Notes from Jamie Nagle on the Boulder Workshop on the Future of Heavy Ion Physics
March 4-5, 2005

**Participants:**

- Jamie Nagle (JN) - University of Colorado (co-organizer)
- Peter Steinberg (PeS) - Brookhaven National Laboratory (co-organizer)
- John Harris (JH) - Yale University
- Ulrich Heinz (UH) - Ohio State University
- Ed Kinney (EK) - University of Colorado
- Al Mueller (AM) - Columbia University
- Berndt Müller (BM) - Duke University
- Rob Pisarski (RP) - Brookhaven National Laboratory
- Raimond Snellings (RS) - NIKHEF
- Dam Son (DS) - University of Washington
- Paul Stankus (PaS) - Oak Ridge National Laboratory
- Derek Teaney (DT) - Brookhaven National Laboratory
- Bill Zajc (WAZ) - Columbia University

**Original Invitation:**

We thought that is would be constructive to plan an informal brainstorming session on the key physics questions to be addressed in the near future encompassed by the RHIC II and LHC program. It seemed good to start with a small group to discuss the "big" questions relevant to the future of the field, in principle independent of particular experiments or even specific accelerator facilities. This is meant to be "outside" the more formal RHIC II workshop process, but ideas coming out of it could be easily re-integrated.

The small gathering is planned to take place in Boulder, CO on the weekend of Mach 4-6. We have tried to invite a reasonable sized (or order 10) people: small enough to allow us all to sit around one table, but diverse enough to include people of a wide variety of backgrounds and ideas.

**Original Input for Questions:**

We would like to request that everyone come to the meeting with a written list of four items either in text or a few slides that outline a key physics question to be discussed in terms of current status and future prospects. We urge people to be ambitious in speculating on what we think can be done. At least one of your four items should be a topic that no one would have predicted would have been one of your items.

Every time someone mentions PHENIX, STAR, New Detector, LHC, budget, etc, they have to buy another bottle of wine for everyone at dinner. Also, laptops should remain closed at all times.

Transcribed Notes from J. Nagle's notepad - 32 pages in total. Some notes and editing by Peter Steinberg.

Friday we went around the table and had each person lead a discussion on their list of items.

# Uli Heinz:

Question #1. What is the equation of state of strongly interacting matter

Diagram $e/T^4$ versus $T/T_c$. Around 3 $T_c$ one approaches 15-20% of the Stefan-Boltzmann (SB) limit – like an ideal gas
And speed of sound $c_s = c/3$.

We need to study elliptic flow to access this physics. We need as inputs the gradient of energy density and speed of sound.

How do we get at $e(T)/e_{SB}(T)$?
Measure of the amount of interactions – e-3P
Could this quantity be zero and still have strong interactions?

Actually, I thought he said that e-3p was not the interaction measure. Rather, it was the ratio $e/e_{SB}$.

JN: We must also be careful if we measure real pressure P, but energy density we measure includes some component that is not thermal.

How to get T, e by other means?
T from thermal photons, virtual photons going to dileptons.
Energy density e from jet tomography - but again this does not measure thermal e, just total.

BM: One might be able to use entropy as a replacement for T
Entropy density (s) and energy density (e) are extensive, instead of intensive (But I thought that only *total* entropy sV and energy eV are extensive) - how does this translate into an advantage?

- $e(T)/e_{SB}(T) \propto s^4 / e^3$
- How to measure entropy? Suggestion is via final particle multiplicity
- How well does that relate to QGP entropy?
- What is entropy generation during evolution?

BM: We compare entropy at freeze-out ($T_{th}$) from multiplicity to entropy from chemical analysis at earlier stage ($T_{ch}$). Both results agree within 10%.

2. Transport Properties of Matter

Importance of shear viscosity η.

DS + RP: Why is shear the most important viscosity – why not bulk?

Bulk is less important if particles are massless, which may not be our case.
Elliptic flow is very sensitive to shear viscosity, but what about bulk?
Bulk vanishes classically for massless particles.
No perturbative calculation of bulk viscosity.
Someone suggested that Prakash calculated bulk viscosity of hadron gas
(need to find reference). (here are several references for shear viscosity of a hadron gas: nucl-th/0408055, (and referneces), nucl-th/0309056, hep-ph/0305151, hep-ph/0112299)

If transport coefficients (viscosity and thermal conductivity) are zero, then entropy is conserved from early equilibration stage to the end. This is a critical point if we want entropy along the lines of earlier argument from BM.

Elliptic flow versus $p_T$
UH: Relativistic viscous hydrodynamic calculations are just at the start
1+1 dimensional codes are just coming out now. We are just at the very beginning.

3. Phase transitions

Without even discussing about determining the order of the transition at this stage, how do we obtain evidence of this transition experimentally?

Region of softness in EOS, speed of sound suddenly drops
Diagrams:

- $c_s^2$ versus T – schematic with and without 1st order
- In true 1st order speed of sound drops to zero in mixed phase – see diagram

PaS: Led interesting discussion about why sound waves through glass of ice water?
If true perfect state with mixed phase all sound wave energy converted to phase changes and thus sound cannot propagate. Consider separation of phases versus mixed phase and glass of ice water case. Another way to say this is that we should distinguish between phase coexistence and a true mixed phase.

