What we have Learned and Challenges Ahead

An experimental overview of SQM 2006

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Strangeness in Quark Matter 2006
and more

UCLA, March 25-31, 2006
What I will cover

- **Experimental** overview (as requested)
  - For students – I will remind you of *some* of the arguments – ask if I don’t
  - I chose to be clear rather than comprehensive
  - Flavor/Particle ID plays a critical role

- Primarily RHIC data from SQM 06
  - SPS data – at the end

- any misconceptions are mine

- Selection of topics/data are mine
  - with apologies
Topics I will not cover or will only briefly mention

- Chiral Symmetry restoration (!)
- Chemical equilibration
- Strangeness enhancement – "the horn, the break"
- Nucleon structure
- Fluctuations
- Exotics
- Astrophysics
What we know: RHIC

- What we know
  - System appears thermally and chemically equilibrated
    - This happens early <2 fm/c
  - Energy density high >10 GeV/fm³
  - Parton energy loss is large
  - Viscosity/entropy, \( \eta/s \) is low (conjecture \( \sim 1/4\pi \)?)

- General picture is stable since ~ 2004
  - More data since QM 2005
  - More theory
  - A clearer view
### Busy days at RHIC

#### Experiment Collisions

<table>
<thead>
<tr>
<th>Energy</th>
<th>p+p</th>
<th>d+Au</th>
<th>Au+Au</th>
<th>Cu+Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.4 GeV</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>62.4 GeV</td>
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<td>130 GeV</td>
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<tr>
<td>200 GeV</td>
<td>○</td>
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</table>

#### Runs

- **Run 1 - 3**
- **Run 4 - 5**
- **Run 6 (?)**

#### Experiments

4 experiments – BRAHMS, PHENIX, PHOBOS, STAR
A cartoon – the life history of the sQGP

Energy Density (GeV/fm$^3$) vs. Time (fm)

1. Melting Colored Glass
2. CGC "glasma"
3. Quark Gluon Matter
4. Thermalization
5. Recombination
6. Hadrons
7. Freeze-out
8. Partonic

Crossover (wanna be 1$^{st}$ order)

L. McLerran (modified by R.S.)
Hadronization
(so I can introduce recombination)
Recombination and the baryon anomaly \( \frac{p_{\bar{b}}}{\pi} \) varies with \( \sqrt{s_{NN}} \) in Cu+Cu

- Originally thought: particle production at “moderate” \( p_T \) from mini-jet Fragmentation

\[ \text{At ISR } \frac{p_{\bar{b}}}{\pi} \sim 0.2 \]

- But

\[ \text{Heavy ion Collisions } \frac{p_{\bar{b}}}{\pi^-} \sim 0.7 \]

Increasing with energy

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![Graph showing the \( \frac{p_{\bar{b}}}{\pi} \) ratio for different energies in Cu+Cu collisions](image)
Baryon/meson (pbar/π⁻) at √s = 200 GeV AuAu

- Scales with N_{part} independent of system at η=0 and 3.2
Explanation: Recombination

- Naively: recombine quasi-partons ("quasiquarks" – Gavai)
  
Mueller et al, Hwa et al, Ko et al

- $P_T$
  - baryons $p_T \rightarrow 3 \ p_T$
  - mesons $p_T \rightarrow 2 \ p_T$ + Thermal spectrum $= \text{Large } p_{bar}/\pi$

This implies that we begin in a "quasi-partonic" thermal system

- Problem: protons exhibit "jettiness"
ReCo Model Modification (Hwa)

Premise:
The production of _ and _ particles is almost exclusively from thermal strange quarks even out to 8 GeV/c

Observables:
The ratio of _/_ yields should rise linearly with $p_T$

Mathew Lamont
energy density

“jet” energy loss
What is the energy density?  “Jet quenching”

**AuAu 200 GeV**

**Calculations:**
\[
dN_g/dy \sim 1000
\]
\[
\Rightarrow \varepsilon \sim 10-15 \text{ GeV/fm}^3
\]
\[
\varepsilon_{\text{critical}} \sim 0.6 \text{ GeV/fm}^3
\]

dave morrison
System dependence
Au+Au and Cu+Cu $\sqrt{s_{NN}} = 200$ GeV
Au+Au and Cu+Cu $\sqrt{s_{NN}} = 200$ GeV

$R_{AA}$ Function of Npart independent of system
How is the energy lost?

- The sQGP has enormous stopping power
  - rifle bullet stopped in a tissue
- Original idea – energy loss by gluon radiation
- In 2001, Dokshitzer and Kharzeev showed “dead cone” effect ⇒ charm quark small energy loss
What about heavy quarks? PHENIX

We see strong suppression even for heavy quark (charm).

