10^{12} Degrees in the Shade: Physics of the quark-gluon plasma

Craig Ogilvie

1. Motivation: non-perturbative quantum chromodynamics (QCD)
2. Results from RHIC
   a. Properties of quark-gluon plasma to study QCD
   b. Outstanding questions, next steps

Non-perturbative QCD

Strength of QCD interaction determined by the coupling ($\alpha_s$) between quarks (q) and gluons (g)

Perturbation series in $\alpha_s$

As $\alpha_s$ nears 1, perturbative tools fail, what happens to the physics when the interaction is very strong? What new phenomena occur?

Two systems to study non-perturbative QCD

proton

QGP

Hive of activity, fluctuations of $q$-̅$q$ pairs, $g$
John Lajoie

confined by vacuum condensate correlated $<q$-̅$q>$

Strongly interacting system
With large average number $q$ and $g$

Easier to use to study QCD?
$\Rightarrow$ Statistical tools
$\Rightarrow$ reduced role of vacuum

Views of heavy-ion collision: Au+Au

Thermal freeze-out

Hadronization

Equilibration
Assertion
- In these complicated events, we have \textit{(a posteriori)} control over the event geometry:
  - Degree of overlap
  - Orientation with respect to overlap

Transverse Dynamics
Physics of the QGP

Is plasma locally thermalized?

Chemical Equilibrium

- Abundance of hadrons determined by their mass and a single common temperature (+ a chemical potential)
  
  \[ \text{Yield} \sim e^{(m/kT)} \]

  Spectacular agreement over 3 orders

  \[ \Rightarrow \text{Consistent with system at chemical equilibrium} \]
Exponential Spectra:

- Random motion + collective expansion ($\beta = v/c \sim 0.6$)
  - Heavier particles larger increase in $p_t$ due to expansion

$$m_t = \sqrt{p_t^2 + m^2}$$

- Expanding, thermal system

Expansion is not isotropic

- If thermalized $\Rightarrow$ pressure gradient is largest in $x$-direction
  - Expansion larger in that direction
- Anisotropy characterized by elliptic flow, $v_2$
Expansion is hydrodynamic

Initial asymmetry propagates to final state
⇒ Low momentum particles reproduced by hydro
(99% of the particles)
⇒ System thermalizes early ($\Delta t < 0.6 \text{ fm/c}$)

What is flowing?

- Quark scaling: divide by $n_q$ valence quarks in particle
- Convert to energy axis $KE_T = \sqrt{p_T^2 + m_q^2}$ (system does work)

Universal scaling
⇒ system flows while it is deconfined quarks
Physics of the QGP

Plasma appears to be locally thermalized
Ongoing question: temperature via emission of photons

Does the QGP behave like a gas of quarks/gluons, or?

Current :) predicted QCD phase diagram

Marzia Rosati, LHC

Hot QGP
Correlated q̅q
sQGP

Attractive interactions in plasma
Non-perturbatively strong
$\alpha_s(q)$ large, since momentum transfer $\sim T$

nuclei
\(\mu\ (\text{MeV})\)

T (MeV)
Probe of strongly coupled fluid: shear viscosity

- Shear gradient of velocity distribution $\text{d}u_1/\text{d}x_2$

  \[ u_1 \rightarrow \text{Exchange of constituents} \rightarrow u_1 \]

- Viscosity $\eta$ reduces shear gradients, e.g. by transport of constituents from one fluid-cell to another

  Long mean-free path
  Eff. Transport of $\rho$
  Strong coupling between fluid elements increases $\eta$

  Minimum viscosity
  cQGP, Nucl-th/0601029

Z Donko, Phys Plasma 7, 45 (2000)

Shear viscosity reduces elliptic flow

P. Romatschke, nucl-th:0706.1522

Perturbative QCD $\eta/s > 0.5 \Rightarrow \text{sQGP}$
Calc $\eta/s$ in non-perturbative QCD...

RHIC viscosity close to conjectured lower quantum bound perfect fluid?
Viscosity in other systems

- Perfect fluid has $\eta = 0$ (or lower bound $\eta/s > 1/4\pi$)

Kovtun et al, PRL 94 111601 (2005)
Physics Today, 58(5)

RHIC, $4\pi^*\eta/s \approx 1$
at $10^{12}$ K

Physics of the QGP

- Plasma appears to be locally thermalized
- QGP behaves like a strongly coupled liquid, $\eta$ key
  Ongoing question: Charm-quark binding with di-quark $\Rightarrow$ flow, spectra, $\Lambda_c$
- How dense is the QGP?
Hard Scattered Parton \{Quark or Gluon\}

**hard-scattered parton:**
- high pt-transfer,
- calc. with perturbative QCD

**hard-scattered parton during Au+Au**
- hadrons have less energy,
- broader angular spread?

High pt cone of hadrons, pt leading hadron

Parton loses energy within plasma

Baseline p+p $\pi^0$ spectra compared to pQCD

\[ d\sigma = f_{a/A}(x_a, \mu^2) \otimes f_{b/A}(x_b, \mu^2) \]

- parton distribution functions, for partons a and b
- measured in DIS, universality

\[ \otimes \hat{\sigma}(a+b \rightarrow c+d) \]

- perturbative cross-section (NLO)
- requires hard scale
- factorization between pdf and cross section

\[ \otimes D_{x/c}(z_x, \mu^2) \]

- fragmentation function
- measured in e+e-

High-pt parton loses energy within QGP

- High-pt parton scatters in plasma, radiates gluons
- Radiated gluon has formation time $\sim 1/E_{\text{gluon}}$
  - During formation time, scatter from many partons in plasma

