PHENIX Quarkonium Results

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On behalf of the PHENIX collaboration

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Motivation – an evolving target!

Original motivation: J/ψ disappearance = direct signature of deconfinement.

But things became complicated:
→ The J/ψ may persist to as much as 2 T_c (eg. Satz, hep-ph/0512217 review).
→ Charm coalescence in QGP can increase the J/ψ yield in HI collisions.
→ Cold nuclear matter effects are large (and poorly known).

Recently Mocsy and Petrecsky (PRL 99, 211602 (2007)) calculated quarkonium spectral functions using a potential model with a screened potential:
→ They found that J/ψ are dissolved by at most 1.2 T_c.
→ The ψ' and χ_c melt at T ≤ T_c.
→ Brings us back to the J/ψ as a “canary” for the onset of deconfinement!
→ But J/ψ may still regenerate as the plasma converts to hadronic matter.
→ And we still have cold nuclear matter effects.

Experimentally, our challenge is to isolate suppression of the J/ψ in the QGP from other mechanisms in HI collisions that affect J/ψ production.
Outline of this talk

Overview of the PHENIX quarkonium program

Quarkonium in p+p

Quarkonium in d+Au

Quarkonium in Au+Au and Cu+Cu
PHENIX

Central arms

\[ J/\psi \rightarrow e^+ e^- \]
\[ P > 0.2 \text{ GeV/c} \]
\[ |\eta| < 0.35 \]
\[ \Delta \phi = \pi \]

Muon arms

\[ J/\psi \rightarrow \mu^+ \mu^- \]
\[ P > 2 \text{ GeV/c} \]
\[ 1.2 < |y| < 2.2 \]
\[ \Delta \phi = 2\pi \]
The PHENIX J/ψ program

Systematic program at 200 GeV/A to characterize the effect of hot dense matter in the final state on J/ψ production. It consists of collisions of:

• **p+p** - Baseline J/ψ production cross sections
• **d+Au** - The cold nuclear matter baseline:
  → J/ψ breakup by collisions with projectile nucleons
  → Shadowing/CGC effects
• **Au+Au** - Hot + cold nuclear matter effects versus Npart
• **Cu+Cu** - Same as Au+Au, but much better precision at low Npart

Run 8 d+Au data contains # J/ψ:
  ~13K at y = 0
  ~90K at |y| = 1.7

That analysis is ongoing. I will not show results from it. The CNM results shown here are from Run 3.
Quarkonium in p+p
J/ψ production in p+p collisions

Our first large statistics J/ψ data set for p+p was from Run 5. It was used as the reference for the Cu+Cu and Au+Au published $R_{AA}$ data.
Run 6 provided a higher statistics J/$\psi$ data set

The mid rapidity p+p J/$\psi$ data from Run 6 were combined with the Run 5 data to provide the reference for the high p$_T$ Cu+Cu R$_{AA}$ data that will be shown later.

They were also analyzed to extract $\psi'$ yields and J/$\psi$ polarization.
The $\psi'$ vs $p_T$ in $p+p$ collisions at mid-rapidity

Within uncertainties $\psi'/(J/\psi)$ agrees with HERA-B & E789 measurements.

- $(\text{BR}^*\psi')/(\text{BR}^*J/\psi) = 1.9\%$

$\sqrt{s} = 39 \text{ GeV}$

$\text{BR}^*\sigma_{\psi'} (p_T < 7 \text{ GeV/c}, |y|<0.35) = 0.88 \pm 0.30/-0.20 \pm 0.12 \text{ nb}$

$(\text{BR}^*\psi')/(\text{BR}^*J/\psi) = 0.019 \pm 0.005 \pm 0.002$

$<0.38 \text{ 90\% CL}$
J/ψ polarization in p+p at 200 GeV

PHENIX results on J/ψ polarization at y=0, |y|=1.7.

