System size dependence of J/ψ nuclear modification from PHOENIX

Matt Durham
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Charmonium production in the nucleus

Charm production (pQCD) + hadronization

$1.2 < |y| < 2.4$

$p + p \rightarrow J/\psi + X$

$\sqrt{s} = 200 \text{ GeV}$

Global uncertainty = 10%

PRD 85 092004 (2012)
Charmonium production in the nucleus

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√s=200 GeV
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Charm production (pQCD) + hadronization + color screening

PRC 84 054912 (2011)
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Charm production (pQCD) + hadronization

-2.2 < y < -1.2 (8.3%)
l_\parallel < 0.35 (7.8%)
1.2 < y < 2.2 (8.2%)

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Charm production (pQCD) + hadronization + color screening
Charmonium production in the nucleus

$R_{dAu}$ data:
- $-2.2 < y < -1.2$ (8.3%)
- $|y| < 0.35$ (7.8%)
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Together have >350 citations
Charmonium production in the nucleus

PDF Modifications

Vogt, PRC 92 034909 (2015)

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**“Breakup” cross section**

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Charmonium production in the nucleus

Wide range of physical mechanisms all describe data.
Varying the initial state

Vary target nucleus:
Changes magnitude of PDF modifications

Vary path length charm precursor state travels inside nucleus
->Affects initial state energy loss

\[ r = 1.2 \, fm \cdot A^{1/3} \]
Varying the final state

Vary projectile:
Changes density of final state particles, especially in backward direction.

![Graph showing varying final state densities](image)

**PHENIX**

- **p+p**
  - Many Runs
  - Run-15

- **p+Al**
  - Run-15

- **p+Au**
  - Run-15
  - Run-3,8,16

- **d+Au**
  - Run-14

**Comovers**

**Short-lived plasma phase**

**“Breakup” cross section**
- Vary projectile:
- Changes density of final state particles, especially in backward direction.

Designed to measure quarkonia down to $p_T = 0$ through dilepton decays at mid and forward rapidity, and open HF through semileptonic decays.

Muons: $1.2 < |y| < 2.2$,
-Tracked with silicon, wire chambers
-Further muon ID with layers of steel and streamer tubes

Electrons: $|y| < 0.35$,
-Tracked with DC, PC
-ID with RICH, EmCal

$$x \approx 3 \times 10^{-2}$$
Near anti-shadowing/shadowing crossover

$$x \approx 8 \times 10^{-2}$$
Anti-shadowing region

Au, Al

$d, p, ^3\text{He}$
Quarkonia in $p+p$ collisions – Run 15

Total Fit:

Crystal Ball function for $J/\psi(1S)$ and $\psi(2S)$

- $M_{\psi(2S)} - M_{J/\psi}$ constrained to PDG value
- Crystal Ball $n$, $\alpha$ parameters same

Background is sum of like sign + exponential

*FVTX silicon tracker not necessary for $J/\psi$, but is necessary to clearly separate $\psi(2S)$ peak
Quarkonia in $p+p$ collisions – Run 15

Run-15 $p+p \sqrt{s} = 200$ GeV

-2.2 < $y$ < -1.2

Run-15 $p+p \sqrt{s} = 200$ GeV

1.2 < $y$ < 2.2
Quarkonia in $p+p$ collisions – Run 15

- Consistent with older data that was recorded with thinner hadron absorber
- Consistent forward/backward

$B_{ll}d\sigma/dy$ (nb)

$p+p \sqrt{s}=200$ GeV

- 2006+2008
- 2015

Quarkonia in $p+p$ collisions
Quarkonia in $p$+Al collisions – Run 15

Run-15 p+Al $\sqrt{s} = 200$ GeV

$-2.2 < y < -1.2$ Al-going

Inclusive $J/\psi \sqrt{s_{NN}}=200$ GeV

PHENIX preliminary

Run-15 p+Al $\sqrt{s} = 200$ GeV

$1.2 < y < 2.2$ p-going

PHENIX preliminary
New results: $p_T$ dependence

Inclusive $J/\psi$ $\sqrt{s_{NN}}=200$ GeV
$-2.2<y<-1.2$ (A-going)

$R_{p+A}$

$p_{T}$ (GeV/c)

Inclusive $J/\psi$ $\sqrt{s_{NN}}=200$ GeV
$1.2<y<2.2$ (p-going)

$R_{p+A}$

$p_{T}$ (GeV/c)
New results: $p_T$ dependence

Some evidence of Cronin broadening
Overall, effects are small.
Quarkonia in \( p+Au \) collisions – Run 15

**Run-15 \( p+Au \) \( \sqrt{s} = 200 \text{ GeV} \)**

-2.2 \( y \) \( < \) 1.2 

\( \text{Au-going} \)

