The Photoproduction of Excited Strange Mesons in
\[ \gamma p \rightarrow \Lambda K^+ \pi^+ \pi^- \]
With CLAS at Jefferson Lab

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Hadron 2015
Overview

- Motivation
- CLAS g12 Experiment
- Analysis
- Summary & Future Plans
Motivation

Most Excited strange states have been hadroproduced, few are photoproduced.

<table>
<thead>
<tr>
<th>$n,{}^{2s+1}\ell_J$</th>
<th>$J^{PC}$</th>
<th>$l = 1$</th>
<th>$l = \frac{1}{2}$</th>
<th>$l = 0$</th>
<th>$l = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$u\bar{d}, \bar{u}d, \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$</td>
<td>$u\bar{s}, d\bar{s}, s\bar{d}, -\bar{s}u$</td>
<td>$f'$</td>
<td>$f$</td>
</tr>
<tr>
<td>$1,{}^1S_0$</td>
<td>$0^{++}$</td>
<td>$\pi$</td>
<td>$K$</td>
<td>$\eta$</td>
<td>$\eta'$(958)</td>
</tr>
<tr>
<td>$1,{}^3S_1$</td>
<td>$1^{--}$</td>
<td>$\rho$(770)</td>
<td>$K^*$(892)</td>
<td>$\phi$(1020)</td>
<td>$\omega$(782)</td>
</tr>
<tr>
<td>$1,{}^1P_1$</td>
<td>$1^{--}$</td>
<td>$b_1$(1235)</td>
<td>$K,^{B\dagger}$</td>
<td>$h_1$(1380)</td>
<td>$h_1$(1170)</td>
</tr>
<tr>
<td>$1,{}^3P_0$</td>
<td>$0^{++}$</td>
<td>$a_0$(1450)</td>
<td>$K_0^*(1430)$</td>
<td>$f_0$(1710)</td>
<td>$f_0$(1370)</td>
</tr>
<tr>
<td>$1,{}^3P_1$</td>
<td>$1^{++}$</td>
<td>$a_1$(1260)</td>
<td>$K_{1A}\dagger$</td>
<td>$f_1$(1420)</td>
<td>$f_1$(1285)</td>
</tr>
<tr>
<td>$1,{}^3P_2$</td>
<td>$2^{++}$</td>
<td>$a_2$(1320)</td>
<td>$K_2^*(1430)$</td>
<td>$f_2$(1525)</td>
<td>$f_2$(1270)</td>
</tr>
<tr>
<td>$1,{}^1D_2$</td>
<td>$2^{--}$</td>
<td>$\pi_2$(1670)</td>
<td>$K_2^*(1770)^\dagger$</td>
<td>$\eta_2$(1870)</td>
<td>$\eta_2$(1645)</td>
</tr>
<tr>
<td>$1,{}^3D_1$</td>
<td>$1^{--}$</td>
<td>$\rho$(1700)</td>
<td>$K^*(1680)$</td>
<td></td>
<td>$\omega$(1650)</td>
</tr>
<tr>
<td>$1,{}^3D_2$</td>
<td>$2^{--}$</td>
<td>$K_2$(1820)</td>
<td></td>
<td></td>
<td>$\omega$(1670)</td>
</tr>
<tr>
<td>$1,{}^3D_3$</td>
<td>$3^{--}$</td>
<td>$\rho_3$(1690)</td>
<td>$K_3^*(1780)$</td>
<td>$\phi_3$(1850)</td>
<td>$\omega_3$(1670)</td>
</tr>
<tr>
<td>$1,{}^3F_4$</td>
<td>$4^{++}$</td>
<td>$a_4$(2040)</td>
<td>$K_4^*(2045)$</td>
<td>$f_4$(2050)</td>
<td></td>
</tr>
<tr>
<td>$1,{}^3G_5$</td>
<td>$5^{--}$</td>
<td>$\rho_5$(2350)</td>
<td></td>
<td></td>
<td>$f_4$(2050)</td>
</tr>
<tr>
<td>$1,{}^3H_6$</td>
<td>$6^{++}$</td>
<td>$a_6$(2450)</td>
<td></td>
<td></td>
<td>$f_6$(2510)</td>
</tr>
<tr>
<td>$2,{}^1S_0$</td>
<td>$0^{++}$</td>
<td>$\pi$(1300)</td>
<td>$K$(1460)</td>
<td>$\eta$(1475)</td>
<td>$\eta$(1295)</td>
</tr>
<tr>
<td>$2,{}^3S_1$</td>
<td>$1^{--}$</td>
<td>$\rho$(1450)</td>
<td>$K^*$(1410)</td>
<td>$\phi$(1680)</td>
<td>$\omega$(1420)</td>
</tr>
</tbody>
</table>

