Recent Results and Perspectives from the GlueX Experiment

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Hadron Spectroscopy and Photoproduction

• Photoproduction is an essential process to study normal hadrons and to search for exotic hadrons

\[
\gamma \rightarrow (\rho, \omega, \phi) \rightarrow X
\]

\[
\rightarrow P(0^{++}), \pi(0^{--}), \rho(1^{--}), \ldots
\]

\[
p, n, \ldots
\]

• Can produce mesons of any \(J^{PC}\) through VMD

• Photon \textit{polarization} provides constraints on production processes

• Studies of polarization transfer and other production observables provides additional insight into hadron properties

\[\text{tetraquark} \quad \text{hybrid meson}\]
Light Meson Spectrum from Lattice QCD

Meson Mass (MeV)

negative parity

positive parity

exotic

lightest hybrids

$J^{PC} = 0^- 1-- 2-- 3-- 4-- 2+ 4+$

Light Meson Spectrum from Lattice QCD

\[ J^{PC}= 0^+ \quad 1^- \quad 2^- \quad 3^- \quad 4^- \quad 2^+ \quad 4^+ \]

\[ m_\pi = 391 \text{ MeV} \]

24\(^3\) × 128

isoscalar

\( \ell_s \)

isovector

\( \ell_v \)


\( \eta_1^{(')} \): recent evidence by BES-III

\( \pi_1 \): best evidence

\( \eta \)

\( \eta' \)

\( \phi \)

\( \omega \)

\( \rho \)

\( 1^- \)

\( 1^+ \)

\( 0^- \)

\( 2^+ \)

\( 4^+ \)

\( 3^- \)

\( 3^+ \)

\( 4^- \)

\( 4^{++} \)

\( 3^{++} \)

\( 2^{++} \)

\( 1^{++} \)

\( 1^- \)

\( 1^+ \)

\( 0^- \)

\( 2^- \)

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\( 4^{++} \)

\( 3^{++} \)

\( 2^{++} \)

\( 1^{++} \)
Light Meson Spectrum from Lattice QCD

\[\eta_1(1440): \text{recent evidence by BES-III}\]

\[\pi_1: \text{best evidence}\]

\[J^{PC}= 0^+ 1^{--} 2^{--} 3^{--} 4^{--} 2^{++} 4^{++}\]

Hybrid Mesons

- Long history of search for “hybrid” mesons with gluonic excitations
- Best evidence is for $\pi_1(1600)$ in COMPASS pion-production data
- Recent evidence for $\eta_1'$ from BES-III in $J/\psi \to \gamma \eta \eta'$ \cite{PRL 129, 192002 (2022)}
- Need to confirm $\pi_1$ and $\eta_1$ and establish the full light quark hybrid spectrum
The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

Optimized for light meson spectroscopy, energy reach up to bound charmonia

Photon beam with linear polarization $P \approx 40\%$ at peak $E_\gamma \approx 9$ GeV

- **GlueX-I (2017–2018)**: $L = 305$ pb$^{-1}$ [$E_\gamma > 8$ GeV]
- **GlueX-II (2020–2025?)**: $L = 320$ pb$^{-1}$ (so far) expect 3-4x GlueX-I
• Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Understand production mechanisms using polarization: Σ, SDMEs, …

Beam Asymmetry Σ

More coming…

SDMEs: ρ, ω, φ in progress

A. Austregesilo, Wed. 2:05 pm

GlueX: PRC 103, 022201 (2021)
Searching for Exotics in Photoproduction @ GlueX

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Understand production mechanisms using polarization: $\Sigma$, SDMEs, ...

Measure cross sections and identify known mesons with amplitude analysis

\[ \gamma p \rightarrow \pi^0 \eta p \]
\[ \gamma p \rightarrow K^+ K^+ \Xi^- \]
\[ \gamma p \rightarrow \omega \eta p \]
Detailed understanding of light-quark meson spectrum requires amplitude analysis.

