Measurement of the $J/\psi$ photoproduction cross section close to threshold

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23-rd International Spin Symposium
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Motivation

**Measured:** \( \sigma(E_\gamma) \) for reaction \( \gamma + p \rightarrow J/\psi + p \) at \( 8.22 \text{(threshold)} < E_\gamma < 12 \text{ GeV} \)

**Existing data:** two experiments from 1975 at \( E > 11 \text{ GeV} \)

1. Photoproduction dynamics
   - \( \sigma(E_\gamma) \) is sensitive to high-\( x \) gluons in the nucleon

2. Spectroscopy: search for the LHCb pentaquark
   - s-channel production \( \gamma + p \rightarrow P_c(4450) \rightarrow J/\psi + p \) at 10.1 GeV
   - The \( P_c \) production would manifest itself as a peak in \( \sigma(E_\gamma) \)

The main topic of this presentation
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at $8.22 (\text{threshold}) < E_\gamma < 12 \text{ GeV}$

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*The main topic of this presentation*
Exotic XYZ states: rich spectroscopy results

Belle, BaBar, CDF, D0, LHCb, BES have detected, mostly in $B$ decays many mesonic states in $\bar{c}c, (\bar{b}b) + X$ final states, as:

$\chi_{c1}(3872) \ 0^+ (1^{++}) \ \Gamma < 1.2 \text{ MeV} \rightarrow J/\psi \pi \pi (> 3\%), \ D^*0 D^0 (> 30\%) \ ... \ \bar{c}c$?

$Z_c(3900) \ 1^+ (1^{+-}) \ \Gamma = 28 \text{ MeV} \rightarrow J/\psi \pi^\pm, \ D^* D... \ \text{exotic (not a} \ \bar{c}c)$

The masses are close to the thresholds of some reactions (say, $\bar{D}^* D$)

The experimental evidence is very strong!

The interpretation is still uncertain:

- Tetraquark: diquark-antidiquark $\bar{3}_c \times 3_c \in 1_c$
- Molecule: meson-antimeson loosely bound $1_c \times 1_c \in 1_c$  
  “hadrocharmonium”
- Cusp - kinematical effect

More information about their properties should help the interpretation
LHCb Pentaquark

**LHCb PRL, 115, 072001 (2015)**  \( \Lambda_b^0 \rightarrow K^-(J/\psi p) \)

- No indications of \( \Lambda^* \rightarrow K^- p \) reflections to \( J/\psi p \)
- PWA leads to two states for \( P_c^+ \rightarrow J/\psi p \):
  - \( M_1 = 4380 \pm 30 \), \( \Gamma_1 = 205 \pm 90 \) MeV/c^2
  - \( M_2 = 4450 \pm 3 \), \( \Gamma_2 = 39 \pm 20 \) MeV/c^2
- \( J^{PC} \): \( (\frac{3}{2}^-, \frac{5}{2}^+) \) or \( (\frac{3}{2}^+, \frac{5}{2}^-) \) or \( (\frac{5}{2}^+, \frac{3}{2}^-) \)

Threshold of \( \Sigma_c(2455) \bar{D}^*(2007) = 4462 \) MeV/c^2. The only mode detected \( J/\psi p \)
Photoproduction of the Pentaquark: Predictions

In a **Broad-band photon beam**
\[ \gamma + p \rightarrow J/\psi + p \] may include
\[ \gamma + p \rightarrow P_c \rightarrow J/\psi + p \]

**Addressed in a number of papers:**
M. Voloshin et al PRD 92, 031502 (2015)
Q. Wang et al PRD 92, 034022 (2015)
M. Karliner et al PL 752, 329 (2016)

- \( P_c \rightarrow J/\psi \ p \overset{VMD}{\Rightarrow} \gamma \ p \rightarrow P_c \)
- Interference of \( t- \) and \( s- \) channels
- Using the measured \( \Gamma(P_c) \) the full cross section is calculable with one free parameter:

\[ \sigma_{\gamma p \rightarrow J/\psi p}(E_{\text{peak}}) \propto BR(P_c \rightarrow J/\psi p)^2 \]

http://cgl.soic.indiana.edu/jpac/PentaQ_JPsi.php
CEBAF at 12 GeV

Beam runs

<table>
<thead>
<tr>
<th>year</th>
<th>$E_{\text{MAX}}$, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>2016</td>
<td>10.9</td>
</tr>
<tr>
<td>2017</td>
<td>10.6</td>
</tr>
<tr>
<td>2018</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Hall D/Gluex Meson Spectroscopy In Photoproduction

12 GeV e⁻
North LINAC

Photon Tagger

Electron Beam Dump

Diamond Radiator

Collimator

Pair Spectrometer & Triplet Polarimeter

Photon Beam Dump

Photon Beam Spectrum

Photon Flux (Arb. Units)

(a)

Diamond: PARA

Diamond: PERP

Aluminum

(b)

Polarization

0
0.1
0.2
0.3
0.4
0.5
1.5% Syst. Uncert.

