalization takes place
- Equation of state is confirmed

**Consequences**
- Viscous effects can be neglected
- QGP as (the most) ideal fluid?
- Strong coupling $\Rightarrow$ sQGP
Strangeness

\[ p+p \]

Strangeness suppression

the number of strange particles is small
strangeness suppressed in hadronic reactions
Strangeness

QGP in AA-Collisions
- QGP signatures
- strangeness production

Strangeness

p+p

Strangeness suppression
the number of strange particles is small
strangeness suppressed in hadronic reactions

A+A

strangeness production
number of strange particles in agreement with grand canonical ensemble
signifies that the matter created in a collision is equilibrated
Comparison between $p+p$ and $Au+Au$

Jets: correlation in azimuthal angle

Comparison between $p+p$ and $Au+Au$

Jets: correlation in azimuthal angle

\[ R_{AA} = \frac{n_{Au+Au}^h(p_{\perp})}{n_{p+p}^h(p_{\perp})} \]

figure from P. Braun-Munzinger, J. Stachel, nature 0608,302–309, based on PHENIX data

Jet quenching

phenomenon of \textit{central} heavy ion collisions

**Interpretation**

energy loss of the jet medium effects change properties of jet
Jet quenching

phenomenon of *central* heavy ion collisions

**Interpretation**

energy loss of the jet medium effects change properties of jet
Other signatures of QGP

Charmonium

J/ψ
Other signatures of QGP

Charmonium

- 17.01.2008: S. Hauf - Charmonium in the QGP - Debye screening à la Matsui & Satz
- 17.01.2008: A. Marin - The experimental status of $J/\psi$ measurements in nucleus-nucleus collisions
- 24.01.2008: Jun Nian - $J/\psi$ suppression and enhancement - the statistical hadronization model
- 31.01.2008: M. Freudenberger - Quarkonium physics in nuclear collisions at the LHC
QGP in AA-Collisions

- QGP signatures
- Other signatures of QGP

Summary

- QGP: matter at high energy density
- attained in nucleus-nucleus collisions
- signatures: collective flow, strangeness, jet quenching ... 
- RHIC-data indicate a thermalized QGP
- many open questions: initial stages, thermalization, dissipation, ...
- some of them will be answered at LHC
Outlook

S. Hauf
Charmonium in the QGP - Debye screening à la Matsui & Satz
17.01.2008
15:30
Additional references


- www.CERN.ch
- www.bnl.gov