- Collect Data
- Understand production mechanisms using polarization: $\Sigma$, SDMEs, …
- Measure cross sections and identify known mesons with amplitude analysis
- Search for exotic mesons
- Theoretical Models (JPAC, ….)
Searching for Exotics in Photoproduction @ GlueX

GlueX Data

- Pseudoscalar + Pseudoscalar
  \(\pi\pi / K\bar{K} / \eta / \eta' / \eta'\)

- Vector + Pseudoscalar
  \(\omega\pi / \omega\eta / \phi\pi / \phi\eta / \phi\omega\)

- 3-body final states
  \(\eta\pi\pi / K\bar{K}\pi / \ldots\)

Possible Exotic Hybrid Meson Decays

- \(\pi_1: \eta\pi / \eta'\pi, \eta_1: \eta\eta'\)

- \(h_2,\omega_0: \omega\eta, h_2',\phi_0: \phi\eta\)
  \(\rho_0: \omega\pi, \phi\pi\)

- \(\eta_1, b_2: \eta\pi\pi, \eta_1', h_2': K\bar{K}\pi\)
GlueX: High Statistics Photoproduction Data

- GlueX has collected orders of magnitude more data than previous experiments at $E_{\gamma} \approx 9$ GeV

$E_{\text{beam}} \approx 9$ GeV

\( f_2(1270) \)
\( \rho' \)

\( \rho(770) \)

\( \gamma p \rightarrow \pi^+ \pi^- p \)

\( W = 4044 \text{ MeV} \)

\( E_{\gamma} = 8.25 \pm 0.25 \text{ GeV} \)
High Statistics $\pi^+\pi^-$ and Excited Vectors

- GlueX can access excited vector mesons decaying to e.g. $\pi^+\pi^-$ and $\omega\pi$
- Need consistent understanding of spectra in photoproduction and $e^+e^-$ annihilation

A. Austregesilo, Wed. 2:05 pm
High Statistics KK and Excited Vectors

- Can extend studies to KK
  - $K_SK_S$: $J^{PC} = \text{even}^{++}$
  - $K_SK_L$: $J^{PC} = \text{odd}^{--}$
- Comparison with $e^+e^-$ annihilation
- Future coupled channel fits for $K_SK_S$

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**Graphs:**

- **KK Analysis:**
  - $f_0(980)$
  - $a_0(980)$
  - $f_2(1270)$
  - $a_2(1320)$
  - $f_2'(1525)$
  - $a_2(1700)$
  - $f_0(1710)$
  - Data from GlueX-I

- **$K_SK_L$ Analysis:**
  - $\phi(1020)$
  - $\phi(1680)$
  - $e^+e^- \rightarrow K_SK_L$
  - BABAR
  - PRD, 89, 092002 (2014)
ηπ Amplitude Analysis at GlueX

- πη / πη’ “golden channels” for π₁ search: small b.f. but experimentally clean
  - Odd L πη⁰ → exotic J^{PC}
  - Study known a₀/a₂ in πη
  - Apply analysis to πη’ with stronger π₁
- Can study several channels
  - γp → ηπ⁰p, γp → ηπ⁻Δ^{++}
  - Control understanding of production
  - with multiple η decays
    - η → γγ, η → π⁺π⁻π⁰
  - Control understanding of acceptance and backgrounds
  - Use polarization to control acceptance, help separate amplitudes
  - Fits with different levels of model-dependence

M. Albrecht,Tue. 2:05 pm
Preliminary $\gamma p \rightarrow a_2(1320)p$ Cross Section

- Preliminary cross sections agree with JPAC prediction
  - Can also extract amplitudes for individual waves
- Photon polarization crucial to control contributions from different production amplitudes
- Informs amplitude fits for exotic waves
Study of $b_1(1235)$ at GlueX

- LQCD predicts dominant $\pi_1$ decay to be $b_1\pi \rightarrow 5\pi$
- First step: understand $b_1$ production and decay to $\omega \pi$
  - Large samples of millions of events
  - Also search for excited vectors and others
  - Extend analysis to other VP channels ($\omega \eta$, $\phi \pi$, $\phi \eta$, …)
- Access to charged and neutral $b_1$
  - $\gamma p \rightarrow b_1^0 p \rightarrow \omega \pi^0 p$
  - $\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega \pi^- \Delta^{++}$
Study of $b_1(1235)$ at GlueX: S/D ratio

- Can use amplitude model for VP photoproduction to measure ratio of D/S amplitudes in $b_1 \to \omega \pi$
- First test of model finds good fits with $1^+$ and $1^-$ waves near $b_1$ peak

HadSpec: PRD 100, 054506 (2019)
LCQD: $|D/S| = 0.27(20)$
\(\omega \eta\) Photoproduction at GlueX

- \(\omega \eta\) photoproduction probes the production of I=0 states:
  - Normal: \(\omega\ (1^{--}), \ h_1\ (1^{+-})\)
  - Exotic: \(0^{--}, \ 2^{+-}\)
  - Unobserved: \(2^{--}\)
- 145k events seen in GlueX-I data
- Amplitude analysis in progress
• $\Lambda(1405)$ lies just below $\bar{K}N$ threshold
  • $I=0, J^P = 1/2^-$
  • Decays to $\Sigma\pi$
• Lineshape not simple B-W
• Nature of state has been long discussed
  • 2 poles?
  • Something else?
• Current lineshape studies limited by knowledge of $\Sigma^0\pi^0$ channel
  • Pure $I=0$, no $\Sigma(1385)$ bkgd.