Diagram with values and then experimental data… $\langle c_s \rangle$ or $v_2$ versus $\sqrt{(s)}$

- Key figure to reproduce in notes - was x axis normalized for density?

If we are always maintaining equilibrium (no viscosity at any stage or any energy) one should see the wiggle (obviously iff the phase diagram looks like the lattice). There is a particular sqrt(s) where one spends the maximum time at the early stages in the softest point region (mixed phase for example).

Key experimental statement: We do not see this effect at all with at least a few points (SPS, 62 GeV RHIC, 130 GeV RHIC, 200 GeV RHIC).
JN: Could it be the EOS is wrong?

UH+DT: Many say the observations are due to viscous effects in low density hadronic phase at lower energies. Thus if (big if) one could correct out the viscous hadronic part, one would "see" the wiggle.
JN: What would we need to do to have such calculations be solid enough to correct the results are see the wiggle such that it would be convincing across the field?

Currently there is no real analytic calculation with viscosity for the hadronic stage. Best out there is using RQMD (DT et al.).

# Al Mueller

1. Initial conditions

Saturation picture. Mainly gluons at the start.
Quite fast equilibration, but there is no such thing as born into equilibrium in the saturation picture as some have ascribed.

- There was a key point about why it is fast later in terms of decoherence time.

Diagram – Initial density of gluons and initial $E_T$ of gluons versus rapidity. Shows expectation from saturation of larger $E_T/N_g$ as one moves away from y=0.

Avoid the "fragmentation regions" – may be most everything at RHIC except midrapidity

Energy per gluon is higher at forward rapidity (complex multiple-scattering type effect in saturation picture), thus harder to equilibrate at forward/backward rapidity.
- Midrapidity should equilibrate the fastest.
- $E_T$/gluon increases by ~ 50% with 3-4 units away from midrapidity

Direct photons versus rapidity may allow time dependence of pre-equilibrium stage.

Diagram $\langle p_T \rangle$ and $\langle v_2 \rangle$ versus rapidity.
Interesting question about rapid fall off of $v_2$ with pseudorapidity from PHOBOS – is it faster using $dN_{ch}/d\eta$ or dy (be careful about effect of Jacobian).

JN: Asked about saturation applied to lower energies. Agreement of Kharzeev CGC all the way down to 19 GeV sqrt(s).

AM: "Calculations work when they should not and don't work when they should."
This is a favorite of everyone's from the workshop.

Discussion about CGC/Saturation phenomenology at RHIC.
Early attempts tried to match particle multiplicity and thus picked too high (?) a saturation scale. Then $E_T$ is too big and must invoke handwaving (at least not calculated in detail) *pdV* longitudinal work.
JN: How can one describe $dN_{ch}/d\eta$ and then invoke enormous longitudinal work to drop $E_T$ by a factor of 3?

AM: If they had tried matching ET try saturation scale $Q_s$ ~ 1 GeV to get that right, but then too few particles. Need entropy production in gluon⇒final particles. What are you trying to match?

Need something sensitive to pre-equilibrium phase to test this, since sensitivity of final $E_T$ and multiplicity to saturation scale is quite limited.
AM: What happens to the pre-equilibrium wavefunction when you hit it with a hammer? Early time probes like photons and heavy quarks are in principle much more sensitive.

No reason for pA over eA purely in terms of physics, but A+A is quite different – see about quote about hitting it with a hammer. AA changes a high occupation of virtual partons to high occupation of quasi-real partons.

pA is a poor man's version of eA – both cases all virtual gluons

Can one make a plot of x and Q^2 coverage for eA and pA, but where you know exactly the Q2 for each event? pA one would need more kinematic information for this to avoid having to average over a range in x - as is true with current single hadron measurements.

AM: eRHIC is not ideal – too low energy. Too bad no nuclei in HERA program. What about e-p or e-A with electron beam in future at LHC!

PS: What sets the scale for bulk - pp versus AA
- Surface to volume
- Correlation length
- Interaction length compared to radius - most agreed on this one.
- Note that in proton-proton, radius is most often much less than 1 fm.

WAZ: At any given accelerator pp has $Q_s$ x2-3 less than AA
Correction factor is $A^{1/3} \times (Z/A)$ – with Z/A for lower energy of beams

Entire area of study – non-equilibrium high density field theory

# Paul Stankus

1. Pre-equilibrium stage – as one approaches equilibrium

If there are quarks and antiquarks around at this stage then one must see thermal radiation via electromagnetic probes ($\gamma$, $\gamma^*$).

Mentioned reference Boyanovsky and Vega, PRD 68, 065018. DS and others said this paper is wrong?

Most interesting is how you get to equilibrium. Equilibrium makes you forget all local information, but global information may survive (UH). Other survivors:
1. relics (pre-equilibrium b quark production …)
2. escapees (gamma, gamma*, Z0)
3. transport of conserved quantities (B, Q, I, …)

Diagrams of dN/dy (B-Bbar) initial versus rapidity and final. How do these quantum numbers get transported? How wide a rapidity coverage does one need?