$^\dagger$ The $1^{\pm\pm}$ and $2^{\pm\pm}$ isospin $\frac{1}{2}$ states mix. In particular, the $K_{1A}$ and $K_{1B}$ are nearly equal (45%) mixtures of the $K_1(1270)$ and $K_1(1400)$. The physical vector mesons listed under $1^3D_1$ and $2^3S_1$ may be mixtures of $1^3D_1$ and $2^3S_1$, or even have hybrid components.

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Most of the available $K\pi\pi$ data is produced with a Kaon beam incident on a proton target (COMPASS, ACCMOR ..)

Motivation

Our dataset is the first photoproduction dataset to study a $(K^+ \pi^+ \pi^-)$ system produced off a $\Lambda$
- CEBAF (Continuous Electron Beam Accelerator Facility) hosted at Jefferson Lab, delivers up to 5.5 GeV photon beam to 4 halls simultaneously.
- CEBAF Large Acceptance Spectrometer (CLAS) hosted in hall B.
- g12 experiment primarily approved for the ongoing search for exotic mesons.
- Up to 5.5 GeV photon beam incident on Liquid hydrogen target.
- 26.2 billion triggers (68 Pb-1, 126 TB) of various topologies.
Data Selection

- 4 charged particles are selected: Proton, K⁺, π⁺, π⁻

- Initial topology: γ p → p K⁺ π⁺ π⁻ [Missing Particle]

\[ P_{\text{Miss}} = (P_\gamma + P_{\text{Target}}) - (P_{K^+} + P_p + P_{\pi^+} + P_{\pi^-}) \]

- About 24 million events with the above topology.
Kinematic Fitting

- Other cuts include particle beta cuts.

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Lambda Mode

$\Lambda$ decays into $p\, [\pi^-]$ or $p\, \pi^-$

Mass($p\, [\pi^-]$)

Future plans include kinematically constraining the $\Lambda$ invariant mass
**Background Reduction**

\[ \Sigma(1385) \text{ Background Eliminated} \]
Background Reduction

Only Events below the K/π separation threshold are chosen.

Low $t'$ cut to enhance peripheral production

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Final Features

\[\rho(770)\]

Events/20 MeV/c^2

\[\text{Entries 16556} \quad \text{Mean 1.044}\]

\[\text{Entries 16556} \quad \text{Mean 1.608}\]

\[\text{Entries 16556} \quad \text{Mean 0.8015}\]

K*(892)

Events/15 MeV/c^2

\[\text{Entries 16556} \quad \text{Mean 1.608}\]

\[\text{Entries 16556} \quad \text{Mean 0.8015}\]

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- Generate $K\pi\pi$ phase space similar to data.
- Events are generated in $K\pi\pi$ such that the accepted events are 10 times the data in every bin.
Partial Wave Analysis

- A mass independent partial wave analysis was performed using an event based likelihood fit.

- Montecarlo events are used to determine the normalization integrals.

Minimize likelihood function to get production amplitudes

Partial Wave Analysis

\[ I(\tau) = \sum_{k \in \alpha \alpha'} \varepsilon^k V^*_\alpha \varepsilon^k V_\alpha \varepsilon A^*_\alpha(\tau) \varepsilon A_\alpha(\tau) \]

Eigen states in the reflectivity basis

\[ |\epsilon, a, m\rangle = |a, m\rangle + \epsilon P(-1)^{a-m} |a, -m\rangle \]

where

\[ \Theta(m) = \begin{cases} 
1 \sqrt{2}, & \text{if } m > 0 \\
1/2, & \text{if } m = 0 \\
0, & \text{if } m < 0 
\end{cases} \]

Normalization integrals from the accepted MC

\[ \varepsilon \Psi^{r}_{\alpha \alpha'} = \frac{1}{n_r} \sum_{i}^{n_r} \varepsilon A_{\alpha}(\tau_i) \varepsilon A^*_\alpha(\tau_i) \]

\[ \varepsilon \Psi^{a}_{\alpha \alpha'} = \frac{1}{n_a} \sum_{i}^{n_a} \varepsilon A_{\alpha}(\tau_i) \varepsilon A^*_\alpha(\tau_i) \]