Theory curves
(1-3) from N. Armesto, et al., PRD 71, 054027
(4) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301
What about heavy quarks? STAR

- Charm high $p_T$ suppression is as strong as light hadrons!!!
- Problem – difficult to reconcile with gluon radiative energy loss
  - theorists have to go back to the drawing board (Steffen?)

Haibin Zhang

Elliptic Flow ($v_2$)

Viscosity

Recombination
Previous Results

- If system free streams
  - spatial anisotropy is lost
  - $v_2$ is not developed
- Hence
  - Early thermalization
  - low viscosity

- detailed hydro calculations
  (QGP+mixed+RG, zero viscosity)
  - $\tau_{\text{therm}} \sim 0.6 - 1.0$ fm/c
  - $\varepsilon \sim 15 - 25$ GeV/fm$^3$
  - (ref: cold matter 0.16 GeV/fm$^3$

(Teany et al, Huovinen et al)
Recombination and $v_2$

1) Three regions of $v_2$

- Geometry-driven momentum anisotropy
- Geometry-driven absorption anisotropy
- From partonic quark number dependent
- From partonic and hadronic mass dependent

Maya Shimomura, SQM'06

Transverse momentum $p_T$ [GeV/c]
2) Data from minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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dave morrison
3) A recombination test
rescale by quark number Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Recombination works!
$v_2$ of strange hadrons from STAR

- Mass ordering observed at lower $p_T$ fit by hydro in hadronic phase
- $v_2$ saturates for $p_T > 3$ GeV/c
- Clear baryon/meson difference at intermediate to high $p_T$ observed

Talk: M. Oldenburg, Poster: Yan Lu
v2 of strange hadrons from STAR

- Mass ordering observed at lower $p_T$ fit by hydro in hadronic phase
- $v_2$ saturates for $p_T > 3$ GeV/c
- Clear baryon/meson difference at intermediate to high $p_T$ observed
- New, high statistics measurement shows deviation from ideal scaling. Mesons above 1, baryons below 1
v2 of strange hadrons from STAR

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The same scaling behaviour is observed in 62 GeV data
The $\phi$ - a test

- the $\phi$
  - mass ~ proton
  - quarks - meson

$V_2$ behaves as recombination says it should

ALL hadrons seem to obey quark number scaling!
Hydrodynamics (in the hadronic phase) and centrality

- Hydro works in min-bias
- not as function of centrality
  - initial cond? (Rafelski)

Centrality dependence of $v_2(p_T)$

Marcus. Oldenburg

STAR preliminary
200 GeV Au+Au

Hydro Model Results

- $K_S^0$
- $\Lambda + \bar{\Lambda}$
- $\Xi^- + \Xi^+$
- $\Omega^- + \bar{\Omega}^+$

[Hydro model results by P. Huovinen, private communication]
Recombination and centrality?

- recombination and number of quark scaling works for centrality dependence

Recombination works well. WHY? What is recombining?? DOF???
A quasi-quark Plasma?

Marcus Oldenburg
$v_2$ heavy quarks and viscosity

The stone in the river

or the concrete canoe

University of Wisconsin Badgers engineer third-straight concrete canoe title
Flow, viscosity, and strong coupling

- Conversion of spatial anisotropy to momentum anisotropy depends on viscosity
- Same phenomena observed in gases of strongly interacting atoms (Li6)

The RHIC fluid behaves like this, viscosity~0

now throw a stone in there

M. Gehm, et al  
Science 298 2179 (2002)
Heavy quarks: Single electron $v_2$

- data prefers charm flow
- for charm to flow interactions must be very strong
  - Viscosity small

Shingo Sakai, SQM’06
B meson contribution heavy quark electron $v_2$

- B electron $v_2$ reduces heavy quark electron $v_2$ @ high $p_T$
- We need to directly measure D’s and B’s

Shingo Sakai
Comment on a quantitative measure of the viscosity

- Upgrades - microvertex detectors - to both STAR and PHENIX will allow measurement of D and B mesons directly
- Theory – will take a while – (Steffen?)
- Meanwhile – viscosity better become part of our ethos
Back to the beginning
How does the sQGP get started?
a candidate - the CGC
CGC

- prediction: suppression in d+Au collisions
  - forward
  - central
  for all particles

Hongyan Yang, BRAHMS

$R_{CP}$ in d+Au collisions
What about charm?