Tracking baryons and quarks may be very interesting. Both B and Q.

Question raised on modification of $Z_0$ in medium due to gluon-$Z_0$ scattering. Note that width of $Z_0$ implies a lifetime of order 0.1 fm/c. Is there a paper by Kapusta on this? Does it imply a very small modification? Also, what is the size of the g-Z coupling?

2. Valid hydrodynamics versus local equilibrium

UH: Viscosity is a non-equilibrium effect, and so local equilibrium and hydrodynamics are the same in this case.

3. Hadronization

Hadron formation Baryons versus Mesons

JN: Asked what can we really hope to develop in terms of greater understanding of hadronic wavefunctions and fragmentation process? Over 20-30 years, development of details phenomenology in string models (LUND) etc.

# Ed Kinney

Insight into hadronic wavefunctions via spin.

JN:  Raised the question about the real connection of the spin program and the heavy ion program.

WAZ quotes B. Mawhinney **"To understand the *inside* of the proton you must understand the *outside* of the proton."**

Confinement requires helicity change.

But question remains, other that indirect connection via QCD which makes them complementary, and their specific measurements from spin which impact heavy ions. Answer seems to be not really.

BM:  Mentioned polarized proton-nucleus program (not flushed out).  Perhaps this type of thing could give insight into Cronin effect.

PAS: showed Abhay's questions, if only to show the spin issues:

> 1) If in the next few years RHIC discovers that $\Delta G$ is zero (all double spin asymmetries are consistent with 0), what then? [I am assuming we have scanned the x region accessible by 200 and 500 GeV running of RHIC.]   Orbital angular momentum of partons will take an enormous importance then in the the nucleon spin equation.
>
> 2) Is there any possible (dreamable) way to get at quark/gluon orbital angular momenta through polarized pp collisions? This would be especially critical if (1) is true. Or would we have to wait for eRHIC to address this issue through off-forward PDFs?
>
> 3) It is the connection between orbital angular momentum in nucleons to any transverse spin effect quantifiable? I.e. is this the way to access orbital angular momentum at RHIC, through any transversity studies? These would be of interest to RHIC II and also for a "fuller"acceptance detector at RHIC.  I think I know partial solutions to these questions using an electron machine, but do not know what one could do with hadron-hadron collisions.

# Dam Son

1. Viscosity

We know that bulk viscosity must be positive. Perfectly spherical expansion would be only sensitive to bulk viscosity, but that is not the case in AA reactions.

C1 eta + c2 zeta
4/3 $\eta$ (shear viscosity)+ $\zeta$ (bulk viscosity) (if purely 1D case)

We are actually sensitive to the combination of these.

Is there an experimental upper limit on viscosity or specifically shear viscosity?

$\eta <= 5/T \sim 1/4\pi$

Somewhat confusing discussion (at least to JN) where DT says we already have a bound lower than for $He^4$ and that may only be a factor of 5 above the conjectured lowest bound. However, there is not general agreement on this value.

DT: High $p_T$ partons scatter at similar rate as low $p_T$ partons. Thus, we should have a picture that includes scattering cross section to explain both low and high $p_T$.

2. Can we learn something from cold atom experiments?

For example, what is the minimal number of particles to get hydro?

WAZ: Can they adjust the interaction to get the most perfect fluid? Is this or will this be a better bound that we can achieve?

Interaction length (lambda) ~ $10^6 \times$ atom size, but they have a very dilute system. They can then tune lambda to infinity by going on resonance. One cannot pass another atom without an interaction.

WAZ – their hydro problem is much simpler than ours.
They can directly measure speed of sound via oscillations – monopole oscillation measured over 100s of oscillations.

Scattering length? Atoms cross section approaches unit limit – cannot miss.
PeS: Are we near this region at RHIC?

pQCD gives very low viscosity within x2-3 of bound. $\eta \propto 1/\alpha_s^2$.

This seems very surprising. Reference is Arnold, Moore, Yaffe hep-ph/0302165: but what about dependence on number of fermions?

JN: Very confused. Thought pQCD is weakly interacting system and thus large viscosity. Still confused after discussion, but issue seems that if pQCD cross sections it takes too long to get to equilibrium.

What is exact mapping of cross section (mean free path) to viscosity? I thought zero viscosity meant zero mean free path? But pQCD has mean free path ~ 2-3 fm, but still very low viscosity.

pQCD mean free path is too long 2-3 fm with $\alpha_s \sim 0.4$ . Note this path is for a RHIC like system including expansion.

How do these quantities relate to relaxation time? DT seems to like thinking in terms of this relaxation time scale.

# Raimond Snellings

1. How to quantify $v_2$ and expectations. What knobs do we have to turn

Diagram from UH talk.

How is the hardness of QGP equation of state tied to the lattice? Lattice has $c_s = 1/3$ above about 2Tc. EOS can only be softer than that.

True absolute upper bound on elliptic flow would be using hardest possible EOS $c_s = 1/3$ from t=0 until freeze out. This upper limit is still of course dependent on initial density, profile and freeze-out time. Would be interesting to plot this (JN).

