Proposal for $J/\psi$ electroproduction @ JLab 12 GeV:
searching for $J/\psi$-nucleon bound state

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Small size configuration workshop
Jefferson Lab, Newport News
March, 26th, 2011
Outline:
- Introduction: physics interest
- Experimental conditions
- Simulation
- Projected results
- Summary, perspectives
Ultimate goal: understand non-perturbative QCD, by observing/measuring nucleon-meson bound state.

-> significant valence-quark-exchange between nucleon and “light” meson ($\pi, \rho, ...$).

-> completely negligible with $J/\psi$ => remains a quasi-pure gluonic contribution.

Hence, interaction between $J/\psi$ and nucleon in a $J/\psi$-$N$ bound state may be described by the exchange of several soft gluons. => QCD “Van der Walls” force.
Brodsky, Schmidt, and de Téramond (1990) discussed the existence of the interaction between quarkonia and nuclei:
- attractive (hence authorizing a binding $J/\psi$-$A$ state)
- first prediction of the order of magnitude (several 100 MeV, for $A>3$);

First correction by Wasson (1991): order of magnitude of several 10 MeV, still for $A>3$;

Several corrections were then brought to this:
Luke, Mahonar, Savage, using OPE finds $\sim 10$ MeV;
Hayashigaki (1999) using QCD sum rules $\Rightarrow 4$-7 MeV;
Also found a positive binding energy for $A = 1$;
Yokokawa et al. (2006) finally made a lattice QCD calculation at low energy for $J/\psi$-$N$ and found a positive binding energy; 
=> need of experimental data to confront to this calculation.

The most feasible experiment is the production of $J/\psi$ on nuclei ($\gamma^{(*)} A \rightarrow J/\psi p' A - I$) near threshold and at high $t$ (to minimize the $J/\psi$ momentum, thus maximizing the probability of forming a binding state). Discrepancy, at high $t$, of the $t$-dependences of the ($\gamma^{(*)} A \rightarrow J/\psi p' A - I$) cross section compared to the ($\gamma^{(*)} p \rightarrow J/\psi p'$) cross section would be the experimental evidence of a $J/\psi$-$A$ bound state.
=> compare, at high $t$ and near threshold, the $t$-dependences of the $(\gamma^* A \to J/\psi p' A I)$ cross section compared to the $(\gamma^* p \to J/\psi p')$ cross section...

**BUT**: no (accurate) data...

A first phase of the experiment would be a precise absolute measurement of $(\gamma^* p \to J/\psi p')$ near threshold

![Graph showing data points and a fitted curve. The x-axis represents $E_{\gamma^*}$ in GeV, and the y-axis represents the cross section in nb.](image)
Experimental conditions

* Experimental requirements;

* Experimental setup, kinematics;

* Further experimental constraints:
  - mechanical constraints;
  - background;
We propose the measurement of $J/\psi$ electroproduction cross section on proton (and deuterium in a second phase) at JLab 12 GeV.

We require full exclusivity on the measurement of the $H(e, e'p [J/\psi \rightarrow e^+e^-])$ reaction (necessary to constraint $A(e\rightarrow e'p [J/\psi \rightarrow e^+e^-])\{A-I\}$) -> “sacrifice” on the acceptance. => Need huge luminosity (several $10^{38}$ cm$^{-2}$ s$^{-1}$).

Kinematics requirements:
- highest beam energy, to be above threshold;
- lowest possible $Q^2$, to achieve decent counting rates.
Experimental conditions: Setup

Decision has been made to propose the experiment in the Hall C, with HMS and SHMS. *Scattered electron in SHMS*, recoil proton in HMS, electrons of the pair in 2 calorimeters.

\[ W = 4.15 \text{ GeV} \]
\[ Q^2 = 0.35 \text{ GeV}^2 \]

\[ \theta = 6.5^\circ, p = 2 \text{ GeV} \]
\[ \theta = 11^\circ \]

3/26/11
Experimental conditions: Setup

Scattered electron in SHMS, recoil proton in HMS, electrons of the pair in 2 calorimeters.

\begin{itemize}
\item one HMS setting in angle;
\item three in momentum:
\begin{itemize}
\item higher $t$ (Kin 13) = -3.1 GeV$^2$
\item intermediate $t$ (Kin 12) = -2.4 GeV$^2$
\item lower $t$ (Kin 11) = -1.9 GeV$^2$
\end{itemize}
\end{itemize}
Scattered electron in SHMS, recoil proton in HMS, electrons of the pair in 2 calorimeters.

Set symmetrically on both sides of the beam (low $Q^2$ favors symmetric decays). Their angle would depend on the $t$ setting.

