Exploring **MESON** Photoproduction with the **GlueX** Experiment

MESON 2023  
June 22-27  
Kraków, Poland

Matthew Shepherd  
Indiana University  
(on behalf of the GlueX Collaboration)
Outline

- A brief introduction to the GlueX experiment
- Production of conventional mesons
  - Beam asymmetries for $\pi^0$, $\pi^-$, $\eta$ production
  - Spin-density matrix elements for $\rho$ production
- Status of the search for hybrid mesons
  - Upper limit on the exotic $\pi_1$ cross section
  - Opportunities for $\pi_1$ discovery in photoproduction
- A standard candle: $a_2$ production properties
- Production of $J/\psi$ at threshold
GlueX Goals

- Conduct a high intensity polarized photoproduction experiment that can explore the hadron spectrum up to $c\bar{c}$ threshold
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• Provide a significant contribution to the search for and study exotic hybrid mesons that
  • arise uniquely from the gluon-gluon interaction in QCD
  • some have quantum numbers that are not populated by conventional $q\bar{q}$ mesons
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- Conduct a high intensity polarized photoproduction experiment that can explore the hadron spectrum up to $c\bar{c}$ threshold
- Provide a significant contribution to the search for and study exotic hybrid mesons that
  - arise uniquely from the gluon-gluon interaction in QCD
  - some have quantum numbers that are not populated by conventional $q\bar{q}$ mesons
- Achieving analysis goals depends on strong theory/experiment collaboration
  - part of a combined effort at Jefferson Lab with the Joint Physics Analysis Center and HadSpec LQCD effort
  - future work with the ExoHad DOE Topical Collaboration
Coverage: $1^\circ < \theta < 120^\circ$, all $\phi$
Tracking: $\sigma_p/p \approx 1\% - 5\%$
Calorimetry: $\sigma_E/E \approx 6\% / \sqrt{E} + 2\%$

Liquid Hydrogen Target

see: S. Adhikari et al., NIM A 987, 164807 (2021)
GlueX Data Volume

Through 2020 we have collected about 250 \( \text{pb}^{-1} \) of integrated luminosity in the coherent peak region roughly split 50/50 as "GlueX-I" and "GlueX-II" which has enhanced kaon identification capability.
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Asymmetry of Pseudoscalar Production

- Angle between beam polarization plane and reaction plane $\phi$ is sensitive to $J^P$ of exchange
  - $\sigma(\phi) = \sigma_0[1 - P_\gamma \Sigma \cos(2\phi)]$
  - $\Sigma = +1 \implies 0^+, 1^-, 2^+, \ldots$
  - $\Sigma = -1 \implies 0^-, 1^+, 2^-, \ldots$
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  - $\Sigma = -1 \implies 0^-, 1^+, 2^-, \ldots$
  - Asymmetry $\Sigma$ depends on $t$ in general

Exchange $J^{PC}$
- $1^{--} : \omega, \rho$
- $1^{+-} : b, h$
Asymmetry of Pseudoscalar Production

- Angle between beam polarization plane and reaction plane $\phi$ is sensitive to $J^P$ of exchange
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  - $\Sigma = - 1 \implies 0^-, 1^+, 2^-, \ldots$
- Asymmetry $\Sigma$ depends on a $t$ in general
- Goal: understand and develop models for photoproduction of known mesons
  - learn about available production mechanisms
  - leverage in search for hybrid mesons

Exchange $J^{PC}$

1$^{--}$: $\omega, \rho$

1$^{+-}$: $b, h$
Asymmetry of Pseudoscalar Production

- No sophisticated understanding of detector acceptance required
- GlueX $\pi^0$ production asymmetry repeats older measurements by SLAC
- General trend: production dominated by natural parity exchange except when $\pi$-exchange is allowed

GlueX Collaboration, PRC 95, 042201(R) (2017)

Asymmetry of Pseudoscalar Production

\[ \gamma p \to p\pi^0 \]

- GlueX $8.4 < E < 9.0$ GeV
- SLAC $E = 10$ GeV
Asymmetry of Pseudoscalar Production