There was discussion of whether on can have $v_2$ from pre-equilibrium. What is in Raju's calculation of $v_2$ from CGC? It seems this is still a collective effect.

There was more discussion of whether $v_2$ experimental measurements at high pT contain contamination from jet correlations. STAR seems concerned about this. PHENIX uses correlation with reaction plane from forward rapidity BBC counters. Does this eliminate the issue?

2. Chiral Symmetry Restoration

Using intermediate $p_T$ hadrons to probe via recombination?

What are the direct probes of chiral symmetry?

PeS: DCC – did we perhaps give up on this too soon? Drives low pT measures.
- ρ mass shift not direct measure of chiral symmetry!
- $a_1$ and ρ become degenerate with restoration

DS: Mathematical correlation of axial and vector current.

Hadronic spectral function can only be indirect indication – shift up or down?

PaS: If quark effective masses are very small they equilibrate very fast, should this lead to more thermal radiation.

Can you tell if there are massless DoF? RS: again issue of recombination.

Quarks in the medium have an effective mass, which is different from a chiral mass.

Dirac or current mass violates chiral symmetry, effective mass does not (I thought that was a consequence of $\chi$SB)

JN: Thought Experiment:

You can a box of particles. In one can you have quarks with a certain chiral mass and in another you have quarks with an effective mass of exactly the same value. Can you tell the difference between these scenarios via thermal radiation?

Still need to think about the above question.

Saturation models may give the best picture of pre-equilibrium partons, but they are all gluons.

AM: One can do a semi-classical calculation for splitting of these gluons to see how fast one builds up qqbar pairs. This would be very interesting.

One note is the failure in general of partonic cascades is a problem for gaining insight on thermal radiation issue.

Ideally need to measure quark left handedness and see if it is still left handed after 2 fm/c then 3 fm/c then 4 fm/c.

JN: Who are the people to talk to about chiral symmetry observables? We have 13 very sharp people in this room and essentially no solid ideas to relate directly to the issue of chiral symmetry restoration. Major observation. Is this a bias in who we invited?

# John Harris

1. Chiral symmetry restoration
2. Deconfinement
3. Effective degrees of freedom

Hadronization

Jet probing the medium may lead to softened/modified fragmentation functions.
This led to a discussion of hadrons forming in medium.

AM: Cannot form a high energy hadron in medium, but that is different from fragmenting in medium. You may fragment a gluon, but not form a full hadronic wavefunction. $p_T \sim 3$ -5 GeV may still be sensitive to in-medium hadronization effects.

$\gamma$-jet viewed as important.
JH: Interested in $\rho$ meson spectral function inside jet production. If $\rho$ is large z, then by Kopeliovich $t \sim 1/(z*(1-z))$ argument you know the rho or precursor was born early.

JN: Says problem is that if very high z then no medium effect – decays outside medium. Question is whether there is an intermediate z with early formation (tagged) but still medium effects. Is there such a kinematic region?

Exotics may also be of interest $\omega$, $\Phi$, $\eta_c$ in jet fragmentation, but rates are certainly an issue.

JH: Notes that RHIC has unique window on proton-proton tests of universality and factorization due to excellent PID. Argument is that using FF from e+e- for pions work quite well in hadron-hadron case (e.g. PHENIX pizero results compared with Vogelsang's calculations). However, using FF from e+e- for baryons gives an underprediction for hadron-hadron case by ~ order of magnitude.

Is this an interesting area of investigation? Could this lead to improved phenomenology (PYTHIA, HERWIG type models) or more fundamental understanding.

JN: Speculates on whether this is STAR/PHENIX consistent since pbar/pi in peripheral Au+Au by PHENIX looks like ratio from e+e- jets.

More discussion on the heavy quark contribution to these hadrons and oddities of the fragmentation functions.

How do partons propagate through the medium?

JN:  What do we learn in total from energy loss of leading partons in jet quenching?

AM:  Jet quenching tells almost nothing about the correlations or deconfinement or Possible bound states.  Only the density of color charges matter.

JN:  Was told by Miklos many years ago.  Think of it like deep inelastic scattering.  If the $Q^2$ is high enough, probing at very short wavelength and so no sensitivity to substructure.

In recent discussion with Urs, he disagreed and said that the $Q^2$ scale is not set by the parton energy, but the individual radiated gluon – which is not so high, some significant part near the infrared cut-off.

AM: Says it is neither of the above.  The scale is set by the total coherent energy loss which as seen at RHIC is quite large.  It is the scale of the measurement that matters.

AM: Analog of heavy quark production and virtuality in terms of the relevant scale.  Ask Al for the reference on this.  It would be good to get agreement in the field on the relevant scale.

Someone noted that there has never been an NLO correction on energy loss (BM mentioned this was in the plan for 2009).

# Rob Pisarski

"Is it the same to live in Geneva or Shirley?"

Diagram of e/T^4 versus T – shows plateau where RHIC and LHC are both on top.

Diagram of $p/p_{SB}$ versus T – shows slower rise and LHC much higher on pressure curve than RHIC. With LHC at 0.85 of ideal like the lattice. The 0.85 is the naively thought of perturbative QGP value.

If one looks at energy density lattice plot RHIC and LHC look visually similar, but pressure curve makes them look different. Watch out for false advertising!