PPNP 120,103868 (2021)
EPJST 230, 1593 (2021)

CLAS, PRC 87, 035206 (2013)
• Preliminary efficiency-corrected mass spectra shown for GlueX-I data in \( \gamma p \rightarrow K^+ \Sigma^0 \pi^0 \)

• Yields shown in 3 t-bins
  • Clear \( \Lambda(1405) \) and \( \Lambda(1520) \) signals

• With full GlueX-I data, we can study \( E_\gamma \) and t-dependence of lineshape using largest sample of \( \Sigma^0 \pi^0 \) available (>10k events in \( \Lambda(1405) \) region)
Prospects for Cascade Spectroscopy

- The Cascade (ssd, ssu) spectrum is poorly known — nothing new since 1988!
  - LQCD predicts rich spectrum, many narrow states
- CLAS observed photoproduction of ground states
  - Production of excited cascades via a forward-going kaon?

\[
\gamma + p \rightarrow K^+ K^+ (\Xi^-, \Xi^-* \rightarrow \Xi^0 \pi^-)
\]

<table>
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<tr>
<th>State</th>
<th>Quality</th>
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<tbody>
<tr>
<td>(\Xi(1320))</td>
<td>(1/2)^+</td>
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<tr>
<td>(\Xi(1530))</td>
<td>(3/2)^+</td>
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<tr>
<td>(\Xi(1690))</td>
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<tr>
<td>(\Xi(1820))</td>
<td>(3/2)^-</td>
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<td>(\Xi(1950))</td>
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<td>(\Xi(2030))</td>
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Hunting for Excited Cascades

- GlueX has identified peaks corresponding to several of these states
- Cross sections and polarization observables are being measured

**Graphs:**

- **$\Xi^-(1320)$**
- **$\Xi^-(1820)$?**
Charmonium Photoproduction Near Threshold

- Production of $c\bar{c}$ near threshold probes the distribution of gluons in the proton and the nature of the proton mass
- Can also look for $s$-channel production of resonant states

\[ \Lambda_b \rightarrow J/\psi \ p \ K^- \]

$\gamma \ p \rightarrow P_c \rightarrow J/\psi \ p$

LHCb, PRL 122, 222001 (2019)
Published GlueX J/ψ Photoproduction Results

- Used portion of GlueX-I data \([469 \ J/ψ]\) to measure cross sections
- Model-dependent limits set on \(P_c\) production, molecular models preferred
- Limits depend on VMD + understanding of production mechanism

GlueX: PRL 123, 072001 (2019)
• Full GlueX-I data yields 2270 ± 58 J/ψ’s
• Overall normalization uncertainty ~20%
• “Dip” above 9 GeV has 2.6σ (1.3σ) local (global) significance
Comparing GlueX-I results to models

- Models based on gluon exchange and QCD factorization predict smooth energy dependence, connect to gluonic structure of the proton

\[ \sigma(p \rightarrow J/\psi, \text{nb}) \]

- Models with open-charm exchange predict structures at thresholds, shallow t-dependence

GLJ: PRD 103, 096010 (2021)

Du et al., EPJC 80, 1053 (2020)
• Calculate $d\sigma/dt$ including event-by-event luminosity weighting
• Report cross sections at bin means (points)
• Differential cross sections generally consistent with expectations of gluonic exchange, except near threshold

• Room for contributions of box diagrams, etc.—affects $P_c$ interpretation

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<table>
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<th>$\chi^2$/ndf</th>
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<td>$p_0$</td>
<td>1.375 ± 0.6935</td>
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<tr>
<td>$p_1$</td>
<td>1.678 ± 0.4026</td>
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<tr>
<td>$p_2$</td>
<td>0.00442 ± 0.00801</td>
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<tr>
<td>$p_3$</td>
<td>-0.4381 ± 0.4186</td>
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<td>$p_1$</td>
<td>1.26 ± 0.3776</td>
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<tr>
<td>$p_2$</td>
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<tr>
<td>$p_3$</td>
<td>0.3356 ± 0.4655</td>
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<td>$p_1$</td>
<td>1.838 ± 0.2868</td>
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<tr>
<td>$p_2$</td>
<td>0.302 ± 0.1726</td>
</tr>
<tr>
<td>$p_3$</td>
<td>0.5406 ± 0.1106</td>
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Summary and Prospects

