Charmonium Production in Heavy Ion Collisions

Physics of Charmonium Production at RHIC

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Outline

- Experimental Capabilities to measure charmonium at RHIC
  - PHENIX
  - STAR
- Charmonium Production in heavy ion collisions
  - Charmonium Suppression or Enhancement?
  - How we can disentangle various factors contributing to the production?
Charmonium Production in Heavy Ion Collisions

PHENIX Detector

- 3 global detectors (centrality)
- 2 central spectrometers $J/\psi \rightarrow \mu\mu$
- 2 forward spectrometers $J/\psi \rightarrow e^+e^-$

Electron Measurement in PHENIX

- $-0.35 < \eta < 0.35$, $d\phi = \pi/2 \times 2$
- charged particle tracking
  - DC / PC / TEC
- hadron rejection at $10^4$ level in Au+Au central collisions
  - RICH / EMCaL / TEC
- good momentum resolution

Marzia Rosati, Iowa State (ITP QCD-RHIC Conference 4/10/02)
Muon Measurement in PHENIX

- $1.2 < \eta < 2.4$ (north), $1.2 < \eta < 2.2$ (south), full $\phi$ coverage
- tracking with 3 stations of chambers in magnetic field
- muon ID with 5 layers of steel absorber and Iarocci tubes
- $\psi$ low energy cutoff at 2 GeV/c

PHENIX with 2 forward arms

PHENIX Measurement Capabilities

<table>
<thead>
<tr>
<th></th>
<th>central (electron) arms</th>
<th>forward (muon) arms</th>
</tr>
</thead>
<tbody>
<tr>
<td>rapidity coverage</td>
<td>$-0.35 &lt; y &lt; 0.35$</td>
<td>$1.2 &lt; y &lt; 2.4$ (north)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.2 &lt; y &lt; 2.2$ (south)</td>
</tr>
<tr>
<td>$J/\Psi$ acceptance</td>
<td>$0.8$ % of $B_{ee}\sigma$</td>
<td>$4.3$ % of $B_{mm}\sigma$ (per arm)</td>
</tr>
<tr>
<td></td>
<td>($4%$ of $B_{ee}\sigma$ in $</td>
<td>y</td>
</tr>
<tr>
<td>$\Upsilon$ acceptance</td>
<td>$1.7$ % of $B_{ee}\sigma$</td>
<td>$3.0$ % of $B_{mm}\sigma$ (per arm)</td>
</tr>
<tr>
<td></td>
<td>($5%$ of $B_{ee}\sigma$ in $</td>
<td>y</td>
</tr>
<tr>
<td>$J/\Psi$ mass resolution</td>
<td>20 MeV</td>
<td>105 MeV</td>
</tr>
<tr>
<td>$\Upsilon$ mass resolution</td>
<td>160 MeV</td>
<td>180 MeV</td>
</tr>
</tbody>
</table>
Charmonium Production in Heavy Ion Collisions

Detector Acceptance for $J/\psi \rightarrow \text{dileptons}$

- Acceptance is the percentage of $J/\psi$ which have both leptons going through the detector.
- Using the p-N cross section predictions as calculated at NLO for the transverse momentum and rapidity distribution.

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

$$\frac{N_{J/\psi \rightarrow \mu^+\mu^-} \text{(accepted)}}{N_{J/\psi \text{total}}} = 8.6\%$$

For $J/\psi \rightarrow e^+e^-$

$$\frac{N_{J/\psi \rightarrow e^+e^-} \text{(accepted)}}{N_{J/\psi \text{total}}} = 0.75\%$$

Simulated performance of PHENIX spectrometers

- Simulated performance of PHENIX spectrometers.
Charmonium Production in Heavy Ion Collisions

Expected Quarkonium Statistics in PHENIX

- In one year of RHIC running at full luminosity
- Assuming no anomalous suppression

<table>
<thead>
<tr>
<th></th>
<th>PHENIX</th>
<th>PHENIX</th>
<th>PHENIX</th>
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<tbody>
<tr>
<td></td>
<td>Muon North</td>
<td>Muon South</td>
<td>Electron</td>
</tr>
<tr>
<td>$Y_{CM}$</td>
<td>1.2 – 2.4</td>
<td>1.2 – 2.2</td>
<td>-0.35 – 0.35</td>
</tr>
<tr>
<td>$J/\Psi$</td>
<td>640k</td>
<td>610k</td>
<td>55k</td>
</tr>
<tr>
<td>$\Psi'$</td>
<td>11.5k</td>
<td>10.5k</td>
<td>900</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td>382</td>
<td>331</td>
<td>----</td>
</tr>
</tbody>
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Charmonium in Central & Forward Arms

- simultaneous access to regions with different energy densities
  - rapidity density of produced particles as a measure
  - good test if suppression is a function of local energy density
Charmonium Production in Heavy Ion Collisions