DS+UH: Note that pressure curve cannot have as sharp a rise as e/t^4 as necessitated by extensive variable relations. (This is effect of latent heat present in 1st order PT)

Perturbative resummation → debye mass ~ gT
But always fails near Tc
Cassing et al. do a calculation where they vary the coupling to reproduce the pressure drop seen on the lattice. Where the coupling g has to start being artificially modified is below 3 Tc (and by Rob's implication somewhere between flying from Geneva to Shirley).

Diagram of $(e-3P)/T^4$ shows very distinct peak between SPS and RHIC. This quantity is sensitive interaction strength and thus both shear and bulk (uniform in all directions) viscosity. (Why is this not somehow relevant to *hadronization*, not SPS to RHIC?)

Deconfinement:

There is no exact order parameter for deconfinement in QCD. There is however the Polykov loop – collective DOF, geometric quantity of gluons explicitly defined as a loop on the lattice.

<l> = 0 confined
<l> = 1 T→ infinity deconfined
<l> != 0, < 1 deconfined, but non-perturbative plasma

PeS: what is <l> ? Above answer of geometric quantity of gluons.
<l> = 1/3 tr P exp(ig $\int A_0$)

Diagram of <l> versus T/Tc

SPS around Tc has <l> = 0.4 – 0.5, RHIC in the middle, and LHC above 0.9! (only with $N_f$=0!) Thus R.P. concludes LHC is perturbative plasma and RHIC is non-perturbative plasma. There was significant discussion and disagreement (WAZ, others) about this.

Thus, one might expect a decrease in flow observables $v_2$ at LHC.

DT disagrees. After just t=1fm/c the energy density at LHC is already similar to RHIC.

Strong-coupled term – what does it mean?

RP: Points out that g is actually not so large around Tc.

3. Rapidity Instabilities

(Based on Arnold, Lenaghan, and Moore - ref?)

t<0 narrow pancakes approaching
t>0 narrow pancakes flying away

Looking at one slice in coordinate space, and keeping in mind that CGC has almost perfect space momentum correlation

Spin 1 color magnetic instabilities, instabilities isotipric – much longer to 3-D thermal bigger fluctuations along the beam than transverse

4. Chiral symmetry issue

If chiral symmetry transition is less than the temperature for deconfinement at $T\neq 0$ and $\mu_B=0$, then $T_{\chi SB} < T_c$ as you move away from $\mu_B=0$.

# Derek Teaney

1. Relaxation Time

Diagram of $v_2$ versus $p_T$ – does v2 flatten with $p_T$

Trying to relate high $p_T$ modification and low $p_T$ flow pattern.

η/(e+p) and q^ are both related to transport properties – do they agree?

AM: q^ can be defined in equilibrium or non-equilibrium, but η/(e+p) are only relevant in equilibrium.

η/s ~ 1/4π bound

How about s/q^?

Does energy loss eventually match high $p_T$ $v_2$? So far the data and calculations are not consistent in this region.

Can recombination of partons help explain large $v_2$ at intermediate $p_T$?

*** Is collisional energy loss important?! ***
Molnar calculation using 18mb cross section ? shows good agreement with basic trend in RAA for pions. Depending on alpha-s – one gluon exchange –
This is elastic as opposed to radiative.

Collisional – fluctuations may be a significant effect . e.g. one collision no survivial scenario. However, Molnar calculation nominally includes this and it still shows factor 5 suppression in pions.

Interesting issue of reconciling Molnar collisional calculation and Vitev radiative calculation and in the same office at Columbia?

If collisional is important, then dN/dy (color charge) from radiate is large overestimate.

# Berndt Müller

1. Measuring number of degrees of freedom

Need e, s, p and T – see paper by Muller and Rajagopal (ref?)
Believe we have S to within 10%. All hadrons at the end (a la Pratt). Independent check with resonance gas in thermal stage. $T_{th}$ and $T_{ch}$ entropy values agree within 10%.
Entropy as the system going towards equilibrium.

So saturation scenario stage of 3x multiplication of gluons is pre-equilibrium. Entropy may be conserved throughtout evolution after that.

q^ ∝ $e^{3/4}$ (Baier?) – is this universal and one just needs the coefficient to get e? Clearly true if q^ ∝ s.

JN: What if, e.g., 80% of energy is equilibrated? Then you measure total e, but get incorrect value for plugging into thermodynamic relation to get d.o.f. You can still generate entropy out of equilibrium, but EOS not obviously relevant.

2. Color wakes

How does the medium itself respond to fast color charges?

Nice parallel example in EM:
- Highly ionized charge → incident on metal foil
- What is the distribution of induced current in the foil? Can easily be measured experimentally by ejected electrons versus angle.

What matters is the dielectric e(k,w)
- Very different in QCD from metal
- Color susceptibility ε in pQCD very damped in space domain
- But imaginary part is large for $|k|>\omega$
- Perturbative Landau damping → massless particles

What if strongly coupled?
Hydrodynamic modes excited – energy and momentum but colorless modes
BM: Calculation of color oscillation modes – so different from earlier calculations

Im(ε) small for small k

Collective part of collisional energy losss → longitudinal modes
BM calculation is not a shock wave a la DT et al.

