Amplitude Analysis of $a_2 \rightarrow \eta \pi$ at GlueX
QNP 2022

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on Behalf of the GlueX Collaboration

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Overview

1. The $\eta\pi$ System
   - What we want to measure

2. The GlueX Experiment
   - Large acceptance detector
   - Polarized $\gamma$ beam at 8.5 GeV

3. Amplitude Analysis of $\eta\pi$ at GlueX
   - $\gamma p \rightarrow \eta\pi^0 p$
   - $\gamma p \rightarrow \eta\pi^- \Delta^{++}$

4. Outlook
• The goal of GlueX is to map the spectrum of light hybrid mesons
• The $\eta(\prime)\pi$ system is an ideal place to start
• For orbital angular momentum $L = 0, 1, 2, 3, \ldots$ of the $\eta(\prime)\pi$ system, we gain access to $J^{PC}$

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• $\eta\pi$ in a $P$–wave results in exotic quantum numbers (non $q\bar{q}$)
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$\eta\pi$ in a $P$–wave results in exotic quantum numbers (non $q\bar{q}$)

Key questions:

1. What is the nature and interpretation of the $\pi_1$ ($J^{PC} = 1^{-+}$)?
2. How are hybrid states produced?
• The goal of GlueX is to map the spectrum of light hybrid mesons
• The $\eta^{(')}\pi$ system is an ideal place to start
• For orbital angular momentum $L = 0, 1, 2, 3, ..$ of the $\eta^{(')}\pi$ system, we gain access to $J^{PC}$

\[
\begin{array}{cccccc}
L & S & P & D & F & \\
J^{PC} & 0^{++} & 1^{--} & 2^{++} & 3^{--} & ...
\end{array}
\]

• $\eta\pi$ in a $P$–wave results in exotic quantum numbers (non $q\bar{q}$)

• Key questions:
  1. What is the nature and interpretation of the $\pi_1$ ($J^{PC} = 1^{--}$)?
  2. How are hybrid states produced?

• Build foundation for hybrid searches by studying $\eta\pi$ system
• Focus of this talk is on $a_2(1320) \rightarrow \eta\pi$
The GlueX Experiment

- Linearly polarized photon beam
- Large acceptance for charged and neutral final state particles
- 120 pb$^{-1}$ data collected in GlueX Phase–1 ($E_\gamma = 8.2 - 8.8$ GeV)
First stage: study known resonances (e.g. $a_0(980) \to \eta\pi$, $a_2(1320) \to \eta\pi$) to build the foundation for hybrid meson searches at GlueX.

- Access to multiple channels:
  1. $\gamma p \to \eta\pi^0 p$
     - $\eta \to \gamma\gamma$
     - $\eta \to \pi^+\pi^-\pi^0$
  2. $\gamma p \to \eta\pi^-\Delta^{++}$
     - $\eta \to \gamma\gamma$
     - $\eta \to \pi^+\pi^-\pi^0$
  3. $\gamma p \to \eta'\pi^0 p$,
     $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
  4. $\gamma p \to \eta'\pi^-\Delta^{++}$,
     $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
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• Access to multiple channels:

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   • $\eta \rightarrow \gamma\gamma$
   • $\eta \rightarrow \pi^+\pi^-\pi^0$

2. $\gamma p \rightarrow \eta\pi^-\Delta^{++}$
   • $\eta \rightarrow \gamma\gamma$
   • $\eta \rightarrow \pi^+\pi^-\pi^0$

3. $\gamma p \rightarrow \eta'\pi^0 p$, $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma\gamma$

4. $\gamma p \rightarrow \eta'\pi^-\Delta^{++}$, $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma\gamma$

• Different decay modes should contain same physics
  ⇒ Understand Acceptance
  ⇒ Handling of backgrounds

• Charged and neutral decays are complementary
\( \gamma p \rightarrow \eta \pi N \)

- Goal is to measure \( a_2 \) cross section as a function of \( t \)
- Mass distributions provide insight into how resonances and backgrounds evolve

\[ 0.1 < -t < 0.3 \text{ GeV}^2 \]
\[ \gamma p \rightarrow \eta \pi N \]

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Angular Distributions in $\eta\pi$

Gottfried-Jackson Frame

![Graph showing angular distributions in $\eta\pi$]

Rest Frame of $X$ where $X \rightarrow \eta\pi$

where $X \rightarrow \eta\pi$

$\vec{p}_{\gamma_i}^{\prime \text{com}} = z_{GJ}$
Angular Distributions in $\eta\pi$

Gottfried-Jackson Frame

- $D_1$ ($L = 2$, $m = 1$) structure at $\approx 1300$ MeV in $\eta\pi^-$ system ($a_2(1320)$)
- Similar to COMPASS $D$ wave in $\eta\pi^-$

(PLB 740, 303 (2015))
Angular Distributions in $\eta\pi$

Gottfried-Jackson Frame

Rest Frame of $X$
where $X \rightarrow \eta\pi$

- $D_2$ ($L = 2, m = 2$) structure at $\approx 1300$ MeV in $\eta\pi^0$ system ($a_2(1320)$)
- Belle: $\gamma\gamma \rightarrow \eta\pi^0$ sees $a_2$ produced in $D_2$ state (PRD 80, 032001 (2009))
Amplitude Analysis on $\gamma p \rightarrow \eta \pi N$

Polarized Amplitudes (PRD 100 (2019) 5, 054017)