- prompt muons charm(bottom) are suppressed in dAu CGC

Xiaorong Wang, SQM 2006

![Graph showing R_{dAu}(Prompt \mu^-) with data points for South and North arms, indicating suppression of charm production in dAu collisions.](Image)
Initial Temperature
Thermal photons - The Spectrum

Compare to NLO pQCD
- L.E. Gordon and W. Vogelsang
- excess above pQCD

Compare to thermal model
- D. d’Enterria, D. Perresounko
- nucl-th/0503054
  2+1 hydro
  \( T_0^{\text{ave}} = 360 \text{ MeV} (T_0^{\text{max}} = 570 \text{ MeV}) \)
  \( \tau_0 = 0.15 \text{ fm/c} \)
- data above thermal at high \( p_T \)

Compare to thermal + pQCD
- data consistent with thermal + pQCD

The Future – PHENIX- HBD
What have we learned

- **Jet quenching**
  - Charm quark energy loss, pretty well established

- **Viscosity**
  - Charm flows – further evidence that viscosity is small (interactions are strong)

- **Recombination**
  - Baryon to meson ratio seems to obey recombination scaling
  - All particles seem to obey $v_2$ recombination scaling. \([\phi, \_\_]\)
    - Some evidence for fine structure
  - Evidence for quasi-partons from Recombination/Lattice

- **CGC**
  - Indications of charm suppression in dAu collisions at forward rapidity

**RHIC is now studying a state of matter clearly above the transition**

**Question:** So where is it? Deconfinement? Is there a critical point?
Deconfinement and Screening (a puzzle)
A Theory update which bothers experimentalists

- J/ψ “melts” at $T > 1.5 \ T_C$ (Agnes Mocsy, Peter Petereczky)
- “Screening likely not responsible for quarkonia suppression” (Agnes Mocsy, Peter Petereczky)
- “You have to use the right potential” (CY Wong)
- Does quarkonia suppression tell us anything about deconfinement!???
- Who is right?!!

an experimentalist
J/$\psi$ suppression

PHENIX 200 GeV J/$\psi$ -- Preliminary

Grandchamp, Rapp, Brown
hep-ph/0306077

$R_{AA}$ vs $N_{\text{part}}$

- Rapp total ($y=0$)
- Rapp direct ($y=0$)
- Rapp regen ($y=0$)

CuCu $\mu\mu$
CuCu $ee$
CuCu $\mu\mu$ 62 GeV
AuAu $\mu\mu$
AuAu $ee$
dAu $\mu\mu$

sum
regeneration
screening
Aside: $R_{AA}$ of J/$\Psi$ in Au+Au/Cu+Cu

Most things depend on Npart independent of species

Why is J/$\psi$ at y=0 different for Cu and Au? Corona?

Might help in understanding suppression mechanism

Andrew Glenn
$\langle p_T^2 \rangle$ as a function of $N_{\text{coll}}$

**Au+Au = RED**

**Cu+Cu = BLUE**

Dashed: without recombination

Solid: includes recombination

Recombination model matches better to the data...

nucl-th/0505055

Andrew Glenn
Recombination predictions vs rapidity

- Recombination (Thews et al., nucl-th/0505055) predicts a narrower rapidity distribution with an increasing $N_{\text{part}}$.

- Going from p+p to the most central Au+Au: no significant change seen in the shape of the rapidity distribution.

Andry R
$R_{AA}$ vs. $p_T$ in Au+Au/Cu+Cu

- Suppression of $J/\Psi$ yield at low $p_T$ in both Au+Au and Cu+Cu.
- Might one expect “pile up” at low $p_T$ for recombination+energy loss?

Andrew Glenn
The critical point?

connecting to lower energies
Connecting to lower energies

- unique things (so far)
  - broadening
  - break in Inverse slopes @ $\sqrt{s_{NN}} \sim 5$
- AGS/SPS/RHIC similarities
  - strangeness enhancement
  - J/psi suppression

Ways to look
- wait for GSI
- wait for JPARK
- RHIC ~ 5GeV
Think Carefully

- Varying beam energy varies energy density — not T
  - Looking for a sharp “step” probably will not work at least not in T

- But we also vary
  - Baryon
    - Could we find the Critical point?

- Rare probes e.g. J/ψ would be tough
Questions

- Can we measure quantitatively the viscosity?
  - Charm, bottom measurements
  - THEORY

- Do we understand why the interaction is so strong?

- Chiral Symmetry?

- Do we understand the DOF?
  - Fluctuations measurements

Interplay of theory and experiment – very important both in the “CGC” and the “sQGP”

thanks – its been fun!
END
Baryon Transport: How much energy available from the collision?

- AGS→RHIC: Stopping -> Transparency
- Rapidity Loss $\langle \delta y \rangle$: 2±0.4; not linearly increase with $y_{\text{beam}}$
- Energy loss $\langle \delta E \rangle$ per nucleon: 73±6 GeV
- Available energy for excitation: ~3/4 of total energy~28 TeV

JH Lee