PARA

PERP

Photon Beam Energy (GeV)

9 GeV

Flux

P ≈ 40%

30 cm LH₂

B = 2.0 T

barrel calorimeter
time-of-flight
forward calorimeter
target
central drift chambers
Hall D/GlueX Meson Spectroscopy In Photoproduction

Photon Tagger

12 GeV e⁻

North LINAC

East ARC

Photon Beam Spectrum

Photon Beam Energy (GeV)

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Diamond Radiator

Electron Beam Dump

Collimator

GlueX Spectrometer

Photon Beam Dump

Pair Spectrometer & Triplet Polarimeter

1.5% Syst. Uncert.

PARA

PERP

Acceptance: $1^\circ < \theta < 120^\circ$

Resolutions:

$h^\pm: \sigma_p/p \sim 1 - 3\%$

$\gamma: \sigma_E/E \sim 6%/\sqrt{E} + 2\%$

Beam energy tagging $\sim 0.1\%$

Trigger: energy in the calorimeters

Spectrometer parameters

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Hall D/GlueX Meson Spectroscopy In Photoproduction

12 GeV e−
North LINAC
East ARC

Photon Tagger
Pair Spectrometer
& Triplet Polarimeter

Diamond Radiator
Electron Beam Dump
Collimator

Photon Beam Dump

Photon Beam Spectrum

(a) Photon Flux (Arb. Units)
(b) Polarization

Photon Beam Energy (GeV)

Photon Beam Spectrum

Experiment GlueX

- Designed for light meson spectroscopy
- Main goal: search for hybrid mesons
- Data taking 80% complete

<table>
<thead>
<tr>
<th>run</th>
<th>$E_{\text{MAX}}$ GeV</th>
<th>Int $L$ pb$^{-1}$</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>12.0</td>
<td>10</td>
<td>analyzed</td>
</tr>
<tr>
<td>2017</td>
<td>11.7</td>
<td>45</td>
<td>analyzed</td>
</tr>
<tr>
<td>2018</td>
<td>11.7</td>
<td>100</td>
<td>not yet analyzed</td>
</tr>
</tbody>
</table>

- Status of data analysis:
  complex final states reconstructed
  understanding the efficiencies: in progress
Hall D/GlueX Meson Spectroscopy In Photoproduction

12 GeV e⁻
North LINAC
East ARC

Photon Tagger

Photon Beam Spectrum

(a) Photon Beam Spectrum
- Diamond: PARA
- Diamond: PERP
- Aluminum

(b) Polarization
- PARA
- PERP
P ≈ 40%

Photon Beam Energy (GeV)

Example of event reconstruction:

\( \eta \pi^0 \pi^0 \) mass

\( f_1(1285) / \eta(1295) \)

\( \gamma p \rightarrow p \eta \pi^0 \pi^0 \rightarrow p 6\gamma \)
Data Analysis for $J/\psi$

Reaction studied: $\gamma p \rightarrow J/\psi p$, $J/\psi \rightarrow e^+ e^-$

$\sigma(\gamma p \rightarrow \psi p) \times BR \sim 30$ pb $\sim 0.3 \cdot 10^{-6} \times \sigma_{tot}(\gamma p \rightarrow \text{hadrons})$

Event identification:

- PID for $p$: TOF, $\frac{dE}{dx}$ in drift chambers
- PID for $e^\pm$: EM calorimeters (challenge: large BG from $\pi^+ \pi^- p$ events)
- Kinematic fit using the photon energy measured with a 0.1% resolution

The Bethe-Heitler reaction $\gamma p \rightarrow (e^+ e^-)p$ used for normalization

*(absolute efficiencies are not fully understood yet)*
Mass Spectrum of $e^+e^-$

GlueX Preliminary: not the final 2016+2017 data sample (about 70%).

All beam energies


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J/ψ photoproduction

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Mass Spectrum of $e^+e^-$

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All beam energies

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$p_0$</td>
<td>24.61 ± 15.96</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$-7.307 ± 5.112$</td>
</tr>
<tr>
<td>$p_2$</td>
<td>50.6 ± 5.5</td>
</tr>
<tr>
<td>$p_3$</td>
<td>3.091 ± 0.001</td>
</tr>
<tr>
<td>$p_4$</td>
<td>0.007472 ± 0.000708</td>
</tr>
</tbody>
</table>

$\chi^2$/ndf = 31.53/35


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$J/\psi$ photoproduction
Energy dependence of the cross section

\begin{align*}
\sigma_g'(p \rightarrow J/\psi p) \text{ nb} \\
\end{align*}

- **SLAC:**
  \begin{align*}
  \text{U.Camerini et al, PRL 35 (1975)} \\
  \text{Calculated from the measured} \\
  \frac{d\sigma}{dt}\bigg|_{t=t_{\text{min}}} \\
  \text{assuming} \\
  \frac{d\sigma}{dt} \propto e^{a \cdot t}, \quad a = 2.9 \pm 0.3 \text{ GeV}^{-2} \\
  \text{measured at 19 GeV}
\end{align*}

- **Cornell:**
  \begin{align*}
  \text{B.Gittelman et al, PRL 35 (1975)} \\
  \text{t-slope} \quad a = 1.25 \pm 0.2 \text{ GeV}^{-2} \\
  \text{horizontal error bar represents} \\
  \text{the acceptance}
\end{align*}
Limit on the Pentaquark Production

