J/Psi Production

E.Chudakov

\(^1\)JLab

For Hall C Summer Workshop, August 2006
Outline

1 Physics Motivations
   - Introduction
   - Photoproduction Mechanisms
   - $\psi N$ Cross Section

2 Program for 12 GeV
   - Overview
   - Conclusion

3 Appendix
   - Supplementary pages
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1. Physics Motivations
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3. Appendix
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Charm at 12 GeV

\[ J/\psi : 32 \]

announced on Nov, 1974

CEBAF at 12 GeV crosses the charm \( \gamma N \) threshold:

<table>
<thead>
<tr>
<th>reaction</th>
<th>( E_\gamma ) GeV</th>
<th>useful decay mode</th>
<th>BR</th>
<th>cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma p \rightarrow \eta_c(1S)p )</td>
<td>7.7 GeV</td>
<td>( \eta_c(1S) \rightarrow p\bar{p} )</td>
<td>0.12%</td>
<td>-</td>
</tr>
<tr>
<td>( \star \gamma p \rightarrow J/\psi(1S)p )</td>
<td>8.2 GeV</td>
<td>( J/\psi(1S) \rightarrow e^- e^+ / \mu^- \mu^+ )</td>
<td>6.0%</td>
<td>11. 0.5±0.2</td>
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<tr>
<td>( \star \gamma p \rightarrow \Lambda_c^+ D^0 )</td>
<td>8.7 GeV</td>
<td>( D^0 \rightarrow K^+ \pi^- )</td>
<td>4.0%</td>
<td>20. ~ 63.±30.</td>
</tr>
<tr>
<td>( \gamma p \rightarrow \chi_{c0}(1P)p )</td>
<td>9.6 GeV</td>
<td>( \chi_{c1}(1P) \rightarrow K^+ K^- )</td>
<td>0.71%</td>
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<td>( \gamma p \rightarrow \chi_{c2}(1P)p )</td>
<td>10.3 GeV</td>
<td>( \chi_{c1}(1P) \rightarrow J/\psi(1S) \gamma )</td>
<td>13.0%</td>
<td></td>
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<tr>
<td>( \gamma p \rightarrow \psi(3770)p )</td>
<td>11.0 GeV</td>
<td>( \psi(3770) \rightarrow e^- e^+ / \mu^- \mu^+ )</td>
<td>0.8%</td>
<td>21. 1.1±0.4</td>
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<tr>
<td>( \gamma p \rightarrow D\bar{D}p )</td>
<td>11.1 GeV</td>
<td></td>
<td></td>
<td>20. ~ 63.±30.</td>
</tr>
</tbody>
</table>
Existing Data on Charm Photoproduction

$\gamma p \rightarrow J/\psi(1S)p \quad E_\gamma > 11 \text{ GeV}$

$\gamma p \rightarrow c\bar{c} + X \quad E_\gamma > 20 \text{ GeV}$

*Only a part of the experimental results are presented*
What is special about $J/\psi$ photoproduction?.. 

- No $c\bar{c}$ in nucleons: $c\bar{c}$ production only via gluons from the target
- Small size
- Important features of charm photoproduction:

\[
\begin{align*}
 m_c & \approx 1.5 \text{ GeV} > \Lambda_{QCD} \\
r_\perp & \approx \frac{1}{m_c} = 0.13 \text{ fm}
\end{align*}
\]

At $E_\gamma \approx 10$ GeV:

\[
\begin{align*}
 \ell_{\text{coh}} &= \frac{2E_\gamma}{4m_c^2 + Q^2} \approx 0.4 \text{ fm} \\
\ell_F &\approx \frac{2}{m_{\psi} - m_{J/\psi}} \left[ \frac{E_{J/\psi}}{2m_c} \right] \sim 1 - 2 \text{ fm} \\
b &\sim \frac{1}{\sqrt{-t}} \approx 0.2 \text{ fm}
\end{align*}
\]

- $c\bar{c}$ is a small size probe of the gluon field of the target
- VDM: $\ell_{\text{coh}} > 1$ fm ($E_\gamma > 25$ GeV)
- Coherent on heavy nucleus: $\ell_{\text{coh}} > 4$ fm ($E_\gamma > 100$ GeV)
- $E_\gamma \sim 10$ GeV $\ell_{\text{coh}} \ll d_{\text{nucleus}}$, $\ell_F < d_{\text{nucleus}}$ no shadowing effects, $c\bar{c}=J/\psi$ propagation through nuclear material
Photoproduction and \( \psi \)-N interaction