- No sophisticated understanding of detector acceptance required
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- General trend: production dominated by natural parity exchange except when $\pi$-exchange is allowed

\[ \gamma p \rightarrow p\pi^0 \]

\[ \gamma p \rightarrow \pi^- \Delta^{++} \]

\[ \text{GlueX Collaboration, PRC 95, 042201(R) (2017)} \]

\[ \text{GlueX Collab., Phys. Rev. C 103, 022201 (2021)} \]
Spin-Density Matrix Elements

- Reaction: $\gamma p \rightarrow p\rho$, where $\rho \rightarrow \pi^+\pi^-$
- SDMEs describe the transfer of polarization from the beam photon to the $\rho$ meson
Spin-Density Matrix Elements

- Reaction: $\gamma p \rightarrow \rho p$, where $\rho \rightarrow \pi^+\pi^-$
- SDMEs describe the transfer of polarization from the beam photon to the $\rho$ meson
- Obtain by fitting three-dimensional angular distribution for data
  - requires understanding of detector acceptance
  - extract as a function of $t$
  - systematics limited

\[
W(\cos \vartheta, \varphi, \phi) = W^0(\cos \vartheta, \varphi) - P_\gamma \cos(2\phi) W^1(\cos \vartheta, \varphi) - P_\gamma \sin(2\phi) W^2(\cos \vartheta, \varphi)
\]

\[
W^0(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \frac{1}{2} (1 - \rho_{00}^0) + \frac{1}{2} (3\rho_{00}^0 - 1) \cos^2 \vartheta - \sqrt{2} \text{Re}\rho_{10}^0 \sin 2\vartheta \cos \varphi - \rho_{1-1}^0 \sin^2 \vartheta \cos 2\varphi \right)
\]

\[
W^1(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \rho_{11}^1 \sin^2 \vartheta + \rho_{00}^1 \cos^2 \vartheta - \sqrt{2} \text{Re}\rho_{10}^1 \sin 2\vartheta \cos \varphi - \rho_{1-1}^1 \sin^2 \vartheta \cos 2\varphi \right)
\]

\[
W^2(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \sqrt{2} \text{Im}\rho_{10}^2 \sin 2\vartheta \sin \varphi + \text{Im}\rho_{1-1}^2 \sin^2 \vartheta \sin 2\varphi \right)
\]
Spin-Density Matrix Elements

- $< 10\%$ of GlueX data collected to date
Spin-Density Matrix Elements

- < 10% of GlueX data collected to date
- Example fit for $-t \approx 0.2$ GeV$^2$

**Data**
- Signal Model
- Background

**Background**

**Signal Model**

**Data**

**Spin-Density Matrix Elements**

$F_{0}$ and $F_{2}$ are very well reproduced. A small asymmetry between the $F_{0}$ and $F_{2}$ wave component, which is not included in the SDME model.

**D. Discussion of Uncertainties**

A study of many possible sources for systematic uncertainties is combined with the statistical uncertainty of the SDMEs calculated for all bins in the design and the operation of the triplet polarimeter instrument.

The largest contribution to the systematic uncertainty originates from the external measurement of the beam-photon polarization. The $1\%$ uncertainty on the photon beam flux and the selection of the signal sample.

The injection of randomly triggered hits into the simulation from an apparent rate dependence of the detector efficiency. The Monte Carlo simulation does not include any detector-specific rate-dependent efficiencies. Since the primary electron beam current was increased from 100 nA to 150 nA for the second part of the data sample, we perform the analysis separately for these two conditions.

The injection of randomly triggered hits into the simulation successfully models the rate effect on the track reconstruction.

The overall normalization uncertainty is less than $5\%$ systematic uncertainty inherent in the polarization extraction is dependent on the polarization.

The $1\%$ uncertainty is combined with the statistical uncertainty of the SDMEs and the uncertainty in the proportion of the data sample polarized.

This overall normalization uncertainty is fully correlated within the range studied.
JPAC model [PRD 97, 094003 (2018)]
expected to be valid in the region where

\[-t < m^2_{\rho} .\]

As \( t \to 0 \) one expects
SDMEs consistent with
\( s \)-channel helicity
conservation and natural
parity exchange.
FIG. 7. The spin-density matrix elements for the photoproduction of \( \rho^0 \) mesons. See comments in Fig. 6 caption for details.

FIG. 8. Parity asymmetry results for the photoproduction of \( \rho^0 \) mesons. See comments in Fig. 6 caption for details.