Calorimeters need to be compact, radiation resistant.

$\theta_C \sim 20-25^\circ$

$\Rightarrow$ chose for model the hall A DVCS PbF$_2$ calorimeter:

13x16 blocks, very compact, one already exists
Experimental conditions: Constraints

Mechanical constraints:
Calorimeter specifications submitted to the SHMS design team: => interferences with the spectrometers snouts at 20°.

seems compatible at 25° (eye estimation)

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Experimental conditions: Constraints

Background from low energy particles

\[ e + H \rightarrow e^{-} + X \text{ at } E_{e} = 11 \text{ GeV}, 15 \text{ cm target} + 2x(5 \text{ mil Al}) \]

At the closest point of the calorimeter, the dose rate from electromagnetic background would be \(~15\) mGy/s at a beam current of 55 µA, on a 15 cm LH2 target

\[ \Rightarrow 40 \text{ kGy over a 720 h run.} \]

PbF2 blocks were observed to stand 35 kGy within 4 hours.
Experimental conditions: Constraints

Rates of accidentals applying a 2 GeV threshold

\[ e + H \rightarrow \gamma + X \quad \text{at } E_e = 11 \text{ GeV, 15 cm target + 2x(5 mil Al)} \]

The rate of > 2 GeV electromagnetic clusters (from photons and electrons) in the calorimeter is 6.5 M/s.
Simulation

* Simulation features

* Cross section model

* Simulation results
Simulation features

Simulation includes:

- Real (external and internal) radiative corrections on incident and scattered electrons;

- Spectrometers resolution effects in momentum and direction;

- Calorimeters resolution effects in momentum and position;

- Cross section model.
Simulation: cross section model

Reference: \( J/\psi \) photoproduction cross section from Cornell on beryllium, for \( 9.3 \text{ GeV} < E_\gamma < 10.4 \text{ GeV} \):

\[
\frac{d\sigma}{dt} = Ae^{bt} \quad (A = 0.94 \text{ nb GeV}^{-2}, \quad b = 0.97 \text{ GeV}^{-2})
\]

multiplied by the usual virtual photon flux:

\[
\Gamma = \frac{\alpha_{\text{QED}} k^' k_y}{2\pi^2} \frac{1}{k Q^2 (1 - \epsilon)}
\]

and weighted with the leading term of the vector meson angular distribution (Schilling and Wolf):

\[
W(\cos \theta) = \frac{3}{8\pi} (1 - r_{00}^{04} + (3 r_{00}^{04} - 1) \cos \theta)
\]

with \( r_{00}^{04} = \frac{\epsilon R}{1 + \epsilon R} \) and \( R = \frac{d\sigma_L}{d\sigma_T} = \left( \frac{a m_{J/\psi}^2 - Q^2}{a m_{J/\psi}^2} \right)^n - 1 \)

parameterized by Fiore et al.

\( (a = 2.164, \quad n = 2.131) \)
Simulation results

Plots of missing masses $ep \rightarrow e'p'X$, $ep \rightarrow e'p'e^+e^-X$, and $e^+e^-$ invariant mass.
No cross section weight.
Projected results

- Projected counting rates
- Projected error bars
Projected counting rates

Counting rates for each kinematics, assuming 20 days per setting, and at a current of 55 µA on a 15 cm liquid H₂ target ($\mathcal{L} = 2.10^{38} \text{ cm}^{-2} \text{ s}^{-1}$):

$$(\theta_{\text{SHMS}} = 6.5^\circ, p_{\text{SHMS}} = 2 \text{ GeV}, \theta_{\text{HMS}} = 11^\circ)$$

<table>
<thead>
<tr>
<th>Kin</th>
<th>$p_{HMS}$ (GeV)</th>
<th>$\theta_C$ (°)</th>
<th>$\int d\sigma$ $(10^{-11} \text{nb})^{-1}$</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.70</td>
<td>25.0</td>
<td>29.20</td>
<td>50</td>
</tr>
<tr>
<td>12</td>
<td>2.03</td>
<td>25.0</td>
<td>26.86</td>
<td>46</td>
</tr>
<tr>
<td>13</td>
<td>2.43</td>
<td>25.0</td>
<td>20.28</td>
<td>35</td>
</tr>
<tr>
<td>total Kin1</td>
<td></td>
<td></td>
<td>76.34</td>
<td>131</td>
</tr>
</tbody>
</table>

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Projected error bars

Projected $d\sigma/dt$ and error bars:

$A = 0.1095 \pm 0.040$ nb GeV$^{-2}$

$b = 0.96 \pm 0.18$ GeV$^{-2}$

Total projected cross section:

compatibility with model input.