- Photoproduction is an interesting process to look for exotic hadrons — crucial to confirm their production in new processes.
- GlueX has collected the world’s largest photoproduction dataset.
  - Collaboration with theory is crucial for understanding.
- First amplitude analyses of $\eta\pi$ and $\eta'\pi$ aim to identify the $\pi_1$ in photoproduction.
  - Analysis of $\omega\pi$ focusing on study of $b_1$ and $\rho'$s.
  - Next step: apply techniques to other PS-PS, V-PS final states.
- Measurements of hyperons like $\Lambda(1405)$ and $\Xi$ baryons promise to provide insight into their structure.
- First detailed studies of $J/\psi$ photoproduction near threshold.
- GlueX-II run in progress, planned to end around 2025.
  - Other approved experimental programs includes JLab Eta Factory, spectroscopy with intense $K_L$ beam ($\approx 10^4$/s), polarized target.
“mass-independent” S-wave

0.1 < t < 0.2 GeV²

$S^+_0$

$S^-_0$

$D^+_2$

$D^-_1$

$a_2(1320)$: Breit-Wigner

M. Albrecht (JLUO 2022)
The GlueX Experiment: Photon Beam

- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization \( P_\gamma \sim 40\% \) in peak
- Intensity of \(~1–5 \times 10^7 \gamma/s\) in peak
Definition of Amplitudes

- Described by three angles: \( \cos(\theta)_\eta \) and \( \phi_\eta \) in the \( \eta \pi \) rest frame, angle \( \Phi \) between polarization vector and production plane

- Amplitudes incorporate beam polarization, are eigenstates of reflectivity \( \epsilon = \pm 1 \)

- Basis: \( Z_l^m \) amplitudes defined as \( Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi} \)

\[
I(\Omega, \Phi) = 2\kappa \sum_k \left\{ (1 - P_\gamma) \left| \sum_{\ell, m} [\ell]_{m;k}^- \text{Re}[Z_\ell^m(\Omega, \Phi)] \right|^2 + (1 - P_\gamma) \left| \sum_{\ell, m} [\ell]_{m;k}^+ \text{Im}[Z_\ell^m(\Omega, \Phi)] \right|^2 + (1 + P_\gamma) \left| \sum_{\ell, m} [\ell]_{m;k}^- \text{Re}[Z_\ell^m(\Omega, \Phi)] \right|^2 + (1 + P_\gamma) \left| \sum_{\ell, m} [\ell]_{m;k}^- \text{Im}[Z_\ell^m(\Omega, \Phi)] \right|^2 \right\}
\]

- Complexity: Positive and negative reflectivity, \( m = -l \ldots l \) allowed

- Frequent exchange with JPAC

[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

Malte Albrecht (IU)
Study of $b_1(1235)$ Decay: Example Fit

- Independent fits for each beam polarization orientation
- Inclusion of $1^{-}$ and $1^{+}$ waves leads to good description of angular distributions
• Clear signals at $a_0(980)$ and $a_2(1320)$ masses
• Different angular dependence $\rightarrow$ different dominant production wave
  • $D_1$ for $\eta\pi^-$, $D_2$ for $\eta\pi^0$

$\eta\pi$ Amplitude Analysis at GlueX

$0.1 < -t < 0.3$ GeV$^2$
• Clear signals at $a_0(980)$ and $a_2(1320)$ masses
  • Peaks have different $t$-dependence

$0.1 < -t < 0.3 \text{ GeV}^2$

$0.3 < -t < 0.6 \text{ GeV}^2$

$0.6 < -t < 1.0 \text{ GeV}^2$
Searching For Hybrid Mesons

- Mesons grouped into nonets of similar $J^{PC}$
  - Must establish quantum numbers and pole parameters through amplitude analysis
- Meson QNs
  - Allowed: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{--}, ...$
  - Forbidden: $0^{--}, 0^{+-}, 1^{+-}, 2^{--}, ...$
- Hybrid Meson QNs
  - $0^{-+}, 0^{+-}, 1^{--}, 1^{+-}, 2^{--}, 2^{+-}, ...$
  - Hybrid mesons can be found with normal and exotic quantum numbers

\[ J=L+S \quad P=(-1)^{L+1} \quad C=(-1)^{L+S} \]

"Normal" Meson

\[(J^{PC})_g = 1^{+-}\]

"Hybrid" Meson

Hybrid–Meson mass splitting $\sim 1.0 - 1.5 \text{ GeV}$
HIGH-T SETTINGS CRUCIAL FOR SENSITIVITY

