Experimental Highlights on QCD Medium Properties at RHIC

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Outline

✧ Introduction
   ✧ 10 years anniversary of perfect fluid in heavy ion collisions (2005-2015)

✧ The RHIC Beam Energy Scan: Mapping QCD PHASE Diagram
   ✧ Determine the energy at which key QGP signatures turn off
   ✧ Search for the critical end point (CEP)

✧ Surprise: QGP-like behavior in Small Colliding Systems
   ✧ BES: Near energy independence of the $v_n(p_T)$ in A+A collisions
   ✧ Non-zero p,d, $^3$He + A $v_n(p_T)$ moments comparable to the A+A ones

✧ Quarkonia as Probe for Hot and Cold Nuclear Matter
   ✧ $J/\psi$ and $Y$ measurements: centrality, system size and energy Dependence

✧ RHIC from now to NN2017
The Collaboration of the four experiments: PHENIX, BRAHMS, PHOBOS and STAR at RHIC

CONCLUDED strongly-interacting matter

RHIC Scientists Serve Up 'Perfect' Liquid: New State of Matter More Remarkable Than Predicted

Apr. 25, 2005 — TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted by physicists and theorists.

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted by physicists and theorists. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

International Journal of High-Energy Physics

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Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

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CERN COURIER

May 6, 2005

RHIC groups serve up 'perfect liquid'

The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory have announced results indicating that they have observed a state of hot, dense matter that is more remarkable than had been predicted. In papers summarizing the first three years of RHIC findings, to be published simultaneously by the journal Nuclear Physics A, the four collaborations (BRAHMS, PHENIX, PHOBOS and STAR) say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.
Relativistic Heavy Ion Collider (RHIC)
### Beam-Beam Collisions at RHIC: 2000 to 2015 (NON-STOP)

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<th>Faisceaux</th>
<th>Énergie centre-de-masse [GeV]</th>
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<td>p+Al</td>
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Motivation: Jet Quenching “Major Discovery”

\[ R_{AA}(p_T, y, b) = \frac{d^2N^{AA}/dp_Td\eta}{\langle T_{AA}(b) \rangle d^2\sigma^{pp}/dp_Td\eta} \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Suppression of \( \pi^0 \) is the major discovery at RHIC as well at LHC
Motivation: Perfect Liquid “Major Discovery”

RHIC and LHC precision measures of higher moments

\[
\frac{dN}{d\phi} = 1 + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + 2v_4 \cos[4(\phi - \Psi_4)] + 2v_5 \cos[5(\phi - \Psi_5)] + \ldots
\]

- Medium is strongly interactive (the large amplitude of \(v_2\))
- Comparisons models hydrodynamic viscous with RHIC and LHC data seem to support very small values for \(\eta/s\). This implies that the nuclear matter created is almost perfect fluid. The properties of this fluid remains to be determined.

Phases of QCD matter

- How do we map the QCD phase diagram?
Phases of QCD matter

• How do we map the QCD phase diagram?

• Vary the collision energy over the full range accessible at RHIC
Phases of QCD matter

• How do we map the QCD phase diagram?

• Vary the collision energy over the full range accessible at RHIC

• Do we observe turn off of the new phenomena that have been observed in full-energy RHIC collisions?
  
  – Constituent quark number scaling of higher moments $v_n (p_T)$

  – Jet quenching in central collisions

• Do we observe signatures of a phase transition and/or critical end point?

  – Elliptic and directed flow: indicators of the “softest point” in momentum space

  – Azimuthally-sensitive HBT: indicator of the “softest point” in coordinate space
Constituent quark number scaling of higher moments $v_n (p_T)$ Au+Au at 200 GeV

Constituent quark scaling is seen as an indication of partonic behavior
Constituent quark number scaling of $v_2(p_T)$ 

Au+Au at 200 GeV

Constituent quark scaling is seen as an indication of partonic behavior

It is known that the $\Phi$ meson does not participate as strongly as others do in hadronic interactions
The magnitude of $v_2$ doesn’t change with energy > 19.6 GeV
The $\phi$ meson no longer follows the trends below 19.6 GeV
Jet quenching

$R_{CP}$ for hadrons can provide a measure of partonic energy loss in the medium.

Insufficient reach to search for evidence of high $p_T$ suppression below 19.6 GeV
Jet quenching

$R_{CP}$ for identified particles can provide a measure of partonic energy loss in the medium.

- Stopped Baryons shows complicated inclusive $R_{CP}$ measurements.
- pQCD calculations show high $p_T$ suppression.
- Hybrid calculations describe the low $p_T$ behavior.

Insufficient reach to search for evidence of high $p_T$ suppression below 19.6 GeV.
Interferometry probe: energy dependence of HBT signals

*HBT radii are sensitive to the expansion dynamics*

These non-monotonic patterns signal an important change in the reaction dynamics; CEP?

\[
R_{\text{side}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T} \frac{T}{2} (\frac{2}{T})^2}
\]

\[
R_{\text{out}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T} \frac{T}{2} (\frac{2}{T})^2} + \frac{2}{T} (\frac{2}{T})^2
\]

\[
R_{\text{long}}^2 \approx \frac{T}{m_T}^2
\]

(\(R_{\text{out}}^2 - R_{\text{side}}^2\)) sensitive to emission duration
Significant $v_2$
and
striking similarity of $v_3$
for p+Pb
and Pb+Pb systems
with drastically
different collision
geometry
QGP-like behavior in Small Colliding Systems

Mass Ordering

Consistent with expectation given a fluid velocity field
QGP-like behavior in Small Colliding Systems

$v_2(\text{EP})$ of charged hadron in 0-5% d+Au

Hydro-like shape in $v_2(p_T)$?