To prove Eq. (30), we expand Eqs. (28) and (29) as follows:

\[
\rho_{ij}^{\sigma} = \rho_{ij}^{\sigma} + \Delta \rho_{ij}^{\sigma}
\]

where the photon helicity and the vector-meson helicity \( l \) are zero, additional relations include terms where the photon helicity and the vector-meson helicity \( l \) is not zero. This provides a complete set of relations for the polarized SDMEs. The systematic uncertainties for the polarized SDMEs are displayed in Fig. 7.

JPAC model [PRD 97, 094003 (2018)] expected to be valid in the region where \(-t < m_{\rho}^2\). As \( t \to 0 \) one expects SDMEs consistent with \( s \)-channel helicity conservation and natural parity exchange.
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In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3) flavor symmetry, we characterize mesons in terms of their SU(3) representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5).

The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the 'light' quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to 'annihilation dynamics.' In Fig. 13 we present the spectra extracted on two lattice volumes.
State of the Art

- Best evidence for existence of exotic hybrid mesons is from pion production at COMPASS which has been analyzed by JPAC
  - only the published partial wave expansion was available for JPAC analysis

exotic $I^+\pi$ amplitudes from COMPASS Collab., PLB 740, 303 (2015)
State of the Art

- Best evidence for existence of exotic hybrid mesons is from pion production at COMPASS which has been analyzed by JPAC
  - only the published partial wave expansion was available for JPAC analysis
- Coupled channel fit to $\eta\pi$ and $\eta'\pi$ partial waves in pion production measured by COMPASS
  - data consistent with a single exotic pole
  - recently extended to include Crystal Barrel (LEAR) data: further constrains the width to about 400 MeV

![Graph showing exotic $I^+\chi$ amplitudes from COMPASS Collab., PLB 740, 303 (2015)](image)
How do hybrids decay?

PHYSICAL REVIEW D 103, 054502 (2021)

Decays of an exotic $1^{-+}$ hybrid meson resonance in QCD

Antoni J. Woss, Jozef J. Dudek, Robert G. Edwards, Christopher E. Thomas, and David J. Wilson

(for the Hadron Spectrum Collaboration)

<table>
<thead>
<tr>
<th>$\Gamma_i/\text{MeV}$</th>
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<tbody>
<tr>
<td>$\eta\pi$</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>$b_1\pi$</td>
</tr>
<tr>
<td>$K^*\bar{K}$</td>
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<tr>
<td>$f_1(1285)\pi$</td>
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$\Sigma_i \Gamma_i$
Decays of an exotic $1^{-+}$ hybrid meson resonance in QCD

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Setting Limits on $\pi_1$ Production

$\mathcal{a}_2(1320)$

$I^G(j^{PC}) = 1^-(2^{++})$

Mass $m = 1318.2 \pm 0.6$ MeV \ $(S = 1.2)$
Full width $\Gamma = 107 \pm 5$ MeV \ [i]

$\mathcal{a}_2(1320)$ DECAY MODES

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Scale factor/Confidence level</th>
<th>$p$ (MeV/c)</th>
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</thead>
<tbody>
<tr>
<td>$3\pi$</td>
<td>(70.1 $\pm$ 2.7) %</td>
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Goals:
- set limit on $\sigma(\gamma p \rightarrow \pi_1^- \Delta^{++}) \times \mathcal{B}(\pi_1 \rightarrow b_1\pi)$
- use LQCD lower limit on $\mathcal{B}(\pi_1 \rightarrow b_1\pi)$ to place an upper limit on $\sigma(\pi_1)$
- repeat for $\Delta^{++} \rightarrow p$
Setting Limits on $\pi_1$ Production

$\bar{a}_2(1320)$

$I^G(j^{PC}) = 1-(2++)$

Mass $m = 1318.2 \pm 0.6$ MeV  \(S = 1.2\)
Full width $\Gamma = 107 \pm 5$ MeV \([i]\)

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- Goals:
  - set limit on $\sigma(\gamma p \rightarrow \pi_1^-\Delta^{++}) \times \mathcal{B}(\pi_1 \rightarrow b_1\pi)$
  - use LQCD lower limit on $\mathcal{B}(\pi_1 \rightarrow b_1\pi)$ to place an upper limit on $\sigma(\pi_1)$
  - repeat for $\Delta^{++} \rightarrow p$

\[
\sigma(\gamma p \rightarrow \omega\pi\pi) < 1.40
\]

\[
\sigma(\pi_t^0)_{ul} < \frac{\sigma(a_2(1320))}{\sigma(\omega\pi\pi)} < 2.09
\]
Implications on the Hybrid Search Strategy

- Use LQCD calculations of partial width limits to guide the exotic hybrid search strategy.