Could have both effects.

One does not see this in perturbative plasma

UH?: Does color neutralization kill this too fast? Color exchange without momentum transfer?

Note that broadened re-interacting radiated gluons are in some sense a background to this collective effect.

JN: Major issue with radiative calculations of broadening is that they never account for re-interations of initial radiated gluons with remaining medium.

3. QQ bound states

Baryons with 2 charmed quarks (cc)q
NRQCD
Could one look for these experimentally at the LHC (large charm overall)?

4. $5^{th}$ dimension

Discussions with P. Frampton in Paris. Correlations between quarks can be described by interaction proceeding via 5th dimension. RHIC collisions, can break this correlations, leading to deconfinement.

Is RHIC the first accelerator to probe these extra dimensions?

Example of theories with phenomenological extra D, but non-compact. Gluons can go onto $5^{th}$ dimension. In fundamental string theory of gravity, even more dimensions come into play.

Can one gain insight with these pictures?

## Bill Zajc

Why are we still here?

Relaxation time propto m/T
So what happens with charm and beauty?  Drag coefficient…

*** Strong coupling – what does it mean?
Does it refer to plasma parameter $\Gamma$ = DV/ DT (potential over kinetic energy)?

DS: Points out there is a problem in a relativistic plasma where there is often no clear distinction of V,T, e.g. when the particles and the forces are not clearly distinguishable.

**CGC:**

Can we describe relativistic heavy ion collisions without invoking the color glass condensate?

Conversely:
What aspects of rhi collisions require a CGC description?

What additional measurements are required to elucidate its role?

Presumably general features of production at low x in both p+A and A+A collisions?

If CGC is correct approach at low x, how to evolve smoothly into 'non-low-x' regime?

What will eRHIC tell us about CGC that RHIC+LHC won't?

What Is It?
A perfect fluid:
- What key measurements determine the viscosity?
- How quantitative can we make the assertion of "perfection"?
- In a perfect world: Blue-book plots of error on $\eta$ as a function of Au+Au integrated luminosity
- How does perfection vary with baryon content? $\eta(\mu) = ?$

A strongly-coupled state of matter
- What is the precise value of $\Gamma$ ? (Measured how?)
- What are the signature of the color-ful bound states?
- Does the Popeye Principle truly apply at $\mu=0$?
- WHAT ARE THE DOF?

A quark-gluon plasma
- All the usual characteristics of a medium:
- EOS, transport coefficients, permittivity, screening length
- How is each determined?
- What precision per inverse nb?
- And how about that thermalization time? Can we determine it rather than just bounding it?

Perfect Primordial Fluid:

Naming has been pre-empted by Gamow over 50 years ago:
R. Alpher, H. Bethe, G. Gamow, "Origin of Chemical Elements," Phys. Rev. 73, 803, (1948)

y·lem A form of matter hypothesized by proponents of the big bang theory to have existed before the formation of the chemical elements. [Middle English, universal matter, from Old French , from Medieval Latin , accusative of , matter, from Greek]

**The Other Phase Transition:**

Do we know anything about the chiral phase transition?
- Is there chiral symmetry restoration in the brave new world of the sQGP ?
- Is it as "simple" as measuring M(e+e-) ?
- Unravel from bound states > $T_C$
- Is there any chiral signal that appears exclusively in quark-gluon matter and not in dense hadronic matter?
- Could HBT actually be useful?:
  - QUANTUM OPACITY, THE RHIC HBT PUZZLE, AND THE CHIRAL PHASE TRANSITION. By John G. Cramer, Gerald A. Miller, Jackson M.S. Wu, Jin-Hee Yoon (Washington U., Seattle),. NT-UW-04-026, Nov 2004. 4pp. e-Print Archive: nucl-th/0411031

**Sizzle That Sells:**

New horizons in QCD (literally)
- There appears to be some there there
- How far can the AdS/CFT correspondence be pushed?
- Will it tell us anything beyond its "successes":
  - $\eta / s = \tilde{N} / 4\pi$
  - $s / s_{SB} = 3 / 4$
- What else?

How to exploit for science:
- "Thus RHIC is in a certain sense a string theory testing machine, analyzing the formation and decay of dual black holes, and giving information about the black hole interior."
  - H. Nastase, hep-th/0501068

How to exploit for $’s?

**<u>Outreach</u>**:

We’ve started some “outreach” to other fields

- “Real” Plasma physics
- Condensed Matter (?)
- Astrophysics (??)
- Strings

Public

- Initial start-up of RHIC did very well in this respect
- But it does not translate into outrage over its potential demise
- My ideal
    - RHIC images as vivid as those from Hubble
    - An opinion column in USA Today urging that the exploration of inner space continue (as there was for HST)

Saturday Discussion:

Three identified topics from yesterday's listings.

1. Jet quenching and hadronization – although this is not a big picture physics topic, as a defined area it has started to dominate the field. Thus, more explicit discussion is warranted.
2. Deconfinement
3. EOS (viscosity), Hydro, thermalization

## **1. Jet quenching**

JN: Even though they may not factorize, we can think of three regimes of jet physics.