$A/<W(\cos \theta)> = 0.92$ nb GeV$^{-2}$

the relatively low counting rates already allows to achieve unprecedented statistical precision.

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Projected counting rates would allow to set a new level of statistical precision to $J/\psi$ electroproduction.

In the actual design status, most of the apparatus is already available, so the experiment would be affordable.

A letter of intent about $J/\psi$ electroproduction in Hall C has already be submitted to PAC37. This letter received encouragements.
Still, work remains to do, mainly about the background issues:

- A Geant 4 simulation of the background is of course underway, to improve the understanding/handling of the background;

- Other instrumental prospects are underway, such as the addition of GEMs to the calorimetric system.
Back-up
Hall C Spectrometers specifications:

<table>
<thead>
<tr>
<th></th>
<th>$p$ range (GeV)</th>
<th>$\delta p/p$ min/max (%)</th>
<th>$\sigma_p/p$ (%)</th>
<th>$\theta_{in}$ range* (°)</th>
<th>$\Delta \theta_{in}$ (mrad)</th>
<th>$\Delta \theta_{out}$ (mrad)</th>
<th>$\sigma_\theta$ (mrad)</th>
<th>$\sigma_v/\sin \theta$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMS</td>
<td>1-7.3</td>
<td>$\pm 9$</td>
<td>0.1</td>
<td>11-90</td>
<td>24</td>
<td>70</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SHMS</td>
<td>2-11</td>
<td>-10/+22</td>
<td>0.1</td>
<td>5.5-25</td>
<td>24</td>
<td>50</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Calorimeters specifications:

<table>
<thead>
<tr>
<th>Material</th>
<th>distance from target (m)</th>
<th>width (cm)</th>
<th>height (cm)</th>
<th>depth (cm)</th>
<th>channel (block) size (cm x cm)</th>
<th>$\delta E/E$ (%)</th>
<th>$\delta x/x$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbF$_2$</td>
<td>1.1</td>
<td>39</td>
<td>48</td>
<td>18.5</td>
<td>3 x 3</td>
<td>$&lt; 2.5$</td>
<td>$&lt; 3$</td>
</tr>
</tbody>
</table>
Background: comparison between $J/\psi$ electroproduction and DVCS

$$e + H \rightarrow e^- + X \quad \text{at} \quad E_e = 11 \text{ GeV}$$

$$e + H \rightarrow e^- + X \quad \text{at} \quad E_e = 6 \text{ GeV}$$
$ep \rightarrow ep J/\psi$ cross section model: full formalism

$$\frac{d^7 \sigma}{dk' d\cos \theta_{k'} d\phi_{k'} dt d\phi_{qq'} d\cos \theta_{qq'_{q_1}} d\phi_{qq'_{q_1}}} = \Gamma \frac{d\sigma}{dt} W(\cos \theta_{qq'_{q_1}})$$

$$\frac{d\sigma}{dt} = A \exp(bt) \quad A = 0.94 \text{ nb GeV}^{-2}, \quad b = 0.97 \text{ GeV}^{-2}$$

$$\Gamma = \frac{\alpha_{QED}}{2\pi^2} \frac{k'}{k} \frac{k_y}{Q^2} \frac{1}{1-\epsilon} \quad k_y = \frac{W^2-M^2}{2M} \quad \epsilon = \left(1 + 2 \frac{\vec{q}_y^2}{Q^2} \tan^2 \theta_{k'}\right)^{-1}$$

$$W(\cos \theta_{qq'_{q_1}}) = \frac{3}{8\pi} \left(1 - r_{00}^{04} + (3r_{00}^{04} - 1) \cos \theta_{qq'_{q_1}}\right)$$

$$r_{00}^{04} = \frac{\epsilon R}{1 + \epsilon R}$$

$$R = \frac{d\sigma_L}{d\sigma_T} = \left(\frac{a m_{J/\psi}^2 - Q^2}{a m_{J/\psi}^2}\right)^n - 1 \quad a = 2.164, \quad n = 2.131$$
Counting rates determination

The number of events for each kinematics is given by:

\[ N = \sum_{i \in 4-coinc} \int \frac{d^7 \sigma}{d \Phi^7} (\Phi_i^n) \times \Delta \Phi_{\text{gen}} \times \frac{N_{\text{gen}}}{N_{\text{gen}}} \times \int L \, dt \times \text{BR}_{J/\psi \rightarrow ee} \times \eta_{\text{spectro}} \]

Integrated cross section over accepted events of the uniform simulation

Generation normalization

Experimental integrated luminosity

Branching ratio of \( J/\psi \) decay in electron pair

Spectrometer global inefficiency

(set to 0.5, likely overestimated)