**STAR Electron Measurement**

- $-1 < \eta < 1$, $d\phi = 2\pi$
- Particle Identification
  - EMCAL, $dE/dx$ in SVT and TPC

**Charmonium Measurement in STAR**

- $J/\psi$ is accepted if both electrons $P > 1.5\text{GeV}/c$ and fall into the EMC
- 40K $J/\psi$ for 1 year of running at full luminosity with signal/background=1:3
Charmonium Production in A+B Collisions

- The cross section can be written as:
  \[ d\sigma_{AB}(y,p_T) = A \cdot B \cdot d\sigma_{NN}(y,p_T) \cdot S(y,p_T) \]

  - Elementary nucleon-nucleon cross section
  - Suppression factor
    - initial state (gluon shadowing)
    - final state (ordinary nuclear absorption and medium effect)

Do we understand the basic production mechanism?

- The production mechanism of charmonium is not yet well understood.
- We need a good measurement of J/ψ cross section in p+p at RHIC.
- Data from RHIC can help to test QCD based models.
Charmonium Production in Heavy Ion Collisions

- In the past few years new results in pp collisions have revealed the severe shortcoming of early charmonium production models.
  Large discrepancy found in $J/\psi$, $\psi'$ production at Tevatron in early '90 (~ x 50) compared to leading order Color Singlet model.

- The Non Relativistic Quantum Chromo Dynamics (NRQCD) formalism factorizes the short distance physics of the heavy quark creation and the long distance physics of bound state formation.
  Within NRQCD, heavy quark pair can also be produced in a Color Octet state and radiate soft gluons at late times after quark pair has expanded to the charmonium size.

$p\bar{p} \rightarrow J/\psi + X$ at the Tevatron
At large $p_T$ ($\gg m_c$) production is dominated by gluon fragmentation. Gluon is on shell and transverse:

\[
\frac{d\Gamma}{d\cos\theta} = 1 + \alpha \cos^2\theta
\]

For transverse polarization

\[\alpha = 1\]

Maybe different power counting needed in NRQCD? (Fleming)
Charmonium Production in Heavy Ion Collisions

- Charmonium production and open charm in pA collisions will help disentangle the gluon shadowing, from the charmonium nuclear absorption and distinguish between cold nuclear matter versus hot (deconfined) nuclear matter.

Charmonium enhancement?

- Statistical hadronization coalescence models and dynamical models for formation in QGP predict J/ψ enhancement.
- Measuring open charm will be an important control.
Charmonium Production in Heavy Ion Collisions

PHENIX Upgrade

- Ultimately we want to detect open charm “directly” via displaced vertices
- Development of required Si tracking for PHENIX well underway

What to expect for Run 2?

- 170M events sampled (minbias + triggered)
- In the absence of anomalous suppression or additional thermal production at RHIC, and assuming

\[ \sigma(pp \rightarrow J/\psi) = 3.3 \times 10^{-6} \text{ b} \]

we will reconstruct of order:

- \( \sim 100 \ J/\psi \rightarrow ee \)
- \( \sim 500 \ J/\psi \rightarrow \mu\mu \)

Note: there is a large uncertainty (both in production and reconstruction) in this estimate
In the future

- Full exploration of J/Ψ production versus “N\text{binary}” ~ A(b)\ast A(b) via
  - A long run with Au-Au
  - A series of shorter light ion runs
- p-A or d-A running

<table>
<thead>
<tr>
<th>Species</th>
<th>Number of J/Ψ/s</th>
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<tbody>
<tr>
<td>O O</td>
<td>1.15E+05</td>
</tr>
<tr>
<td>SiSi</td>
<td>1.44E+05</td>
</tr>
<tr>
<td>CuCu</td>
<td>1.56E+05</td>
</tr>
<tr>
<td>II</td>
<td>1.73E+05</td>
</tr>
<tr>
<td>AuAu</td>
<td>1.79E+05</td>
</tr>
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</table>

Experimental Plan

- To establish that the (to be observed) charmonium suppression/enhancement pattern results from QGP
  - Study vs. p_T
  - Study vs. centrality
  - Study in lighter systems
  - Study vs. a control
    - (a vector meson that should not be suppressed/enhanced, the Upsilon)
How can theorists help?

- Detailed predictions of the $J/\psi$ suppression and enhancement
  - Their rapidity dependencies
  - Their $dN/d\eta$ dependencies
  - Their consequences on other observables
  - etc. etc.

- Detailed calculation to estimate temperature will various quarkonium states i.e. if all $J/\psi$ melt are we at $T_c$.

Conclusions

- PHENIX and STAR have the capability to measure charmonium production at RHIC
  - wide rapidity coverage
  - high statistics
  - variety of beam combination

- the future looks bright! Both theorists and experimentalists have a lot of work to do