> a.) What happens to the leading parton… currently used via radiative calculations to extract color charge density
>
> b.) What happens to fragmentation of color fields in or near medium? Recombination pictures may be relevant, modification of field strength
>
> c.) What is the reaction of the medium to the passage of a high energy color charge?

The last one may be the most interesting, though the newest and perhaps most speculative. Measuring fundamental properties like speed of sound and truly collective reaction would be very exciting.

JN: Raises issue that just like Mach cone calculation one needs uniform speed of sound (through medium and in our case through time evolution) and no phase modification of propagating waves (color or otherwise). With transition to softest point in time evolution and large decrease in speed of sound, these static calculations must be an overestimate of such a coherent effect.

AM: Large energy loss makes it a very hard scale probe… not sensitive to deconfinement or otherwise.
BM: How do we confirm that factorization applies? Gamma-jet may be very important.
AM: Is the hadronization in medium? Definitely not at LHC, but not so clear at RHIC.

Dirty laundry – Poisson distribution of emitted gluons is assumed in calculations, but may not be right. Abelian case is certainly Poisson, but non-Abelian may correlate everything.

Tagging photon events and looking at the jets is critical to "confirm the picture."

JN: This may be hard to sell since so many in the field refer to the radiative calculations as very solid.
AM: Points out that radiative calculations are not a priori fundamental QCD calculations.

Suggestion that charm jets may be preferable to light quark jets due to simpler fragmentation. Some note that many in field still use delta(z) for fragmentation, so maybe not so simple for everyone.

JN: Throws out idea that at very high $p_T$, one learns nothing new from charm jets versus light quarks jets. General agreement, but that might only be at very high $p_T$.

Dead cone effect is a velocity effect, with nothing specific to heavy flavor. QCD is flavor symmetric.

JH: Control the kinematics with full jet reconsturctiion or gamma-jet with large statistics. If zero kT, then jet axis and photon energy + direction constraints x1, x2, Q2. However, if one relaxes the $k_T$=0 assumption one additionally needs the jet energy.

In spin program they want to statistically tag incoming partons, here we want to tag outgoing partons.

JN: Agrees this would be great, but can it really be done with real detector and finite dollars?

JN: Raises issue of no complete simulations for jet energy resolution at RHIC as a function of energy.

JH: Recalls old STAR study with 30 GeV jet for b > 5.5 fm, a 15% energy resolution using EMC + tracking. JH and JN agree that updated studies needed.

More discussion of heavy flavor in medium. Could one see more distinctly a drag effect?

## 2. Thermalization, EOS, Hydro (P.S.)

### Thermalization:

AM, DS: CGC does not have partons born into thermal equilibrium, though this is often stated in the field. Major misconception.

AM: However, high occupation number yields a very low entropy per particle. Thus there is a very large and fast entropy production as one has decoherence of the wavefunction. Quick way to get lots of entropy.

JN asks if one can calculate S/Smax as a function of time in DS and AM published result of saturation to thermalization. Everyone agrees there is no sharp time of thermalization, but rather an approach. Can we make this plot?

PeS etc.: Bjorken versus Landau?
Longitudinal work
Longitudinal correlations
Even Landau solutions approaches hydrodynamic scaling
Thermalization time ~ $\tau \sim 1/\sqrt{s}$

Can we discriminate these pictures beyond staring at rapidity distribution (flat or not). Very, very hot early time in Landau picture.

PeS: says very hot at early times, but that period is very short lived.
AM, BM: photons emitted in time period ~ 1/T, and with production ~ $T^4$. thus the Landau picture may be or is [?] ruled out because it predicts an enormous flux of thermal photons. Check refernces and detailed calculations by Renk (hep-ph/0503082)

Everyone agrees there may be a continuum of scenarios between Bjorken and Landau.

**EOS:**

How do we map the lattice results out?

DT: Do not do a more finely grained energy scan, though UH thinks a couple more points will help.

DT: Relaxation time gets big in phase transition region at low energy, and thus very hard to calculate.

Big discussion about how to control viscous hadronic phase. Is RQMD a sufficient check?

UH notes that RQMD is not used for production (ala strings, ropes, etc.), but just for scattering and reactions. Discussion of whether there are enough resonances and 3→2 and 2→3.

BM: If there were very large non-equilibrium effects in hadronic phase, why does this not lead to quenches at lower energies (and therefore DCC-like effects)?

**"Brown-Shuryak Bound-States" $(BS)^2$:**

DT: Not reliable calculation. Not so well motivated because does not increase intereaction strength in any way. Bound states are heavy and should lead to longer relaxation time, contradicts fast thermalization.

DS: Using static potential for ultrarelativistic particles is wrong

WAZ: Suggests that this might be applicable for charm (ie. Non-relativistic)

RP: Lattice shows no evidence for these bound states.

BM: Liquid does not have long lived quasi-particles. No particular basis provides a better description.

Question raised how to experimentally push our understanding and challenge the existing pictures.

- Going to higher $p_T$ is not clear. Above 4-5 GeV are the observed deviations due to viscous effects or by an admixture of fundamentally non-thermal processes.