- Similarity between the two processes
- Check the model on photoproduction
Exclusive $J/\psi$ production in $ep$: High vs. low $W$

- Unique probe of small-size gluon configuration in proton
- Dipole moment $\sim r_{c\bar{c}}$
- "Color transparency"

$W \gg M_{c\bar{c}}^2$ - HERA, FNAL

- Momentum transfer $|\Delta_\perp| < 1 \text{ GeV/c}$,
  $\Delta_\parallel$ - small
- Gluon GPD $x_1 \sim x_2 \ll 1$
- "Transverse gluon imaging"

$W \sim M_{c\bar{c}}^2$ - JLab

- Large $\Delta_\parallel$, large $|t_{\text{min}}|$,
- Gluon GPD $x_1 \neq x_2 \sim 1$ ("skewness")
- Probes transition form factor of gluon dipole moment at high $t$
**Physics Motivations**

Program for 12 GeV

Appendix

**t-Dependence: dipole approximation**


\[ \gamma + p \rightarrow J/\psi + p, \langle E_\gamma \rangle = 100 \text{ GeV} \]

\[ \gamma + p \rightarrow J/\psi + p, \langle E_\gamma \rangle = 11 \text{ GeV} \]

\[ x \ll 1 \quad \frac{d\sigma_{\gamma \rightarrow J/\psi p}}{dt} \propto \frac{H_g(x,t)^2}{H_g(x,0)^2} \]

⇒ FT ⇒ spacial distribution

Argued: dipole approximation:

\[ H_g(x, t) \propto (1 - t/m_g^2)^{-2} \]

\[ m_g^2 \approx 1.1 \text{ GeV}/c^2 \text{ at } x \sim 0.1 \]

\[ \langle \rho^2 \rangle = 8/m_g^2 \approx 0.28 \text{ fm}^2 \]

\[ \frac{d\sigma_{\gamma \rightarrow J/\psi p}}{dt} \propto (1 - t/1.0 \text{GeV}^2)^{-4} \]

\[ \langle \rho^2 \rangle = 0.4 \text{ fm}^2 \]

\[ \langle \rho^2 \rangle = 0.2 \text{ fm}^2 \]

\[ \langle \rho^2 \rangle = 0.0 \text{ fm}^2 \]

\[ x \]

\[ \times 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]

\[ < \rho^2 > [\text{fm}^2] \]

\[ \alpha' \]

pion cloud

HERA

fixed target

E. Chudakov JLab J/Psi Production
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**t-Dependence: dipole approximation**


\[
\frac{d\sigma_{\gamma p \rightarrow J/\psi p}}{dt} \propto \frac{H_g(x,t)^2}{H_g(x,0)^2}
\]

\[x \ll 1 \Rightarrow FT \Rightarrow \text{spacial distribution}\]

Argued: dipole approximation:

\[H_g(x, t) \propto (1 - t/m_g^2)^{-2}\]

\[m_g^2 \approx 1.1 \text{ GeV/c}^2 \text{ at } x \sim 0.1\]

\[\langle \rho^2 \rangle = \frac{8}{m_g^2} \approx 0.28 \text{ fm}^2\]

\[
\frac{d\sigma_{\gamma P \rightarrow J/\psi P}}{dt} \propto (1 - t/1.0 \text{GeV}^2)^{-4}
\]

**HERA: exponential provides a better fit**

\[\alpha' \quad \text{pion cloud}\]

\[\langle \rho^2 \rangle \quad \text{HERA}\]

\[\alpha' \quad \text{fixed target}\]
Calculation of $\sigma(\psi N)_{tot}$ and $\psi$ Photoproduction


- VDM extended to a multi-channel case (account for $J/\psi$ $\psi'$ mixing)
- dipole interaction
- accurate setting of the wave functions etc
- no tune to $J/\psi$ data

- Photoproduction: good agreement at high energies
- $\sigma(\psi N)$ - extrapolation to low energies?
Experiment: Low Energy Photoproduction

Cornell and SLAC:

SLAC:
Double Arm: published
Single arm: unpublished
large errors <12 GeV

\[ \sigma: \text{SLAC} \approx \text{Cornell} \]

\[ \frac{d\sigma}{dt} = A \cdot \exp Bt \]

\begin{align*}
E_\gamma \text{ GeV} & \quad 11.19 \\
B (\text{GeV})^{-2} & \quad 1.13 \pm 0.18 \quad 2.9 \pm 0.3
\end{align*}

Indication: a slow decrease of cross section towards the threshold
Production near threshold

Should probe the particle distributions at high $x$. Several constituents from the target should take part. **No** detailed calculation exists so far.

