Search for Exotic Mesons in Photoproduction at JLAB CLAS

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New Partial Wave ANALYSIS TOOLS FOR NEXT GENERATION HADRON SPECTROSCOPY EXPERIMENTS
CLAS g12 Run Summary

CLAS geometry optimized for peripheral production acceptance

\[ E_\gamma \text{ 5.715 GeV} \]

\text{g12 run period} \quad 70 \text{ days experimental run}

\textbf{Production Data}

\begin{itemize}
  \item \( I = 60-65 \text{ nA} \)
  \item \( E_\gamma = 3.584 - 5.453 \text{ GeV} \)
  \item 26.2 Billion events
  \item mixed triggers
  \item 68 \text{ pb}^{-1}
\end{itemize}

\textbf{Hadron Spectroscopy Analyses}

\begin{align*}
\gamma p & \rightarrow n \pi^+ \pi^+ \\ 
\gamma p & \rightarrow p \pi^- \pi^+ \pi^0 \\ 
\gamma p & \rightarrow p K^+ K^- \eta \\ 
\gamma p & \rightarrow \Delta^{++} \pi^- \eta \\ 
\gamma p & \rightarrow \Delta^{++} \pi^- \pi^- \pi^+ \\ 
\gamma p & \rightarrow \Lambda K^+ \pi^- \pi^+ \\ 
\gamma p & \rightarrow \Xi^- K^+ K^+ \\ 
\gamma p & \rightarrow p p \text{ anti-p} \\
+ & \ldots
\end{align*}
Analysis of $\gamma p \rightarrow n \pi^+\pi^+\pi^- *$

3\pi Event Selection

Identification of $\gamma p \rightarrow \pi^+\pi^+\pi^- n$ events

- $\pi^+\pi^+\pi^-$ events isolated by vertex and timing cuts
- Neutron identified by missing mass

Identification of $\gamma p \rightarrow Xn \rightarrow \pi^+\pi^+\pi^- n$ events

- $\gamma p \rightarrow N^*\pi\pi$ events removed by requiring low-$t'$ and small $\theta_{lab}$ for both $\pi^+$
3π Invariant Mass

Sharp $t$ dependence consistent with $\pi$-exchange production

Baryon background cuts: $|t'| < 0.1 \text{ and } \theta_{\text{lab}}(\pi^+) < 25^\circ$
PWA wave set

Major waves

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^{\varepsilon}$</th>
<th>$L$</th>
<th>$Y$</th>
<th># waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>1++</td>
<td>$1^{\pm}$</td>
<td>$S$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>1++</td>
<td>$1^{\pm}, 0^{+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>3</td>
</tr>
<tr>
<td>1--</td>
<td>$0^{-}, 1^{\pm}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>3</td>
</tr>
<tr>
<td>2++</td>
<td>$1^{\pm}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>2--</td>
<td>$0^{-}, 1^{\pm}$</td>
<td>$S,P,D$</td>
<td>$f_2(1270), \rho(770)$</td>
<td>9</td>
</tr>
</tbody>
</table>

+ isotropic background wave

unpolarized beam
- Photon beam is a coherent mixture of both parity eigenstates
- Final states of different reflectivity do not interfere

π exchange dominance
- Equal production of $M^{\varepsilon} = 1^{+}$ and $1^{-}$ (ambiguity)
- No $M^{\varepsilon} = 0^{\varepsilon}$
  - No $J=0$ meson production (spin zero filter)
PWA 2++

$2^{++} 1^{\pm} [\rho(770)\pi]$ Intensity

- Equal population of both reflectivity states
- No observation in $M=0$ wave

$\text{Events per 20 MeV/c}^2$

$a_2(1320)$
PWA 1++ S wave

$1^{++}1^\pm [\rho\pi]_S$ Intensity

Events per 20 MeV$/c^2$

$M(\pi^+\pi^+\pi^-)$ (MeV$/c^2$)

preliminary
PWA: $1^{++} - 2^{++}$ Mass Dependency

$a_1(1260)$
PDG nominal values
$M = 1230 \pm 40 \text{ MeV}$
$\Gamma = 250 - 600 \text{ MeV}$

$a_2(1320)$
PDG nominal values
$M = 1318 \text{ MeV}$
$\Gamma = 107 \text{ MeV}$

preliminary
PWA: $2^{-+} f_2 \pi$ S–waves

$\times 10^5 2^{-+} [f_2(1270)\pi]_S$ Intensity

• Large signal in $M=0$ wave

$\pi_2(1670)$

preliminary
PWA: 2−+ D & P waves

\[ \pi_2(1670) \rightarrow f_2\pi \]
D–wave

\[ \pi_2(1670) \rightarrow \rho\pi \]
P–wave

\[ M^e = 1^- \]

preliminary
**PWA 2--+ Intensity**

BW Fit to the $2^{-+} f_{2\pi}$ Intensity

- $A = 3.34 \times 10^5 \pm 1.46 \times 10^4$
- $M = 1.65 \times 10^3 \pm 4.06$
- $\Gamma = 235 \pm 11.6$