JN?: Heavy flavor c,b may help to constrain viscosity and drag effect, diffusion coefficient.

- It might be important to completely reconstruct D→pi K to keep kinematic information particularly at low pT.

DT wants to see unified picture of energy loss interactions and push towards thermalization of bulk. Use energy loss to constrain relaxation time.

JN: relates that Urs thinks of high $p_T$ parton as a non-equilibrium probe which one can use to study evolution towards thermalization.

EK: Can we relate the microscopic process to heat capacity of medium?

- Most agreed we didn't have such fine control over temperature yet!

pQCD calculation of Arnold, Moore, Yaffe (hep-ph/0302165) of viscosity within x2-3 of viscosity bound (setting alpha-s = 0.5). Perhaps this is unrealistic $\alpha_s$, but this seems odd since we always thing of perturbative "plasma" ("wQGP"as weakly interacting → at least to JN this means large viscosity. To PeS it's true for a gas)

BM: Mentions that 3D hydro including viscosity is a project promised as a deliverable to DOE by 2009. Note that also NLO jet quenching was promised by 2010.

WAZ

1. Understanding perfect fluid behaviour
2. Looking for deconfinement

Can you change DT calculation to vary initial conditions and already set a preliminary viscosity bound?
• Diagram η/s for different materials from DS's paper. Are we below $He^4$?

JN and WAZ (and PeS, thank you) pushing on theorists. DT thinks an estimate that is reliable could be made, but UH disagrees.

DT still worried about whether all of $v_2$ has hydrodynamic origin (vs. Kovchegov?)

WAZ suggests new ratio:

$$R_{\$\$} = \frac{\eta}{s}\frac{\hbar}{4\pi k_B}$$

**3. Deconfinement:**

BM: if $R_{\$\$}$=1, then mean free path / interparticle distance = 1/3. I do not understand this [nor do I]

1. BM: There is no established order parameter for deconfinement in real QCD
2. RP: There is <l> Polykov loop as a diagnostic of confinement
3. Signatures

Chemical equilibration (e.g. strangeness), but this has sort of maxed out[?]. Indicative but not definitive.

Quark recombination.

J/ψ, ψ', $\chi_c$, ϒ and NRQCD for spectral functions appears okay [?] and converging.

JN: There are calculations (Qiu et al) using multiple scattering and if enough mean $p_T$ between c and cbar then breakup. This is in contrast to Debye screening length $\lambda_D$ < size of object. Are these distinct or two different ways to look at the same thing – microscopic versus field? [But both are "scattering" processes, even for the fields]

Shielding versus collisional – AM – are they parametrically the same?

RP – in the large $N_c$ limit you have screening but no collisions. BM disagrees.

AM: "Deconfinement is a property of the medium. Confinement is a property of the vacuum."

JN: Scattering model for quarkonia should be able to be done in same framework as collisional contribution to energy loss calculations.

Formation time of these states is also an issue.

JN: What are real predictions from screening for $p_T$ and path length dependence of suppression? Cannot be done on the lattice – static.

Answer appears to be that there are none done. One could do a dynamical calculation in NRQCD framework – really needs to be done.
- Why not done in the past? Turn off from NA50 changing data, but future RHIC data will get people's attention.

NRQCD can calculate an evolving wavefunction through the medium adding in the gluon density [Reference?]. This is a critical step.
- Calculations via scattering could be done for $p_T$ and path length dependence.

Naively we thought that if $J/\psi$ is in medium longer than formation time then it will be suppressed. This would seem to strongly predict surface emission only. Can check Satz prediction of large suppression in Cu+Cu at RHIC.

<u>4. Degrees of Freedom</u>
- $S = (2\pi^2/45)\nu T^3$ (black body)
- $\nu = [2\ (N_c^2-1) + 7/2\ N_c N_f]\ (1 - O(\alpha_s))$

Krishna and Muller paper – need reference

Using entropy from multiplicity and energy density from Bjorken estimate (roughly - 7 $GeV/fm^3$ instead of 5), one gets consistentcy with 37 dof. But very sensitive (large power of $\varepsilon$), so slight change and very different DOF.

JN: very enticing, but can it provide definitive picture of DOF?

**<u>Wrapping things Up:</u>**

WAZ – suggestion that each person sends an email pointing out the most surprising item for them from the workshop.

How important is string theory connection?
Polchinski, Witten others asking about RHIC physics.

AM: suggests separating issue of perfect fluid from AdS/CFT, WAZ disagrees

AM: suggests experimentalists leave it to the theorists, most experimentalists disagree

JN: suggests that implication of new approach to QCD and broadened community of people interesting can only be a positive thing.

BM: many measurements can be made that may be insightful, but need more theory development to know how quantitative advances will be.

BM: 2006 budget cuts could reduce theory community effort by 30% !

We should not advertise future as precision physics, makes us all think of electro-weak. We are still a discovery community.

We have made many experimentally driven discoveries to date, and it is imperative to follow them up with measurements to test our understanding of these phenomena hand-in-hand with critical theoretical developments.

One participant:  "There is no where else in the world I could have spent two days and learned more."

Organizers profusely thank participants for coming and a very lively and productive discussion.