Qualitative arguments on $\sigma(E_\gamma)$


$$\frac{d\sigma}{dt} = N_2 g v \left( \frac{1-x}{R^2 M^2} \right) F_1 \left( \frac{t}{4} \right) (s - m_p^2)^2$$

$$\frac{d\sigma}{dt} = N_3 g v \left( \frac{1-x}{R^4 M^4} \right) F_1 \left( \frac{t}{9} \right) (s - m_p^2)^2$$

where: $x = \frac{s_{\text{thresh}} - m_p^2}{s - m_p^2}$, $M = 2 m_c$, $R \approx 1/m_c$

- Applicable at $x \sim 1 \Rightarrow E_\gamma < 12 - 15 \text{ GeV}$
- The factors $N$ - fit to the data
Production near threshold

- “2-gluon” fit to high E points
- “3-gluon” fit to 2 low energy points
Production near threshold

- “2-gluon” fit to high E points
- “3-gluon” fit to 2 low energy points

Subthreshold experiment E-03-008

No J/ψ observed
Large cross section at threshold ruled out

Are the old data correct?
ψN Interactions

ψN interactions: attention from theorists
Practical interest: J/ψ deficit = signature for QGP

Features:
- small color dipole interacting with nuclear matter
- breakup by excitation to D\overline{D} \Delta E \sim 0.6 \, GeV
- possible loss due to ψ+N→Λ_c^+\overline{D} at \, P_\psi > 1.8 \, GeV/c

At low energy:
- attractive potential (Van der Waals) (Luke,Manohar,Savage,1992)
  \, E_{binding} \sim 8 \, MeV
- \, \sigma(ψN)_{tot} \sim 7 \, mb \, (Brodsky,Miller,1997), falling with energy

How to compare these predictions with experiment?
ψN measurements and interpretations

Experimental situation: was confusing. **Now improving.**

Methods:

- From photoproduction, using VDM, optical theorem and assumptions on Re(A)/Im(A) (∼ 0)
  
  - 20 GeV: $d\sigma(J/\psi N \rightarrow J/\psi N)/dt \bigg|_{t=0} \sim 25 \, \mu b$
  
  - 20-200 GeV: $\sigma(J/\psi N)_{tot} \sim 1 \, mb \Rightarrow 2.8 - 4.1 \, mb$

- From A-dependence of photo and hadro-production, using Glauber model and considering : color transparency effects at $l_{coh}, l_F > R_{target}$
  
  - 20 GeV $\gamma A$: $\sigma(J/\psi N)_{abs} \approx 3.5 \pm 0.8 \pm 0.6 \, mb$
  
  - 80-150 GeV $pA$: $\sigma(J/\psi N)_{abs} \approx 7 \, mb \Rightarrow 3.6 \, mb$
  
  - 400-450 GeV $pA$: $\sigma(J/\psi N)_{abs} \approx 4.3 \pm 0.3 \, mb$
SLAC results on $\gamma A \rightarrow \psi + X$

Single spectrometer measurements  
(From: R.Andersen et al PRL 38, 263 (1977))

- **20 GeV $e^-$** on Be and Ta targets
- **20 GeV** spectrometer, $\mu^-$, $\mu$-filter
- High statistics on a high background
- The background was calculated:
  - decays
  - Bethe-Heitler

\[ \sigma(\text{Be})/\sigma(\text{Ta}) = 1.21 \pm 0.7 \]

$\Rightarrow \sigma_{\psi N} = 3.5 \pm 0.8 \text{ mb}$

Attempts to measure the cross section down to 9 GeV: unpublished
Program for JLab at 11 GeV

(1) Measure $\sigma(J/\psi N)_{abs}$ using A-dependence of $\sigma(\gamma A \rightarrow J/\psi X)$

Advantages (to SLAC):
- lower energy - smaller effects from $l_{coh}, l_F$
- low background for $J/\psi$
- reconstructed kinematics of $J/\psi$
- separation of coherent and incoherent production
- several targets used

Disadvantages comparing to the SLAC experiment:
- lower energy - stronger effect from Fermi motion

(2) Measure $\frac{d\sigma}{dt}(E)$ for $\gamma p \rightarrow J/\psi p$

Goals:
- Provide Fermi-motion correction for (1)
- Measurement in a new energy range (3-gluon exchange?)