- Introduce polarized photoproduction amplitudes to incorporate beam polarization
- System described by $\Omega = \theta, \phi$ (in GJ or Helicity frame) and $\Phi$, the polarization angle

$$I(\Omega, \Phi) \propto (1 - P_\gamma) \sum_{\ell} |[\ell]_m^{(-)} \text{Re}[Z_{\ell}^m(\Omega, \Phi)]|^2 + (1 - P_\gamma) \sum_{\ell} |[\ell]_m^{(+) \text{Im}}[Z_{\ell}^m(\Omega, \Phi)]|^2$$

$$+ (1 + P_\gamma) \sum_{\ell} |[\ell]_m^{(+)} \text{Re}[Z_{\ell}^m(\Omega, \Phi)]|^2 + (1 + P_\gamma) \sum_{\ell} |[\ell]_m^{(-)} \text{Im}[Z_{\ell}^m(\Omega, \Phi)]|^2$$

- Basis: $Z_{\ell}^m(\Omega, \Phi) = Y_{\ell}^m(\Omega)e^{-i\Phi}$
- Fit $[\ell]_m^\pm$ coefficients to the data
  - $\pm$ corresponds to the naturality of exchange particle
  - $m = -\ell, \ldots, \ell$
Introduce polarized photoproduction amplitudes to incorporate beam polarization

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- Starting waveset $(S^{\pm}_0, D^{\pm}_{-1,0,1}, D^{+}_2)$ set chosen from tensor meson decay model from JPAC (PRD 102 (2020))
Mass Independent Fit to $\gamma p \rightarrow \eta\pi^0 p$

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

- Dominant structure in $a_0(980)$ is the $S^+_0$ wave ✓
- Large $S^+_0$ under $a_2(1320)$
  - Leakage or acceptance effect?
  - Contribution from other resonance?
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- Similar intensities of $S_0^+$ and $D_2^+$?
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- Working on identifying $a_2(1700)$
  - Will need to identify correct waves and confirm phase motion for hybrid search
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- Similar intensities of $S_0^+$ and $D_2^+$?
- Working on identifying $a_2(1700)$
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- How does $D$ wave evolve as a function of $-t$?
Our goal is to try to extract \( t \)-dependent cross section of \( a_2 \rightarrow \eta \pi \).

Initial strategy: mass independent fits to extract intensities, phase difference

- Model independent, but challenges arise in waveset choice, ambiguities, leakage, etc.

New approach: “Model Semi-Independent” fit

- The \( a_2(1320) \) is isolated, so we can limit the fit to the relevant mass range
- Model \( a_2(1320) \) with a relativistic Breit Wigner
- Phase-motion of D-wave (BW) serves as anchor-point in these fits, may eliminate ambiguities
- \( S_0 \) wave is fit on a bin by bin basis
$a_2(1320) \rightarrow \eta \pi^0$ Model Semi-Independent Fit

“mass-independent” S-wave

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

$S_0$

$a_2(1320)$

Theory (JPAC)

$\Gamma_B(1320)$: Breit-Wigner
$a_2(1320) \rightarrow \eta\pi^0$ Cross Section

- Good agreement between theory and data
- Systematic studies underway
- Inclusion of $a_2(1700)$ has significant impact on extracted cross section
Mass Independent Fits for $\gamma p \rightarrow \eta\pi^-\Delta^{++}$

- Dominant structure in $a_0^-(980)$ is the $S_0^-$ wave ✓
- Some $S_0^+$ under $a_2(1320)$
• Dominant structure in $a_0^-(980)$ is the $S_0^-$ wave ✓
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• $a_2^-(1320)$ should be dominated by $D_1^-$
Mass Independent Fits for $\gamma p \rightarrow \eta\pi^- \Delta^{++}$

- Dominant structure in $a_0^-(980)$ is the $S_0^-$ wave ✓
- Some $S_0^+$ under $a_2(1320)$
- $a_2^-(1320)$ should be dominated by $D_1^-$

- Dominant structure is $D_1^-$ ✓
  - unnatural ($\pi$) parity exchange expected to dominate at low $-t$
- $D_0^-$ also has a large contribution
- Tail in $D_1^-$ wave related to $a_2(1700)$?
- Progress being made on hybrid fits and cross sections in the channel
Comparison of the Neutral and Charged Channels

\[ a_2(1320) \rightarrow \eta \pi^0 \]

- Dominated by natural parity \((\rho, \omega)\) exchange at low \(t\)
- \(m = 2\) wave has the largest contribution
Comparison of the Neutral and Charged Channels

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Comparison of the Neutral and Charged Channels

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\[ a_2(1320) \rightarrow \eta\pi^- \]
- Dominated by unnatural parity \((\pi)\) exchange at low \(t\)
- \(m = 1\) wave has the largest contribution

- Both channels have the \(D\) wave structure evolving with \(t\)
- Targeting \(a_2(1320)\) production for a near term publication
- Laying the foundation for hybrid meson \((P\) wave\) searches at GlueX
Outlook

- Large, high-quality data set with access to multiple $\eta\pi$ channels
- Focusing on understanding $a_2$ production before moving onto weaker $P$ wave
- Preliminary results are consistent with $\pi$, $\eta$ production at low $t$
- Critical for us to understand $a_2(1700)$, phase motion, and alternative processes
- Close relationship with theorists (JPAC) on interpretation of results
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• Critical for us to understand $a_2(1700)$, phase motion, and alternative processes
• Close relationship with theorists (JPAC) on interpretation of results
• Building the foundation for hybrid searches in $\eta^{(')}\pi$

• GlueX Acknowledgments: gluex.org/thanks