QGP-like behavior in Small Colliding Systems

Central collision events of p-Pb, d-Au, $^3$He-Au

Averaged density profile of central events: (PHOBOS Monte Carlo Glauber)

Hydro-like shape in $v_2(p_T)$?

Azimuthal flow, $v_n$ (n=2,3) in $^3$He+Au

Li Yan, RBRC workshop
Why study Quarkonia?

➢ To learn about thermal properties of QGP medium
  ✓ Quarkonia are expected to dissociate due to Debye screening of heavy quark potential \( r_D \propto 1/T \)
  \[ \text{Phys. Lett. B178, 416} \]

\[ \begin{align*}
  T &< T_c \\
  T &\approx 1.2 T_c \\
  T &\approx 3 T_c
\end{align*} \]

\[ \psi \chi_{c\bar{c}} \psi', Y \chi_b Y', Y \chi_{b\bar{c}} \]

\[ T \leq 1.2 T_c \]

\[ T \leq 3 T_c \]

\[ \text{Phys. Rev. D77, 014501} \]
Quarkonia as Probe for \textbf{Hot} and \textbf{Cold} Nuclear Matter

- \textbf{System Size/ Collision Asymmetry}:
  - Change the relative contributions of \textit{Cold} and \textit{Hot} nuclear matter effects

- \textbf{Centrality}:
  - Suppression vs path length

- \textbf{Collision Energy}:
  - Change system energy density

- \textbf{Momentum}:
  - Hard collision dynamics

- \textbf{Rapidity}:
  - Probes different gluon (anti)shadowing

- \textbf{Heavy/Light}:
  - Mass ordering of suppression

- \textbf{Particle Species}:
  - Break-up, Temperature?

Each parameter probes different admixtures of nuclear modification
In Au+Au and at forward rapidity:

\( R_{AA} \) show similar suppression at different collision energies:

- 200 GeV
- 62.4 GeV
- 39 GeV

Significant \( J/\psi \) suppression at mid- and forward rapidity regions is observed in central Au + Au collisions. \( R_{AA} \) decreases with increasing \( \text{N}_{\text{part}} \).
System Size study:
Cu+Cu, Au+Au and U +U ≈ 200 GeV

$J/\psi \rightarrow \mu^+ \mu^-$ at forward rapidity

$1.2 < |y| < 2.2$

Not much net effect on $R_{AA}$ at forward rapidity from increasing system size of colliding nuclei!
Is this what we expected?

System Size study:
Cu+Au vs Au+Au at 200 GeV

$J/\psi \rightarrow \mu^+ \mu^-$

- Similar suppression in Cu+Au compared to Au+Au
- Forward (Cu-going) more suppressed than Backward $\rightarrow$ CNM effects?
Results of A+A support the idea of quarkonia dissociation in hot QGP medium

Y suppression pattern supports sequential melting

but what about p+A?

Why the dissociation pattern of J/ψ and Y(1S) is different in RHIC and LHC?
Upgrades: PHENIX $\rightarrow$ sPHENIX

high-rate DAQ, full calorimetry, exploiting high RHIC luminosity $\rightarrow$ huge range of microscope “resolving power”

Extended kinematics

Fully resolved Upsilon mass states

Au+Au 0-10\% 10B events

Invariant mass (GeV/c²)
The STAR Upgrades and BES Phase II

Major improvements for BES-II

**iTPC Upgrade:**
- Rebuilds the inner sectors of the TPC
- Full (azimuth) coverage improves dE/dx
- Extends $\eta$ coverage from 1.0 to 1.7
- Lowers $p_T$ cut-in from 125 MeV/c to 60 MeV/c

**EndCap TOF Upgrade:**
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

**EPD Upgrade:**
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics
Conclusions

- RHIC is a remarkable QCD Machine and versatile facility!
  - Au+Au at 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV
  - d+Au at 200 GeV, p+p (polarized!) at 200, 500, and 510 GeV
  - U+U at 193 GeV
  - Cu+Au at 62.4 and 200 GeV
  - 2015: p+Au and p+Al at 200 GeV

- The RHIC Beam Energy Scan is mapping out the QCD phase diagram
  - Don’t yet have a smoking gun for the critical end point but the search window is narrowed
  - Beam Energy Scan Phase-II (2019) will shed light on the critical end point

- Recent results from RHIC and LHC in small p, d, $^3$He+A collisions provide brand new insight into the role of initial and final state effects. These have proven to be interesting and more surprising than originally anticipated; and could conceivably shed new light in our understanding of collective behavior in heavy-ion physics

- Quarkonia is an excellent probe to learn about thermal properties of QGP medium

- Upgrades to the accelerator, PHENIX, and STAR will usher in the RHIC heavy flavor and jets eras

- Watch for many more new results at NN2017