A NEARLY PERFECT INK:
The quest for the quark-gluon plasma at the Relativistic Heavy Ion Collider

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The Road to the Quark-Gluon Plasma…

…Is Hexagonal and 2.4 Miles Long

Insights and Scientific Challenges from the RHIC Experiments
The quest for simplicity

The equation of state of strongly interacting matter according to lattice QCD

• Before the 1975, matter at high energy density was considered a *real mess*!

• QCD predicts that hot matter becomes *simple* – the QGP (not necessarily weakly interacting!).

• Characteristic features: deconfinement and chiral symmetry restoration.

\[ T_c \approx 160 \text{ MeV} \]
The QCD phase diagram

- **Hadronic matter**
- **Quark-Gluon**
- **Critical endpoint?**
- **Plasma**
- **Chiral symmetry broken**
- **Chiral symmetry restored**
- **1st order line?**
- **Colour superconductor**

**RHIC**

Temperature ($T$) and chemical potential ($\mu_B$) axes.
Space-time picture of a r.h.i.c.
RHIC data gathering

Charged particle tracks from a central Au+Au collision

RHIC has had runs with:

- Au+Au at 200, 130, 62 GeV
- Cu+Cu at 200, 62 GeV
- d+Au at 200 GeV
- p+p at 200, 130 GeV
Frequently Asked Questions

• How do we know that we have produced *equilibrated matter*, not just a huge bunch of particles?

• What makes this matter *special*?

• How do we measure its *properties*?

• Which evidence do we have that quarks are *deconfined* for a brief moment (about $10^{-23}$ s)?

• Which evidence do we have for temporary *chiral symmetry restoration*?

• What do we still need to learn?
  
  – Translation: When can RHIC be closed down?
FAQ #1

How do we know that we produced *equilibrated matter*, not just a bunch of particles?

Answer:

Particles are thermally distributed and flow collectively!
Chemical equilibrium

- Chemical equilibrium fits work, *except* where they should not (resonances with large rescattering).

**RHIC Au+Au @ 200 GeV**

- $T_{ch} = 160 \pm 10$ MeV
- $\mu_B = 24 \pm 5$ MeV
Elliptic flow

Coordinate space:
initial asymmetry

Momentum space:
final asymmetry

Pressure gradient
collective flow

Two-particle correlations
\[ \frac{dN}{d(\phi_1 - \phi_2)} \propto 1 + 2v_2^2 \cos(2[\phi_1 - \phi_2]) \]
FAQ #2

What makes this matter *special*?

Answer:

It flows astonishingly smoothly!

“The least viscous non-superfluid ever seen”
\( v_2 \) requires low viscosity

Relativistic viscous fluid dynamics:

\[
\nabla_\mu T^{\mu\nu} = 0 \quad \text{with}
\]

\[
T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \eta (\nabla^\mu u^\nu + \nabla^\nu u^\mu - \text{trace})
\]

Shear viscosity \( \eta \) tends to smear out the effects of sharp gradients

pQCD: \( \eta \sim \rho \vec{p} \lambda \approx \frac{4 T^3}{3 \alpha_s^2 \ln \frac{1}{\alpha_s}} \)

But what is \( \alpha_s \)?

Dimensionless quantity

\[
\frac{\text{shear viscosity}}{\text{entropy density}} = \frac{\eta}{s} \approx \frac{1}{15 \alpha_s^2 \ln \frac{1}{\alpha_s}}
\]
Viscosity must be ultra-low

\[ v_2 \] data comparison with (2D) relativistic hydrodynamics results suggests \( \eta/s \leq 0.1 \)

Recent excitement:

Quantum lower bound on \( \eta/s \):

\[ \frac{\eta}{s} = \frac{1}{4\pi} \] (Kovtun, Son, Starinets)

Realized in strongly coupled \((g \gg 1)\)
\( N = 4 \) SUSY YM theory, also in QCD?

\[ \eta/s = \frac{1}{4\pi} \implies \lambda_f \sim (5 T)^{-1} \sim 0.3 \, \text{d} \]
FAQ #3

How do we measure its properties?