![Graph 1](image1.png)

\[ \gamma p \rightarrow \eta \pi^0 p \]

- Events/20 MeV/c^2

\[ M(\eta \pi^0) [\text{GeV/c}^2] \]

![Graph 2](image2.png)

\[ \gamma p \rightarrow \eta \pi^- \Delta^{++} \]

- Events/20 MeV/c^2

\[ M(\eta \pi^-) [\text{GeV/c}^2] \]
Implications on the Hybrid Search Strategy

- Use LQCD calculations of partial width limits to guide the exotic hybrid search strategy
- Large $P$-wave contribution is excluded for $\eta\pi$ but not $\eta'\pi$
- Need to use $a_2(1320)$ as a "standard candle" and interferometer for the hybrid search
Production of $a_2(1320)^-0$ and $a_0(980)^-0$ at low $t$

$0.1 < -t < 0.3$ GeV$^2$

- Production of $a_2^-$ and $a_0^0$ clearly populate different $a_2$ polarization states
- $a_2$ polarization is independent of whether it decays to $\eta\pi$ or $\eta'\pi$
- Use high statistics $\eta\pi$ decay to constrain $a_2$ amplitude in $\eta'\pi$ analysis
Role of Photon Polarization

- Make use of this additional dimension ($\Phi$) in the amplitude analysis to gain insight into production mechanisms as well as resonance properties through decay ($\phi, \theta$)

---

$$\vec{\gamma}p \rightarrow \eta\pi p'$$

($\eta\pi$ helicity frame)

V. Mathieu et al. [JPAC], PRD 100, 054017 (2019)
Role of Photon Polarization

- Make use of this additional dimension ($\Phi$) in the amplitude analysis to gain insight into production mechanisms as well as resonance properties through decay ($\phi, \theta$)
- Write amplitudes in the reflectivity basis: $\epsilon = \pm 1$, which have a non-trivial distribution in $\Phi$
- Define naturality: $P(-1)^J$
  - natural parity: $P(-1)^J = +1$; $\mathcal{J}^P = 0^+, 1^-, 2^+, \ldots$
  - unnatural parity: $P(-1)^J = -1$; $\mathcal{J}^P = 0^-, 1^+, 2^-, \ldots$
- High energy $t$-channel picture: the reflectivity fixes the product of the naturalities of the exchange particle and the produced resonance
Extracting $a_2^0$ Production

- In general $a_2$ can be produced in 2 exchanges, each with 5 polarizations
  - theory argues for a small set of dominant amplitudes [JPAC, PRD 102, 014003 (2020)]
- dominant: $D_2^+$ -- $m = 2$ natural parity
  - similar to $a_2$ production in two photon collisions
- exchange mechanisms add incoherently: extract differential cross section for each mechanism

$S^+_0$

$D_2^+$

$M(\eta\pi) [\text{GeV/c}^2]$

Entries / 40 MeV

$M(\eta\pi) [\text{GeV/c}^2]$

Entries / 40 MeV

assume $a_2$ is a textbook Breit-Wigner resonance

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assume $a_2$ is a textbook Breit-Wigner resonance
Additional Mechanism for $a_2^-$ Production

- Production of $a_2^-$ can proceed by pion exchange
  - large $a_2 \rightarrow \rho \pi$ coupling
- Observe polarization transfer from beam to $a_2$ ($m = 1$)
- The $a_2^-$ cross section is about an order of magnitude larger than $a_2^0$

At low momentum transfer, $a_2^-$ production is dominated by unnatural parity ($\epsilon = -$) exchange.

\[ \gamma p \rightarrow \eta \pi^- \Delta^{++} \]

\[ J^e_m = \]

- Total
- $D_1^-$
- $D_1^+$
- $D_2^+$

Preliminary

\[ \frac{a_2^0}{\pi} = \frac{a_2^0}{m} \]

\[ a_2(1320) \]

\[ a_0(980) \]
Current Status of $\pi_1$ Search

- Lattice QCD calculations from hadSpec combined with data confirm that $\gamma p \to \eta' \pi^- \Delta^{++}$ is the most promising reaction to search.