Predictions from Lansberg & Haberzettl, hep ph/0806.4001 (2008)
→ Color singlet model with (new) s-channel cut
→ Parameters fixed using CDF data
→ Reproduces $d^2\sigma/dy/dp_T$
→ does not include effect of feed-down from $\chi_c$ & $\psi'$

Starting to see useful levels of precision for p+p polarization measurements. We hope to be able to do this also for AA collisions in high luminosity runs.
$J/\psi$ production in d+Au collisions
Cold nuclear matter effects from d+Au data

We want to be able to extract from our d+Au data a prediction of the cold nuclear matter $R_{AA}$ for A+A.

The first exploration of this, using Run 3 d+Au data, was published in PRC 77, 024912(2008).

Our method was to take a calculation by Ramona Vogt of production of J/$\psi$ from cold nuclear matter effects using two shadowing models, with a J/$\psi$ absorption cross section added to account for destruction of the forming J/$\psi$ by collisions with projectile nucleons.

The absorption cross section was determined by fitting it to the PHENIX $R_{dAu}$ data.

Best fit dissociation cross section for the d+Au rapidity distribution:

EKS: \( \sigma_{\text{breakup}} = 2.8^{+1.7}_{-1.4} \) mb

NDSG: \( \sigma_{\text{breakup}} = 2.2^{+1.6}_{-1.5} \) mb

This can then be used to calculate the CNM only RAA for Au+Au at mid and forward rapidity.

**However** – since the absorption cross section is the same at all rapidities, the ratio of Au+Au \( R_{AA} \) at \( y=1.7 \) to \( y=0 \) is entirely a prediction of the shadowing model!
NOTE: Mistake in extracting $\sigma_{\text{breakup}}$ from d+Au data

- The data points, statistical and systematic uncertainties in the previous slide are all **correct**.
- The one standard deviation **uncertainty band** for the breakup cross section contains a mistake.
- The band does not account for all the systematic uncertainties, as intended in the paper.
- Correctly including the systematic uncertainties will make the band larger.
- This mistake affects all of the cold nuclear matter projections shown in this talk.
- **We expect to release corrected values soon.**
Ad hoc fits to d+Au centrality dependence

Fit the J/ψ breakup cross section in the Vogt calculations to the d+Au $R_{AA}$ vs centrality separately for $y=0$ and $|y|=1.7$. This yields:

<table>
<thead>
<tr>
<th></th>
<th>y=0</th>
<th>$\sigma_B$=2.3 $+2.1–1.8$ mb</th>
<th>y=1.7</th>
<th>$\sigma_B$=3.9+$1.3-1.2$ mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>EKS</td>
<td></td>
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<tr>
<td>NDSG</td>
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</tbody>
</table>

Using different breakup cross sections at forward and mid rapidity means that we are no longer using a self-consistent model to fit all of the d+Au data.

But it gives us parameterizations of the d+Au data at $y=0$ and $|y|=1.7$ that are independent of each other and have independent uncertainties.

We then estimate the Cu+Cu and Au+Au $R_{AA}$ due to CNM effects alone by using the fitted absorption cross section at each rapidity, in concert with the appropriate PDF's from EKS or NDSG.

**We will compare these with Cu+Cu and Au+Au data later.**
J/$\psi$ Production in Au+Au and Cu+Cu
QGP effects on J/$\psi$ production

Stronger J/$\psi$ suppression at forward rapidity in Au+Au. Why?

• Stronger CNM suppression at $y=1.7$?
• Color screening difference?
• Larger regeneration at $y=0$ than $y=1.7$?

Three potentially compensating effects!
→ Too many poorly controlled parameters.

What can we do experimentally to help?

• CNM baseline $R_{AA}$ – d+Au
• Measure open charm cross sections more precisely – poorly known from data
• Look for effects of open charm flow
• Better experimental measurements in turn-on region at Npart ~ 50 – Cu+Cu
The turn-on region: Add J/ψ from Cu+Cu collisions

Cu+Cu has the advantage of providing much better statistical precision and much lower systematic uncertainties than Au+Au for the region of Npart ~ 4-100.

The critical energy density for deconfinement is expected to be reached for $\sqrt{s}=200$ GeV collisions at ~ Npart ~ 40-50.
Comparison with CNM baseline

Cu+Cu and Au+Au data compared with **CNM baseline** from ad hoc fits to d+Au (Vogt EKS calculations fitted independently at mid and forward/backward rapidity to d+Au centrality dependence).