(3) Look for more exotic effects:
- “Hidden color” $\gamma D \rightarrow J/\psi pn$
- Bound state: peak in $\sigma/V$ at $x=1$ (threshold)
J/ψ(1S) on nuclear targets

σ_ψN can be derived from the A-dependence of the cross-section Hall C setup:

- LH, LD 15 cm, with a 6%RL radiator
- Heavy targets of 7.7%RL (≈ 6% radiator + LH target)
- For J/ψ(1S) production σ_A ≈ A \cdot σ_N
- Beam 11 GeV, 50 µA
- HMS 21°, 4.3 GeV/c, SHMS 15°, 6.1 GeV/c ⇒ E_γ > 10.5 GeV, |t| < 1.2 (GeV/c)^2, acceptance 1.2 \cdot 10^{-4}
- Assume \frac{dσ}{dt} (E_γ = 10.5 – 11) = 0.6 \cdot e^{1.1 \cdot t} nb/GeV² (Cornell)
- Combined efficiency 50%
- Coherent production excluded by kinematics and J/ψ angle

<table>
<thead>
<tr>
<th>target</th>
<th>^1H</th>
<th>^2H</th>
<th>Be</th>
<th>C</th>
<th>Al</th>
<th>Cu</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ(1S)/day</td>
<td>(1 – x)^2</td>
<td>160</td>
<td>320</td>
<td>550</td>
<td>360</td>
<td>210</td>
<td>110</td>
</tr>
</tbody>
</table>

1000 events per target: ~ 50 days run
Extraction of $\sigma_{\psi N}$

- Nuclear transparency: $T = \sigma_{\gamma A} / (A \cdot \sigma_{\gamma N})$

SLAC model: semi-classical eikonal approximation of nuclear rescattering

Assumed: statistical error for each target $3\%$

<table>
<thead>
<tr>
<th>$\sigma_{\psi N}$ mb</th>
<th>9</th>
<th>12</th>
<th>27</th>
<th>63</th>
<th>108</th>
<th>207</th>
<th>$\sigma (\sigma_{\psi N})$ mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>1.0</td>
<td>0.982</td>
<td>0.980</td>
<td>0.974</td>
<td>0.963</td>
<td>0.952</td>
<td>0.929</td>
</tr>
<tr>
<td>3.5</td>
<td>0.988</td>
<td>0.931</td>
<td>0.908</td>
<td>0.870</td>
<td>0.833</td>
<td>0.751</td>
<td>0.24</td>
</tr>
<tr>
<td>7.0</td>
<td>0.876</td>
<td>0.863</td>
<td>0.816</td>
<td>0.740</td>
<td>0.665</td>
<td>0.502</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- Fermi-motion correction.
  (kinematically suppressed?)
Conclusion

At 12 GeV JLab is capable of using $c\bar{c}$ as a probe of nuclear matter:

(1) Measurements of $\psi$-Nucleon cross-section. The expected errors are about 10% statistical and 15% systematic. This measurements are aiming to test if there is a considerable gluonic potential between colorless states. This cross-section has also been of a considerable interest for heavy ion physics.

(2) Measurements of $\frac{d\sigma}{dt}(E_\gamma)$ of $J/\psi(1S)$ is needed in order to fulfill (1). It is also of independent interest, probing compact, coherent states of valence quarks.

Experimental possibilities:
- The part (1) SHMS+HMS in 2 months
- The part (2) - longer time (several options)
Physics Motivations

Program for 12 GeV

Appendix

J/ψ(1S) Photoproduction on Nuclei

Vertex detectors:
- **NA14**: $^6Li$ 50-150 GeV
- **E687**: $^9Be$ 120-370 GeV

- A large coherent production: $\approx 40\%$
- “Coherent” slopes: NA14 and E687 are inconsistent
- NA14 and E687 - good $t$ resolution, recoil undetected
- full cross-section A-dependence $\approx A^1$
- $L_{coh} > 2$ fm $E_\gamma > 50$ GeV

Generalized VDM

L.Frankfurt, M.Strikman... hep-ph/0304301
Calculation of $\sigma(\psi N)_{tot}$ and $\psi$ Photoproduction


Calculation of $\sigma(\psi N)_{tot}$ (rigorous in heavy quark limit):
- short-distance QCD (similar to DIS)
- using gluon PDF of the nucleon

Is $m_c$ large enough?
Test:
$\psi N \rightarrow \gamma p \rightarrow \psi p$, using:
- VDM: $E_\gamma > 25$ GeV
- optical theorem
- dispersion relations