π₂(1670)

PDG nominal values
- $M = 1672$ MeV
- $\Gamma = 259$ MeV

preliminary
PWA 1−+ Exotic Wave

- No clear resonance signal
- High mass results fluctuate
- Accounts for at most 2% of total intensity
No evidence for exotic $1^{-+}$ phase motion

Phase motion consistent with resonating $2^{-+}$
Where is the $\pi_1(1600)$ in photoproduction?

Current CLAS g12 analysis

$\gamma \rightarrow X^+ \to \pi^+$ exchange

$\pi^-$ exchange

Also observed via: $X^- \to \eta', f_1\pi^-, (b_1\pi)^-$

Non-observation of $\pi_1(1600)$ in charge exchange photoproduction is consistent with exotic production via Pomeron

However, $\pi_1(1600) \to \rho\pi$ but not $\rho\pi \to \pi_1(1600)$

If true then C–Parity forbids photoproduction of $\pi_1(1600)$

Allowed $J^{PC}$:
[S, P, D wave pomeron production]

1--, 0++, 1+, 2++, 1--, 2--, 3--

Isovector $G = +1$ channels:

2$\pi$, 2$\pi\eta$,..

Isoscaler $G = -1$ channels:

$\pi\eta$, $\pi\eta\eta$, 3$\pi$, 3$\pi\eta$,..
Conclusions

- CLAS–g12 acquired new data set of ~1M exclusive $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$ events
- Performed mass independent PWA from 1.0 – 2.0 GeV/c$^2$ on several subset of events
  - Unpolarized photon beam with pion exchange dominance (low t `cut)
    - J = 0 and M = 0 suppression, equal production of $M^\pm = 1^+ \& 1^-$
- Cleanly observe 1$^{++}$, 2$^{++}$, and 2$^{-+}$ well known resonance features
  - Narrow 1$^{++}$ may indicate a Deck free $a_1(1260)$ observation
- $\pi_1(1600)$ exotic signal is not observed in charged exchanged photoproduction
  - If $\pi_1(1600) \rightarrow \rho\pi$ exists, then non-observation in charge exchange photoproduction is consistent with hybrid production via Pomeron
    - If true then C-Parity forbids photoproduction of $\pi_1(1600)$
3π Data Features

before final selections

Copious baryon backgrounds present!
**Baryon background reduction**

Before Selection

After Selection

\[ \left| t' \right| < 0.105 \]
\[ \theta_{lab}(\pi^+) < 25^\circ \text{ (both)} \]

\[ e^{-3.9t'} \]

Sharp \( t' \) dependence consistent with \( \pi \)-exchange production
Data Features

Mandelstam $t$ & $t'$
Data Features

Accepted Yields
Data Features

Accepted Yields
$3\pi$ from other experiments
Partial Wave Analysis

\[ I(\tau) = \sum_{k \in \mathbb{E}} \epsilon \epsilon' \rho_{\epsilon \epsilon'}(\delta) \sum_{\alpha \alpha'}^{k \in \mathbb{E}} V_{\alpha}^* \epsilon' A_{\alpha'}^{\epsilon'}(\tau) k \epsilon V_{\alpha} \epsilon A_{\alpha}(\tau) \]

For unpolarized beam & target:

\[ I(\tau) = \frac{1}{2} \sum_{k \in \mathbb{E}} \left| \sum_{\alpha}^{k \in \mathbb{E}} V_{\alpha} \epsilon A_{\alpha}(\tau) \right|^2 \]

Helicity Decay Amplitudes

\[ A_{\alpha, M}(\tau) = A_{\lambda_1, \lambda_2; M}^{X} \ast A_{\nu_1, \nu_2; \lambda_1; \ldots}^{iso} \]

\[ A_{\lambda_1, \lambda_2; M}^{X} = D_{\lambda M}^{J}(\theta, \phi) \frac{\tilde{L}}{J} (L \Theta; S \lambda | J \lambda) (S_1 \lambda_1; S_2 - \lambda_2 | S \lambda) K \]