**\( \mu^+ \mu^- \) mass (GeV/c^2)**

\[ \text{raw counts/(50 MeV/c}^2) \]

**Run-15 \( p+Au \) \( \sqrt{s} = 200 \text{ GeV} \)**

1.2 \( y \) \( < \) 2.2 

\( \text{p-going} \)

\[ \text{raw counts/(50 MeV/c}^2) \]

**Inclusive \( J/\psi \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \)**

**\( R_{AB} \)**

**\( y \) \text{ rapidity}**

Inclusive J/\( \psi \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

**\( \mu^+ \mu^- \) mass (GeV/c^2)**

**\( \text{raw counts/(50 MeV/c}^2) \)**
New results: $p_T$ dependence

- $p_T$ dependence
- $p+Au$
- PHENIX preliminary

Inclusive $J/\psi$ \( \sqrt{s_{NN}}=200 \text{ GeV} \)

$-2.2<y<-1.2$ (A-going)

$1.2<y<2.2$ (p-going)
New results: $p_T$ dependence

$p+A$, $p+Au$ differences at low $p_T$
New results: $p_T$ dependence

Consistent with $d+Au$ within uncertainties.
Quarkonia in $^3$He+Au collisions – Run 14

Run-14 $^3$He+Au $\sqrt{s} = 200$ GeV

-2.2 < $y$ < -1.2  
Au-going

$^3$He+Au

Inclusive $J/\psi$ $\sqrt{s_{NN}}$=200 GeV

$R_{AB}$

0  0.5  1  1.5

-2  0  2

rapidity

Run-14 $^3$He+Au $\sqrt{s} = 200$ GeV

1.2 < $y$ < 2.2  
$^3$He-going

$\psi$

Inclusive J/

Quarkonia in $^3$He+Au collisions – Run 14
New results: $p_T$ dependence

$R_{3He+Au}$

Inclusive $J/\psi$, $\sqrt{s_{NN}}=200$ GeV

-2.2 < $y$ < -1.2 (A-going)

1.2 < $y$ < 2.2 ($^3$He-going)
New results: $p_T$ dependence

Consistent with $p$+Au within uncertainties.
$R_{AB}$ vs N_{part} in small systems

Inclusive J/$\psi$ \( \sqrt{s_{NN}} = 200 \) GeV
-2.2 < $y$ < 1.2 (Al/Au-going)

1.2 < $y$ < 2.2 (p/d/$^3$He-going)
$R_{AB}$ vs N_{part} in small systems

Inclusive $J/\psi$ \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

-2.2 < $y$ < 1.2 (Al/Au-going) 

p+Al
p+Au
d+Au PRL 111 202301 (2013)

$^3$He+Au

N_{part}

0 10 20

0 0.5 1 1.5

$R_{AB}$

p+Al
p+Au
d+Au PRL 111 202301 (2013)

$^3$He+Au

N_{part}

0 10 20

0 0.5 1 1.5

$R_{AB}$

Charged hadrons

-2.2 < $y$ < 1.2, p+Au (Au-going)
-2.2 < $y$ < 1.2, p+Al (Al-going)
1.2 < $y$ < 2.4, p+Au (p-going)
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$^{h_1}$, 2.5 < $p_T$ < 5 GeV/c

10% global sys. uncertainty

PHENIX preliminary
$R_{AB}$ vs $N_{part}$ in small systems

**Charged hadrons**

- Charged hadrons suppressed
- $J/\psi$ suppressed
- Suggests initial state effect

**Shadowing** may be dominant effect here
R_{AB} vs N_{part} in small systems

Charged hadrons

Forward rapidity: relatively low hadron density
- Charged hadrons suppressed
- J/\psi suppressed
Suggests initial state effect
shadowing may be dominant effect here

Backward rapidity: relatively high hadron density
Charged hadrons enhanced
J/\psi suppressed
Suggests final state effect
“breakup” may be dominant effect here

 Charged hadrons

- -2.2<\eta<-1.2, p+Au (Au-going)
- 1.2<\eta<2.4, p+Au (p-going)
- 2.5<p_T<5 GeV/c

10% global sys. uncertainty
Comparing charm across small systems

Open HF muons

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Summary

• PHENIX has measured $J/\psi$ production across a wide range of system size

• Similar effects are seen in forward direction for all small systems with the same nuclear target, suggesting initial state effects in nucleus dominate
  • Shadowing and/or energy loss are prime suspects

• Comparisons with open charm and hadron production suggests final state effects on $J/\psi$ are significant at backwards rapidity, and very important for excited states

• Centrality dependence in small systems coming soon