Discrepancy at 17 GeV $\times 10$
Fast drop at $E < 20$ GeV
At $E \sim 10$ GeV - decisive
SLAC results on $\gamma p \rightarrow \psi p$ at 13-21 GeV

Double spectrometer measurements

(From: U.Camerini et al PRL 35, 483 (1975))

5% RL, 30 cm $^1H$, $^2H$

20, 8 GeV spectrometers

$J/\psi(1S) \rightarrow e^+e^-, \mu^+\mu^-$

1200 $J/\psi(1S)$ and 13 $\psi(3770)$

at 13 GeV:

$$\left. \frac{d\sigma}{dt} \right|_{t_{\text{min}}} = 3.8 \pm 0.8 \text{ nb/GeV}^2$$

at 20 GeV:

$$\sigma: \psi(3100)/\psi(3770) \sim 6.8 \pm 2.4$$

From VDM: $d\sigma(\psi N \rightarrow \psi N)/dt \big|_{t=0} \approx 25 \mu b$
Cornell Results at 11.8 GeV

- $J/\psi \rightarrow e^+e^-$ detected with lead-glass calorimeters ($\frac{\sigma E}{E} = 0.16\sqrt{E}$)
- $\langle \gamma\text{-flux} \rangle \cdot 10^9 / s$ for $8.5 < E_\gamma < 11.8$ GeV, duty cycle=7%, Be $2.9g/cm^2$

- Background: neutrals $\times 10$ charged, charged - BH
- Signal/background $\sim 470/70$
- Results: $\frac{d\sigma}{dt} = 0.9 \pm 0.1 \text{ nb/GeV}^2 \cdot e^{1.13 \pm 0.18 \cdot t}$

No dependence of cross-section on $E_\gamma$ observed!
<table>
<thead>
<tr>
<th>hall</th>
<th>beam $\mu A$</th>
<th>setup</th>
<th>$\Delta \Omega$ ster</th>
<th>$\theta_{\text{min}}$ deg</th>
<th>$P_{\text{max}}$ GeV</th>
<th>$\pm \frac{\Delta P}{P}$ %</th>
<th>$\frac{\sigma P}{P}$ %</th>
<th>$\sigma \theta_{\text{in}}$ mrad</th>
<th>$\sigma \theta_{\text{out}}$ mrad</th>
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</thead>
<tbody>
<tr>
<td>Hall A</td>
<td>100</td>
<td>HRS</td>
<td>0.006</td>
<td>12.5</td>
<td>4.0</td>
<td>-5./+5.</td>
<td>0.02</td>
<td>0.6</td>
<td>1.0</td>
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<td>12.5</td>
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<td>MAD</td>
<td>0.030</td>
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<td>-15./+30.</td>
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<td>0.006</td>
<td>12.0</td>
<td>8.0</td>
<td>-15./+30.</td>
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<td>Hall C</td>
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<td></td>
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<td></td>
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<td>-15./+25.</td>
<td>0.2</td>
<td>3.0</td>
<td>1.5</td>
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<tr>
<td>Hall B</td>
<td>0.03</td>
<td>CLAS</td>
<td>$\sim 2\pi$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td></td>
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<tr>
<td>Hall D</td>
<td>$\gamma$</td>
<td></td>
<td>$\sim 4\pi$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$&lt;1.$</td>
<td></td>
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</tbody>
</table>
Luminosity and Acceptance

Possible photon flux:

- Halls A,C: \(50\mu A\) at 6\% RL radiator: \(6 \cdot 10^{12} \gamma/s\) 8.5-11 GeV on 10 cm LH
- A,C ECAL: \(2\mu A\) at 6\% RL radiator: \(3 \cdot 10^{11} \gamma/s\) 8.5-11 GeV on 4 cm LH
- Halls B: no tagging forseen
- Halls B: \(\mathcal{L} < 10^{35} \text{ cm}^{-2}\text{s}^{-1}\): \(1.2 \cdot 10^9 \gamma/s\) 8.5-11 GeV on 10 cm LH
- Halls D, tagged:
  \(\sim 2 \cdot 10^7/s\) in \(8.4 < E_\gamma < 9.1\text{GeV}\) coherent
  \(\sim 2 \cdot 10^7/s\) in \(8.4 < E_\gamma < 11\text{GeV}\) incoherent

- “Standard” 12 GeV equipment: acceptance A/B/C/D/ECAL
  \(0.2 \cdot 10^{-3} / 0.2 / 0.1 \cdot 10^{-3} / 0.4 / 0.2\)