Answer:

With hard QCD probes, such as jets, photons, or heavy quarks
“Jet quenching” = Parton energy loss

High-energy parton loses energy by rescattering in dense, hot medium.

Radiative energy loss: \[ \frac{dE}{dx} \sim \sigma \rho L \langle k_T^2 \rangle \]

Scattering centers = color charges

Density of scattering centers

Scattering power of the QCD medium:

\[ \hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \sigma \rho \langle k_T^2 \rangle = \frac{\mu^2}{\lambda} \]

Range of color force
Suppression of fast pions ($\pi^0$)

**Phenix preliminary**

- $R_{AA}^{\pi^0} 200$ GeV:
  - $\Delta$: Au+Au 0-10% Central
  - $\triangledown$: Au+Au 70-80% Central

\[
R_{AA} = \frac{N_{AA}^{\pi}}{N_{coll}^{\pi} N_{pp}^{\pi}}
\]

- **Peripheral collisions**
- **Central collisions**
Energy loss at RHIC

- Data are described by a very large loss parameter for central collisions:

$$\langle \hat{q} \rangle \approx 5 - 10 \text{ GeV}^2/\text{fm}$$

(Dainese, Loizides, Paic, hep-ph/0406201)

Larger than expected from perturbation theory?
Does QCD perturbation theory work?

What is the appropriate value of QCD coupling $\alpha_s$?
FAQ #4

Which evidence do we have that quarks are *deconfined* for a brief moment (about 10^{-23} s) ?

Answer:

Baryons and mesons are formed from independently flowing quarks
What makes baryons different from mesons?
Hadronization Mechanisms

Fragmentation

Baryon \( \ll 1 \)

Meson

Recombination

Baryon \( \approx 1 \)

Meson

\( p_M \approx 2p_Q \quad p_B \approx 3p_Q \)

This is not coalescence from a dilute medium!
Recombination “wins” …

… always for a thermal source

Baryons compete with mesons

Fragmentation still wins for a power law tail
Recombination vs. Fragmentation

R.J. Fries, BM, C. Nonaka, S.A. Bass

\[ T_{\text{eff}} = 350 \text{ MeV} \]  
blue-shifted temperature  
\[ T = 180 \text{ MeV} \]

Baryon enhancement

pQCD spectrum shifted by 2.2 GeV
Hadron $v_2$ reflects quark flow!

Recombination model suggests that hadronic flow reflects partonic flow ($n =$ number of valence quarks):

$$v_2^{had} \approx n v_2^{part}$$

$$p_T^{had} \approx n p_T^{part}$$

Provides measurement of partonic $v_2$!
FAQ #5

Which evidence do we have for temporary chiral symmetry restoration?
Strangeness in Au+Au at RHIC

Mass (MeV)

QCD mass disappears
FAQ #6:
What do we still need to (or want to) learn?

- Number of degrees of freedom:
  - via energy density – entropy relation.
- Color screening:
  - via dissolution of heavy quark bound states (J/Ψ).
- Chiral symmetry restoration:
  - modification of hadron masses via $e^+e^-$ spectroscopy.
- Quantitative determination of transport properties:
  - viscosity, stopping power, sound velocity, etc.
- What exactly is the “s”QGP?
QCD equation of state

\[ \varepsilon = \frac{\nu \pi^2}{30} T^4 \]

Challenge: Devise method for determining \( \nu \) from data
**Alternative method**

Eliminate $T$ from $\varepsilon$ and $s$:

\[
\begin{align*}
\varepsilon &= \nu \frac{\pi^2}{30} T^4 \\
 s &= \nu \frac{2\pi^2}{45} T^3
\end{align*}
\]

\[
\nu = \frac{1215}{128\pi^2} \frac{s^4}{\varepsilon^3} \approx 0.96 \frac{s^4}{\varepsilon^3}
\]

Lower limit on $\nu$ requires lower limit on $s$ and upper limit on $\varepsilon$.  

BM & K. Rajagopal, hep-ph/0502174 
Eur. J. Phys. C (in print)
Measuring $\varepsilon$ and $s$

- Entropy is related to produced particle number and is conserved in the expansion of the (nearly) ideal fluid: $\frac{dN}{dy} \approx S \Rightarrow s = \frac{S}{V}$.