Improved sensitivity at high t for a given coupling

- Setting 1 with t-channel
  - $P_c(4312,1/2^-)$
  - $P_c(4440,1/2^- + 4457,3/2^-)$

- Setting 2 with t-channel
  - $P_c(4312,1/2^-)$
  - $P_c(4440,1/2^- + 4457,3/2^-)$

- Setting 3 with t-channel
  - $P_c(4312,1/2^-)$
  - $P_c(4440,1/2^- + 4457,3/2^-)$

- Setting 4 with t-channel
  - $P_c(4312,1/2^-)$
  - $P_c(4440,1/2^- + 4457,3/2^-)$

Graphs show the variation of sensitivity with energy for different settings.
4% scale uncertainty on cross section

**SIGNIFICANCE**

**FIT**

**Fit 1**: bare Gaussian shape describes the cross section well

**Fit 2**: Signal + background at GlueX upper limit (90% confidence interval). The resonances lead to major tension with the data at high-$t$.

**Fit 3**: Same as 2, but with Pc at upper limit (90% confidence interval) from the preliminary J/$\psi$-$007$ results themselves

The data suggest a stringent upper limit on the resonant cross section (see next slide).
RESULTS AND IMPLICATIONS

Cross-section at the resonance peak for model-independent upper limits

Upper limit for $P_c$ cross section almost order of magnitude below GlueX limit.

Results are inconsistent with reasonable assumptions for true 5-quark states.

Door is still open for molecular states, but will be very hard to measure in photoproduction due to small overlap with both $\gamma p$ initial state and $J/\psi p$ final state.

To learn more we need a large-acceptance high-intensity photoproduction experiment, and potentially access to polarization observables. This can be achieved with the SoLID-$J/\psi$ experiment.

4% scale uncertainty on cross section limit
Prospects for future $J/\psi$ production measurements

- JLab Hall C measurements also see no clear $P_c$, limits are similarly model-dependent, CLAS12 measurements under way
  - Proposal for double polarization measurements in Hall A
- Future: electro- and photoproduction at SOLID ($\mathcal{L} = 10^{37}\text{ cm}^{-2}\text{s}^{-1}$)
- More future: linearly polarized photoproduction at GlueX with energy-upgraded CEBAF


L. Pentchev, $J/\psi +$ Beyond Workshop
Open Charm Production Near Threshold

- Hadron ($c\bar{c}$) molecules like to decay to open-charm final states, can we see them at GlueX? (c.f. LHCb)
- Also will help with $J/\psi$ interpretation
- Open charm photoproduction cross section measured at SLAC for $E_\gamma \approx 20$ GeV based on $\sim 50$ events
  - Roughly 5-10 larger than $J/\psi$ cross section
  - Exclusive reconstruction of e.g. $D^{(*)0} \Lambda_c^+$ is a factor $\approx 25$ lower due to b.f.s
- Likely need full GlueX-II statistics with improved $\pi/K$ separation

PRL 51, 156 (1983)
Charmonium Photoproduction Near Threshold

Current GlueX energy range

Current max CEBAF energy allows study of bound $c\bar{c}$, $P_c$ states

- 17 GeV $e^-$ gives access to most exotic candidates
- 22 GeV $e^-$ gives good phasespace, linear polarization
JPAC Cross Section Predictions

- JPAC predictions using fixed-spin exchanges near threshold
  - PRD 102, 114010 (2020)
- GlueX can test model by measuring $\chi_{c1}(1P)$, $\psi(2S)$ production
Projections for $J/\psi\pi^+\pi^-$ Photoproduction at GlueX

$\gamma p \rightarrow J/\psi\pi^+\pi^- p$, $J/\psi \rightarrow e^+e^-$

- Assumes 1 year @ 500 pb$^{-1}$, $\text{Br}(X,Y \rightarrow \pi^+\pi^- J/\psi) = 5\%$
- 17 GeV: $N(\psi(2S)) = 400$, $N(X(3872)) = 650$, $N(Y(4260)) = 20$
- 22 GeV: $N(\psi(2S)) = 900$, $N(X(3872)) = 2300$, $N(Y(4260)) = 120$
γp → J/ψπ+π−p, J/ψ → e+e−

- Assumes 1 year @ 500 pb$^{-1}$, Br(X,Y → π+π−J/ψ) = 5%
- 17 GeV [J/ψπ+π−]: N(ψ(2S)) = 400, N(X(3872)) = 650
- 17 GeV [J/ψπ0π0]: N(ψ(2S)) = 40, N(X(3872)) = 300