First measurement of near-threshold $J/\psi$ photoproduction and search for the LHCb $P_c^+$ states at GlueX

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[For the GlueX Collaboration]

HADRON 2019
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J/ψ Photoproduction Near Threshold

- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
  - Probes distributions of high-x gluons in proton, trace anomaly, …
    Kharzeev et al., NPA 661, 568 (1999)
    Brodsky et al., PLB 498, 23 (2001)
- Experimentally little-explored
  - 1970’s dual-arm spectrometer measurements at SLAC and Cornell

Leading-twist vs. higher-twist

$\gamma N \rightarrow J/\psi$ elastic

Cornell 75
SLAC 75

fit to the data at 11 -22 GeV
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leading-twist

higher-twist

GlueX energy range

fit to the data at 11 -22 GeV
Many “exotic” hadrons with cc-bar content have been observed in recent years

Most interesting: charged exotics
Strongly implies multiquark content, but what type?

In 2015, LHCb identified two (J/ψ p) states in an amplitude analysis of the decay Λ_b → K^− J/ψ p

One narrow, one wide

Preferred J = 3/2 and 5/2 with opposite parity

LHCb, PRL 115 072001 (2015)
LHCb $P_c$ States

- In 2019, LHCb identified three narrow ($J/\psi\,p$) states in a fit of the mass spectrum with a 9x larger sample
  - Near mass thresholds
  - No spin-parity identification
- Many possible descriptions, including:
  - Tightly-bound or “molecular” multiquark states
  - Hadrocharmonia
  - Cusps, triangle singularities, or other kinematic effects

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>(&lt; 27)</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>(&lt; 49)</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>(&lt; 20)</td>
</tr>
</tbody>
</table>
• Look in different production mechanism: coupling of $J/\psi+p$ resonances to photon
• Kinematic effects from decay will not be reproduced
• $P_c$’s produced at $E(\gamma) \approx 9.5-10.3$ GeV
• Assuming VMD, primary uncertainty is $B(P_c \rightarrow J/\psi \, p)$

Theory papers:
Wang, Liu, and Zhao, PRD 92, 034022 (2015).
Karliner and Rosner, PLB 752, 329 (2016).
Hiller Blin et al. (JPAC), PRD 94, 034002 (2016).
and many more…
The GlueX Experiment

Large acceptance spectrometer
for charged and neutral particles

Luminosity for $E_\gamma > 8$ GeV

- **2016**: 10 pb$^{-1}$
- **2017**: 45 pb$^{-1}$
- **2018**: $\approx 150$ pb$^{-1}$ in spring & fall, GlueX Phase-I is now finished!

Data currently analyzed
The GlueX Experiment

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Tagged Photon

$$\sigma(E)/E \sim 0.1\%$$

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Data currently analyzed
J/ψ Photoproduction at GlueX: Mass Spectrum

- Reconstruct and kinematically fit exclusive reaction
- Calculate J/ψ cross sections normalized by non-resonant e^+e^−
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J/ψ Photoproduction at GlueX: Normalization

- Calculate J/ψ cross sections normalized by non-resonant e⁺e⁻
- Events in normalization region about 50% pions
- Extract e⁺e⁻ non-resonant yield from p(track)/E(cal) distribution

![Signal and background slices](image.png)

\[ \chi^2/\text{ndf} = 56.08/21 \]
\[ \text{SD} = 0.049 \pm 0.001 \]

\[ \chi^2/\text{ndf} = 33.81/22 \]
\[ \text{SD} = 0.050 \pm 0.002 \]
J/ψ Photoproduction at GlueX: Normalization

- Calculate J/ψ cross sections normalized by non-resonant e⁺e⁻
- Events in normalization region about 50% pions
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Background fixed by sideband

Background subtracted
J/ψ @ GlueX: Cross sections vs. theory

PRL 123, 072001 (2019): Editor’s Suggestion!

- First J/ψ cross section measurement at threshold
- 27% normalization uncertainty
- Higher-order contributions needed to describe near-threshold behavior (Brodsky et al.)
- Gluonic contribution to the nucleon mass is large (Kharzeev et al., Y. Hatta et al., Phys. Rev. D 100, 014032 (2019))

- SLAC points calculated from measured dσ/dt and dipole t-dependence
- Cornell horizontal error bars illustrate acceptance

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J/ψ @ GlueX: Search for P_c states

PRL 123, 072001 (2019): Editor’s Suggestion!

- No evidence of P_c states!
- Model-dependent upper limits at 90% CL (assuming J^P=3/2^-):
  - \( \text{Br}(P_c(4312) \rightarrow J/ψ \ p) < 4.6\% \)
  - \( \text{Br}(P_c(4440) \rightarrow J/ψ \ p) < 2.3\% \)
  - \( \text{Br}(P_c(4457) \rightarrow J/ψ \ p) < 3.8\% \)
    [ULs scale as (2J+1)]
- Disfavors hadrocharmonium and some molecular models. P_c’s could preferentially couple to other channels?
  - Need consistent picture with \( Λ_b \) decays.

J/ψ @ GlueX: Unbinned E(γ) vs. t

- Points: GlueX data in J/ψ mass region
- JPAC model: 5% $P_c(4440)$, $J^P = 3/2^-$

- More sensitive search will come from fitting $E(γ)$ vs. $t$ dependence
- Distribution not corrected for beam spectrum or acceptance
- No clear evidence for s-channel production
- Fit requires detailed study of backgrounds and beam energy calibration
Summary

• GlueX has measured $J/\psi$ photoproduction near threshold
  • First determination of $\sigma_{\text{total}}$ shape for $E_\gamma < 12$ GeV
  • No evidence for $P_c$ states, determined model-dependent upper limits on $\mathcal{B}(P_c^+ \rightarrow J/\psi \ p)$ of less than a few percent
• Further analyses are ongoing with additional data
  • $> 1500 \ J/\psi$ on tape, will be able to measure $d\sigma / dE \ dt$
  • Unbinned fits will allow more sensitive searches for $P_c$ states
  • GlueX has large acceptance and large data volume, will be able to search for more charm-quark hadrons
  • High-intensity run starts this Fall!
Backup Slides
J/ψ @ GlueX: Background Rejection

\begin{figure}
\centering
\includegraphics[width=\textwidth]{gluex_background_rejection}
\caption{Background rejection at GlueX.}
\end{figure}

\textbf{Entries} 1.349104e+07

- initial "pion" distribution
- 2σ p/E cuts on both leptons

\textbf{GLUEX Preliminary}

\textbf{~5\% of total statistics}

\textbf{~5,000 suppression}
$J/\psi$ @ GlueX: t-slope

Measurements near threshold

- Cornell at $\sim$11 GeV
  \[ 1.25 \pm 0.20 \text{ GeV}^{-2} \]

- GlueX at 10–11.8 GeV
  \[ 1.67 \pm 0.35 \text{ GeV}^{-2} \]

- SLAC at 19 GeV
  \[ 2.9 \pm 0.3 \text{ GeV}^{-2} \]