Mass Dependent Isobar Propagator

\[ \rho_{\epsilon \epsilon'}(\delta) = \frac{1}{2} \left( 1 - P (\cos^2(\delta) - \sin^2(\delta)) \right) P \cos(\delta) \sin(\delta) \]

\[ P \cos(\delta) \sin(\delta) \quad \frac{1}{2} (1 + P (\cos^2(\delta) - \sin^2(\delta))) \]

unknown

Complex parameters varied in the PWA to fit the data

Helicity states are not eigenstate of parity

\[ \epsilon A_{\alpha}(\tau) = a [ A_{\alpha, M}(\tau) \pm b A_{\alpha, -M}(\tau) ] \]

\[ \delta = \text{angle between polarization vector and the normal to the production plane} \]
Overview of PWA results

Intensity by $J^{PC}$

Events per 20 MeV/c$^2$

$M(\pi^+\pi^+\pi^-)$ (GeV/c$^2$)

Isotropic BG
Total intensity
All 1$^{++}$
All 2$^{++}$
All 1$^{-+}$
All 2$^{--}$
PWA $1^{++} - 2^{++}$ phase motion

\[ 1^{++} 1^- S \ [Y=\rho(770)] - 2^{++} 1^- D \ [Y=\rho(770)] \ \delta\phi \]
PWA 1++ D waves

consistent with leakage from $a_2$ signal
PWA Systematic effects from baryon background

effects from $\pi^+$ angle cut

Isotropic Background Wave Intensity
PWA Systematic effects from baryon background
effects from $\pi^+$ angle cut

1$++1$S Intensities

2$++1$D Intensities
PWA Systematic effects from baryon background

effects from $\pi^+$ angle cut

Exotic $1^{-+}1^{-}P$ Intensities
PWA: 2-+ D & P waves

$2^{-+} \rightarrow f_{2\pi}$

$2^{-+} \rightarrow \rho\pi$

$M^\epsilon = 1^-$

$M^\epsilon = 0^-$

$D^-$ wave

$P^-$ wave
\( \pi\pi \) S-wave variations in BNL-E852

**0\(^{-+}\) intensity**

*vs \( \pi\pi \) S-wave parametrization*

**1\(^{++}\) intensity**

*vs \( \pi\pi \) S-wave parametrization*

FIG. 13. Intensity of the 0\(^{-+}\)S0\(^{+}\) waves summed over \( \pi\pi \) S-wave isobars for the different \( \pi\pi \) S-wave parametrizations: (a) 21-wave fit, modified “M” solution parametrization; (b) 27-wave fit, same parametrization; (c) 24-wave fit, simple Breit-Wigner parametrization. See text for details.

FIG. 20. Intensity of the 1\(^{++}\)[\( \rho \)]P1\(^{+}\) wave (a,c) and its phase difference with respect to the 2\(^{-+}\)[\( f_2 \)]S0\(^{+}\) wave (b,d) in the 21-wave PWA fit with the Au-Morgan-Pennington parametrization of the \( \pi\pi \) S-wave (a,b), and the 24-wave PWA fit with the Breit-Wigner parametrization (c,d).

\[ \pi - p \rightarrow p \quad \pi - \pi - \pi^+ \]

**BNL-E852**

**PRD65 072001**
Acceptance Correcting Accounting

Extended Likelihood Function \( \mathcal{L} \)

\[
\mathcal{L} = e^{-N_o(\epsilon V_\alpha)} \prod_i I(\epsilon V_\alpha; \tau_i)
\]

Acceptance

\[
N_o(\epsilon V_\alpha) = \int I(\epsilon V_\alpha; \tau) \eta(\tau) d\text{Lips}
\]

average number of events one would expect if the same experiment were repeated many times

\[
-\ln \mathcal{L} = \ln \left( \prod_i I(\epsilon V_\alpha; \tau_i) \right) - \sum_{\alpha \alpha'}^{k \epsilon V_\alpha N_a} \epsilon A_\alpha^{*} \epsilon A_\alpha \cdot \eta(\tau) d\text{Lips}
\]

\[
\epsilon \Phi_{\alpha \alpha'}^{\text{accepted}} = \frac{1}{N_g} \sum_{i}^{N_a} \epsilon A_\alpha^{*} (\tau_i) \epsilon A_\alpha (\tau_i)
\]
Identification of QCD Exotics

Quark Model Meson Spectra

\[ J = L + S \]
\[ S = 0, 1 \]
\[ L = 0, 1, 2, 3, \ldots \]

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

Meson quantum numbers characterized by given \( J^{PC} \)

Allowed States:
\[ J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+--}, 1^{++}, 2^{--}, 2^{+-}, 2^{++}, \ldots \]

Forbidden States (Exotics):
\[ J^{PC} = 0^{+-}, 0^{--}, 1^{+}, 2^{+-}, 3^{--}, 4^{+-}, \ldots \]
Photoproduction of Gluonic Excitations

It has been pointed out\(^1,2,3\) that in the case of photoproduction exotic hybrids should be produced copiously.