- Energy density is more difficult to determine:
  - Energy contained in transverse degrees of freedom is not conserved during hydrodynamical expansion.
  - Focus in the past has been on obtaining a lower limit on $\varepsilon$; here we need an upper limit.
  - New aspect at RHIC: parton energy loss. $dE/dx$ is telling us something important – but what exactly?
Entropy

• Two approaches:
  1) Use inferred particle numbers at chemical freeze-out from statistical model fits of hadron yields;
  2) Use measured hadron yields and HBT system size parameters as kinetic freeze-out (Pratt & Pal).

• Method 2 is closer to data, but requires more assumptions (HBT radii = geometric radii, isentropic expansion of hadronic gas).

• Good news: results agree within errors:
  – $dS/dy = 5100 \pm 400$ for Au+Au (6% central, 200 GeV/NN)
State of the art

- 6% central $s_{NN}^{1/2} = 200$ GeV Au+Au collisions ($\tau_0 = 1$ fm/c):
  
  - $dS/\text{dy} = 5100 \pm 400$ ? $s = (dS/\text{dy})/(\pi R^2 \tau_0) = 33 \pm 3$ fm$^{-3}$
  
  - $dE_T/\text{dy} = 650$ GeV/fm$^3$ ? $\varepsilon_{Bj} = (dE_T/\text{dy})/(\pi R^2 \tau_0) = 4.2$ GeV/fm$^3$

  □ $\varepsilon > \varepsilon_{Bj}$ due to longitudinal hydrodynamic work done.
  PHOBOS estimate is $\varepsilon > 5$ GeV/fm$^3$ at $\tau_0 = 1$ fm/c.

Some examples:
  
  □ $\varepsilon = 5$ GeV/fm$^3$ ? $\nu = 71 \pm 22$
  □ $\varepsilon = 7$ GeV/fm$^3$ ? $\nu = 26 \pm 8$
  □ $\varepsilon = 9$ GeV/fm$^3$ ? $\nu = 12 \pm 4$

- Improved determination of $\varepsilon$ must be an immediate goal.
Heavy quarks

Heavy quarks ($c$, $b$) provide a hard scale via their mass. Three ways to make use of this:

- Color screening of (Q-Qbar) bound states;
- Energy loss of “slow” heavy quarks;
- $D$, $B$-mesons as probes of collective flow.

RHIC program: $c$-quarks and $J/\Psi$;
LHC-HI program: $b$-quarks and $\Upsilon$.

- RHIC data for $J/\Psi$ are forthcoming (Runs 4 & 5).
The Baier plot - again

- Plotted against $\varepsilon$, $\hat{q}$ is the same for a $\pi$ gas and for a perturbative QGP.
- Suggests that $\hat{q}$ is really a measure of the energy density.
  - Data suggest that $\hat{q}$ may be larger than compatible with Baier plot.
  - Better calculations are needed.

- One approach (Turbide et al.) based on complete LO HTL transport theory, gets $R_{AA}$ right (hep-ph/0502248)
\( V_{qq} \) is screened at scale \((gT)^{-1} \rightarrow \) heavy quark bound states dissolve above some \( T_d \).

Quenched lattice simulations, with analytic continuation to real time, suggest \( T_d \geq 2T_c \).

**Color singlet free energy**

S. Datta et al. (PRD 69, 094507)

**Challenge: Compute \( J/\Psi \) spectral function in unquenched QCD**
Di-hadron correlations

**STAR Data**

Away-side jet: $Q' \sim (\Delta R/R)^2$

**Correlations depend on selected momentum windows**

- (a) 0.5%
- (b) 5-10%
- (c) 10-20%
- (d) 20-40%
- (e) 40-60%
- (f) 90-100%
“Waking” the sQGP

\[ v = 0.55c \]

\[ v = 0.99c \]
Outlook

- The “discovery phase” of RHIC is just hitting its full stride.
- Several important observables still waiting to be explored.
- Run-4 and -5 data are eagerly anticipated.
- More than $10^9$ events will provide many answers and help us to refine the questions.
- Many well defined theoretical challenges.