Scattering centers = color charges

- Multiple-scatters treated coherently
  - Reduces total gluon emission rate
  - Reduces energy-loss (though still large :)

Au+Au $\pi^0$ spectra

$R_{AA} = \text{ratio } (\text{Au+Au})/(p+p)$

Enhanced

Suppressed
How Opaque is QGP?

\[ \hat{q} = \frac{\mu^2}{\lambda} = \text{momentum transferred} \]
\[ \lambda = \text{mean free path} \]

Scattering power of the QCD medium:

- **Range probable values**

Strong energy-loss not fully understood

Larger than expected from QGP that interacts perturbatively

Calculate \( q \) in non-perturbative QCD, compare to expt

- **RHIC data**

\[ \frac{g}{(\text{GeV}/\text{fm})} \]
\[ \epsilon (\text{GeV}/\text{fm}^2) \]
Fate of Gluons

parton loses energy within plasma

Do radiated gluons produce broader jet?

- Jets broader in Cu+Cu than p+p
  - Fragmentation of induced gluon radiation?

Physics of the QGP

Plasma appears to be locally thermalized

QGP behaves like a strongly coupled liquid

QGP is opaque colored system, Scattering power, q, is key
Ongoing question: is the modeling of gluon radiation right?
Energy-loss of charm-quarks
VTX $8M upgrade, C. Ogilvie project manager

Designed to provide early time probe
Charm, beauty: open questions sQGP

silicon pixel+strip detectors
Tracks extrapolate back to collision
Displaced vertices
=> charm (D), beauty (B)
Requires ~ 50 μm precision

Oct 3, 2007 Craig Ogilvie
Wafers Testing at BNL

Rachid Nouicer (BNL), Kieran Boyle (SBU), Hua Pei (ISU) and Junkichi Asai (RBRC)

Strip Front-End Electronics

On the ladder
Signal from hit strip => digitized => collected by read-out-card (ROC)

Led by Alan Dion (ISU post-doc)
1) Testing, debugging ROCs
2) Optimizing ROC+sensor
To establish the existence, then study the strongest possible gluon field

Process continues until saturation
\[ \Rightarrow \text{Maximum strength color field} \]
Kirill Tuchin

Gluon splitting
\[ \Rightarrow \text{lower momenta} \]

Summary

Non-perturbative QCD
As \( \alpha_s \) nears 1, perturbative tools fail, what happens to the physics when the interaction is very strong?

Strongly coupled QGP
\[ \Rightarrow \text{Colored, opaque, and low-viscosity} \]
\[ \Rightarrow \text{Use these quantities (q, } \eta \text{) to test QCD} \]

Open questions <= VTX upgrade
1. Energy-loss + gluon radiation
2. Charm coupled to di-quarks in fluid?
Thanks!

Backup
Viscosity lower bound

\[ \frac{F}{A} = \eta \nabla y y_x \]

For dilute systems, \( \eta \sim \text{mean free path, transport of momentum across fluid cells} \)

\[ \eta \sim n \rho \lambda \]

Limit on \( \eta \), use Heisenberg

\[ p \lambda \geq h \]

\[ \eta \geq n h \quad \text{or} \quad \frac{\eta}{n} \geq h \]

For relativistic systems, number of particles not so well defined, Entropy density \( s \sim k_B n \)

\[ \frac{\eta}{s} \geq \frac{h}{k_B} \]

Expansion

[Graph showing expansion spectra and HBT]
PHENIX Experiment at RHIC

- In operation since 2000
- Designed for penetrating probes to characterize QGP

Focus on mid-rapidity arms

Charged tracking + Calorimetry => photons, $\pi^0$...+ J/$\psi$...

$\sqrt{s}=200$ GeV, $p+p \Rightarrow x$
NLO QCD agrees well with data

D. d’Enterria
nucl-ex/0611012
Partons lose energy as they travel through QGP

\[ \pi^0 \text{ spectra at } \sqrt{s} = 200 \text{ GeV} \]

\[ \text{nucl-ex/0611007 PHENIX} \]

- p+p cross-section scaled by parton-flux in Au+Au
- Fewer high-pt \( \pi^0 \) in Au+Au
  - Energy-lost by parton \( \Rightarrow \) info on density of QGP

Ratio of (Au+Au)/(scaled p+p spectra)

- Mesons suppressed \( \times 5 \rightarrow \) energy-lost in QGP
- \( \gamma \) scale with parton flux
Particles correlated with high-pt trigger

\[ \Delta \phi = \phi_1 - \phi_2 \]

- Correlation survives high-multiplicity environment of A+A

Response of medium to passage of high-pt parton

- Near-side, generation of ridge => strength large \( \Delta \eta \) (STAR talk)
- Far-side: does super-sonic parton generate a mach-cone?

hep-ph/0410067; H.Stocker; Jorge Casalderry-Solana
Far-side Production of Particles

Observation of particles produced ~1 radian away from back-to-back!

Fit with 2 Gaussians, each D radians away from π
D scales with system size

=> emission consistent with medium’s response to jet

Suppression of heavy-quark spectra in A+A

Suppression of e, $p_T > 3.0$ GeV/c
Slightly smaller than light quarks

Challenge for models to reproduce both light, heavy-q $E_{loss}$
Expt. need to increase statistics, reduce systematics
silicon upgrade=> displaced vertices
Spectra:
- Random motion + collective expansion ($\beta=v/c$)
  - Heavier particles are boosted more by expansion

- Expanding, thermal system