![Graph showing $\gamma p \to \eta' \pi^- \Delta^{++}$]
Current Status of $\pi_1$ Search

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![Graph](image.png)

GlueX Phase-I

search for resonances in decay angles
Current Status of $\pi_1$ Search

- Lattice QCD calculations from hadSpec combined with data confirm that $\gamma p \to \eta' \pi^- \Delta^{++}$ is the most promising reaction to search.
- Distribution of $\eta'\pi^-$ decay is consistent with COMPASS data:
  - interpreted by JPAC as interference between $a_2$ and exotic $\pi_1$ resonances.
  - forward/backward asymmetry indicates interference between even and odd (exotic) partial waves.
- Further analysis is needed to draw quantitative conclusions:
  - phenomenology of $a_2$ production is a key ingredient.

**Figure 1.** Invariant mass spectra (not acceptance corrected) for (a) $\pi^-$ in the mass range $40\text{ MeV} - 1.320\text{ GeV}$.

**Figure 2.** Positive $t$-wave interference pattern as COMPASS data is consistent with COMPASS data.
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Photoproduction of $J/\psi$

- Threshold: $E_\gamma = 8.3$ GeV

$J/\psi$ yield: 
$2270 \pm 58$ events
Photoproduction of $J/\psi$

- Threshold: $E_\gamma = 8.3$ GeV
- Multiple physics interests:
  - gluon exchange as a probe of proton structure
  - search for pentaquark resonances
- Understanding production mechanism is critical

![Graph showing photoproduction of $J/\psi$]
Total and Differential Cross Section

- Structure in $\sigma$ vs. $E_{\gamma}$

$\sigma(\gamma p \rightarrow J/\psi p)$ [nb]

$E_{\gamma}$ [GeV]
Total and Differential Cross Section

- Structure in $\sigma$ vs. $E_\gamma$
- Interesting $d\sigma/dt$ at low $E_\gamma$
- Consistent with $J/\psi - 007$ (Hall C)
Thresholds and Pentaquark Resonances

- Conspicuous structure at open charm thresholds
- Production mechanism must be understood to interpret data
- More precision and polarization observables would be desirable

![Graph showing integrated cross section of all four models compared to GlueX data](image)

**JPAC, arXiv:2305.01449**

**JPAC**

see talk by A. Szczepaniak on Tuesday

**GlueX Collab., arXiv:2304.03845**

to be published in Phys. Rev. C
Summary and Outlook

• The GlueX experiment is pursuing a broad program in hadron physics using polarized photoproduction (see also the talk by Volker Crede on Friday evening)

acknowledgement: gluex.org/thanks
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• Initial results provide detailed information about the production mechanisms of conventional mesons: motivates theoretical descriptions

• Using Lattice QCD and previous experimental data we can limit $\pi_1$ cross section in photoproduction and identify most promising discovery opportunities in photoproduction

• stay tuned -- anticipate more results in the future

• first step in a broader hybrid search in photoproduction (see also talk by Frank Nerling on Saturday afternoon)

• Photoproduction of $J/\psi$ at threshold has interesting implications on spectroscopy and proton structure -- more data and polarization observables is desirable

acknowledgement: gluex.org/thanks
Summary and Outlook

- The GlueX experiment is pursuing a broad program in hadron physics using polarized photoproduction (see also the talk by Volker Crede on Friday evening).
- Initial results provide detailed information about the production mechanisms of conventional mesons: motivates theoretical descriptions.
- Using Lattice QCD and previous experimental data we can limit \( \pi_1 \) cross section in photoproduction and identify most promising discovery opportunities in photoproduction.
  
- Stay tuned -- anticipate more results in the future.
- First step in a broader hybrid search in photoproduction (see also talk by Frank Nerling on Saturday afternoon).
- Photoproduction of \( J/\psi \) at threshold has interesting implications on spectroscopy and proton structure -- more data and polarization observables is desirable.
- GlueX will resume data taking in 2024 after a calorimeter upgrade; plenty of topics to work on -- new collaborators are welcome!

acknowledgement: gluex.org/thanks