Fit: 2 + 3-gluon exchange

Brodsky et al, PL 498 (2001)
2 free parameters \( \chi^2/ndf = 0.8 \)

Limit for \( P_c(4450) \) \( \Gamma = 40 \text{ MeV} \)
JPAC model, assumptions:
\( \sigma(10.1) = 0.64 \text{ nb non-reson.} \)
no wide state \( P_c(4380) \) added

<table>
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<tr>
<th>( J^P C )</th>
<th>BR</th>
<th>10.1 ± 0.6 GeV (2 bins)</th>
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<tr>
<td></td>
<td></td>
<td>JPAC nb</td>
</tr>
<tr>
<td>3/2-</td>
<td>2.0%</td>
<td>0.81</td>
</tr>
<tr>
<td>5/2+</td>
<td>0.7%</td>
<td>0.81</td>
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Systematic to be addressed:
- \( t \) and s-channel interference
- VMD model dependence
- The wide state influence
Limit on the Pentaquark Production

Fit: $2 + 3$-gluon exchange

*Brodsky et al, PL 498 (2001)*

2 free parameters $\chi^2/ndf = 0.1$

Limit for $P_c(4450) \Gamma = 40$ MeV

JPAC model, assumptions:

- $\sigma(10.1) = 0.64$ nb non-reson.
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Systematic to be addressed:
- $t$ and $s$-channel interference
- VMD model dependence
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Unbinned distribution $t$ vs $E$

The beam energy resolution is about $0.1\% \ll 0.6$ GeV bins. The $P_c$ is expected to produce broad $t$-distribution.

- JPAC: $\frac{5}{2}^+ \ BR = 3\%$
- White dots: $J/\psi$ events from the peak
- No indication of event concentration at 10.1 GeV
Summary & Outlook

- **Summary of the preliminary GlueX results**
  - The first measurement of the cross section of the reaction $\gamma p \rightarrow J/\psi p$ close to threshold has been reported.
  - No statistically-significant evidence for the LHCb pentaquark has been observed. The model-predicted yield from $P_c(4450)(\frac{3}{2}^-) \rightarrow J/\psi p$, BR=2% (or $\frac{5}{2}^+$, BR=0.7%) is about $3\sigma_{(\text{stat})}$ above the experimental result.

- **Outlook**
  - GlueX is planning to analyze the full data sample and finalize the results before the end of the year. Also, we are planning to increase the sensitivity to the $P_c(4450)$ detection by using $t-E$ unbinned event analysis. Later, the 2018 data is expected to triple the statistics.
  - Other experiments at JLab (CLAS12 and Hall C) have been scheduled to the near future to measure the same process. Potentially, they would be able to reach a higher sensitivity.
Identification of $e^\pm$

Using the track momentum $p$ and the calorimeter energy $E$

Pion background for BH sample
$1.5 < M(e^+e^-) < 2.5$ GeV

- One $e^\pm$ identified
- $p/E$ for pions - shape measured
- Average background $36 \pm 1.2\%$
- Energy-dependent BG correction
Beam flux is measured with the Pair Spectrometer using $e^+e^-$ pair production with a $\sim 0.1\%$ converter.

“Tagged flux” measures photons in coincidence with the tagger detectors.

The structure of the tagged flux is caused by coherent peaks and the tagger geometry/efficiency.

Flux-normalized yield of $\gamma p \rightarrow \rho p$ is smooth.
### Systematic Error Budget

<table>
<thead>
<tr>
<th>Systematic error source</th>
<th>Estimate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ to BH relative yield</td>
<td>18</td>
</tr>
<tr>
<td>BH cross section calculation</td>
<td>10</td>
</tr>
<tr>
<td>Pion contamination to BH</td>
<td>5</td>
</tr>
<tr>
<td>$\rho$ contamination to BH</td>
<td>5</td>
</tr>
<tr>
<td>t-dependence of efficiency</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24</strong></td>
</tr>
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Exotic XYZ states: rich spectroscopy results

Belle, BaBar, CDF, D0, LHCb, BES have detected, mostly in $B$ decays many mesonic states in $\bar{c}c, (\bar{b}b) + X$ final states, as:

- $\chi_{c1}(3872) \ 0^+ (1^{++}) \ \Gamma < 1.2 \rightarrow J/\psi \pi \pi (> 3\%), \ \bar{D}^* D^0 (> 30\%)$ ...

- $Z_c(3900) \ 1^+ (1^{-+}) \ \Gamma = 28 \rightarrow J/\psi \pi^\pm, \ \bar{D}^* D ...$ exotic (not a $\bar{c}c$)

The masses are close to the thresholds of some reactions (say, $\bar{D}^* D$)

$$e^+ e^- \rightarrow \pi^\pm (Z_C^\mp \rightarrow \pi^\mp J/\psi) \quad e^+ e^- \rightarrow \pi^\pm (Z_C^\mp \rightarrow (\bar{D}^* D)^\mp)$$

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