- Eigen State for 1+1+S waves

\[ |1111\rangle = \frac{1}{\sqrt{2}} (|111\rangle + |1-11\rangle) \]
A Study of the dependence of the decay amplitudes on the \((K^+ \pi^+ \pi^-)\) mass

- Mass independent fit
- Data is binned in 100 MeV bins, then shifted by 50 MeV
- 19 waves included in the fit
- Flat background included in the fit
- Rank 1 Spin density matrix
$K^*(1410) \rightarrow K^*(892) \pi^+$

**PWA Results**

$K^*(1410)$

\[ J^P = \frac{1}{2}(1^-) \]

Mass $m = 1414 \pm 15$ MeV \quad (S = 1.3)

Full width $\Gamma = 232 \pm 21$ MeV \quad (S = 1.1)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ($\Gamma_i/\Gamma$)</th>
<th>Confidence level</th>
<th>$p$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)\pi$</td>
<td>$&gt; 40$ %</td>
<td>95%</td>
<td>410</td>
</tr>
<tr>
<td>$K\pi$</td>
<td>$(6.6\pm1.3)$ %</td>
<td>95%</td>
<td>612</td>
</tr>
<tr>
<td>$K\rho$</td>
<td>$&lt; 7$ %</td>
<td>95%</td>
<td>305</td>
</tr>
<tr>
<td>$\gamma K^0$</td>
<td>seen</td>
<td>95%</td>
<td>619</td>
</tr>
</tbody>
</table>

$1^- P, K^*(892)\pi^+$

$1^- P, \rho K^+$

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**PWA Results**

1\(^+\), \(K^{*}(892)\) \(\pi^+\) Intensity

![Graph showing the intensity of \(K^{*}(892)\) \(\pi^+\) events as a function of mass.]

\[1^{+}, \, K^{*}(892) \, \pi^+ \text{ Intensity}\]

\[\text{Events/100 MeV/c}^2\]

![Graph showing the intensity of \(\rho K^+\) events as a function of mass.]

\[1^{+}, \, \rho \, K^+ \text{ Intensity}\]

\[\text{Events/100 MeV/c}^2\]

The \(K_1(1650)\), reported but not confirmed
- Mass: 1600-1900 MeV
- Width: 150 – 250 MeV
- Reported decay modes: \(K \pi \pi\), \(K\Phi\)

\[K_1(1400)\]

\[I(J^P) = \frac{1}{2}(1^+)\]

Mass \(m = 1403 \pm 7\) MeV

Full width \(\Gamma = 174 \pm 13\) MeV \((S = 1.6)\)

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2+ , K*(892) π+ Intensity

2+ , ρ K+ Intensity

\[ \text{Events/100 MeV/c} \]

\[ \text{Mass}(K^+ \pi^+ \pi^-) \ [\text{GeV/c}^2] \]

\[ K_2^*(1430)^\pm \] mass \( m = 1425.6 \pm 1.5 \text{ MeV} \) \quad (S = 1.1)

\[ K_2^*(1430)^0 \] mass \( m = 1432.4 \pm 1.3 \text{ MeV} \)

\[ K_2^*(1430)^\pm \] full width \( \Gamma = 98.5 \pm 2.7 \text{ MeV} \) \quad (S = 1.1)

\[ K_2^*(1430)^0 \] full width \( \Gamma = 109 \pm 5 \text{ MeV} \) \quad (S = 1.9)
Summary

- Over 16,500 events of the type $\gamma p \rightarrow \Lambda K^+ \pi^+ \pi^-$ have been acquired in a search for photoproduction of excited strange mesons.
- Largest ($\Lambda K^+ \pi^+ \pi^-$) photoproduction dataset to date.
- Two dominating decay modes observed in the $K^+ \pi^+ \pi^-$ system: $K^*(892) \pi^+$ and $\rho K^+$.
- A mass independent partial wave analysis was performed.
- Preliminary results for $J^P = 1^-$ are consistent with a $K^*(1410)$ decaying dominantly to a $K^*(892) \pi$ relative to $\rho K$ in agreement with known observations.
- Other features of the PWA results are still under investigation.