Note that the **ratio** (lower panel) of forward rapidity to mid rapidity data points lies inside the **1-sigma band** (dashed lines) around the CNM best estimate from d+Au.

The different suppression at forward and mid rapidity could be due entirely to CNM effects!
Same as the previous slide, but **CNM baseline** this time is from ad hoc fits to d+Au (Vogt NDSG calculations fitted independently at mid and forward/backward rapidity to d+Au centrality dependence).

Very similar conclusion to the EKS case: The ratio of forward to mid rapidity $R_{AA}$ could be from CNM alone.
Correcting for CNM baseline

Now we plot in the lower panel the $R_{AA}$ divided by the CNM baseline. This uses the ad hoc fit to d+Au with the Vogt EKS calculations.

We do this for Cu+Cu only - the CNM uncertainty is too large to be useful for the Au+Au case.
Same as for the previous slide, except that the ad hoc fit to d+Au with the Vogt NDSG calculations is used.

Very similar conclusion to the previous slide.

We see that at both forward and mid rapidity the Cu+Cu $R_{AA}$ is found to be consistent with CNM effects alone within 15% uncertainties up to $N_{part} \sim 50$.

This corresponds to

$\varepsilon_{\text{Bjorken}} \tau \sim 1.5 \text{ GeV/fm}^2/c$

We need a better CNM reference to go beyond that.
Higher $p_T$: PHENIX Cu+Cu $R_{AA}$ data

PHENIX Minbias Cu+Cu $R_{AA}$ extended to higher $p_T$ using the combined Run 5 and Run 6 pp data as the reference.
Higher $p_T$: PHENIX Cu+Cu $R_{AA}$ data

PHENIX Minbias Cu+Cu $R_{AA}$ extended to higher $p_T$ using the combined Run 5 and Run 6 pp data as the reference.

The PHENIX data seem flatter with $p_T$ than the STAR 0-60% centrality data.
Comparison with several models of $p_T$ dependence

AdS/CFT ("hot wind") - more suppression at high $p_T$:

Liu, Rajagopal, Wiedemann  
PRL 98, 182301 (2007)

Regeneration (2-component):  
Zhao, Rapp  
PLB 664, 253 (2008) & private communication

Equilibrating Parton Plasma:  
Xu, Kharzeev, Satz, Wang,  
hep-ph/9511331

Gluonic dissoc. & flow:  
Patra, Menon, nucl-th/0503034

Cronin – less suppression at higher $p_T$:  
→ need Run 8 d+Au data as a guide
J/ψ flow?

J/ψ’s from regeneration should inherit the large charm-quark elliptic flow.

This is a first measurement of J/ψ $v_2$, made at both mid- and forward-rapidity.

Very limited statistics, no conclusion can be drawn.

→ Need more data for this measurement.

→ But it is do-able!
Where do we stand?

- We have marginally good enough p+p reference statistics at high $p_T$.  
  → This may become a problem as the Spin focus moves to 500 GeV

- Our Run 3 d+Au CNM reference data are statistically inadequate.

- A new CNM analysis based on the 40 x larger yields from Run 8 d+Au data is underway – hope to have preliminary result by QM09.

- We have decent Au+Au and Cu+Cu statistics to go with the improved d+Au statistics from Run 8. We will have a well defined CNM baseline and good $R_{AA}$ data to go with it.

- In future, we also expect:
  → Higher $p_T$ - more integrated luminosity – coming next few years
  → $J/\psi$ flow - more integrated luminosity – coming next few years
  → $J/\psi$ polarization - more luminosity – coming next few years
  → Better open charm cross sections  - Si upgrades – also coming
  → Other quarkonia
Backup
PHENIX & STAR Preliminary Y p+p Cross Sections

1st Upsilons at RHIC

BR*dsig/dy (pb)

Rapidity

STAR QM06 Preliminary
PHENIX QM05 Preliminary
NLO MRST - R. Vogt