Properties of the $\Lambda(1405)$ Hyperon Measured at CLAS

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Outline

1. Introduction
   - motivation for the study of the $\Lambda(1405)$ – what is it?
   - theory of the $\Lambda(1405)$
   - goals of this analysis

2. CLAS Analysis
   - the g11a data set in CLAS at Jlab
   - cuts to the data
   - background
   - fits to the lineshape

3. Results
   - lineshape
   - cross section
   - spin-parity

4. Conclusion
what is the $\Lambda(1405)$?

- **** resonance just below $N\bar{K}$ threshold
- $J^P = \frac{1}{2}^-$ (experimentally unconfirmed)
- can only be observed by reconstructing $(\Sigma\pi)^0$ spectrum
- has always been a puzzle on what the nature of the state is
  - past experiments have found the lineshape ($\equiv$ invariant $\Sigma\pi$ mass distribution) to be distorted from a simple Breit-Wigner form
- what is the nature of this distorted lineshape?
  - “normal” $qqq$-baryon resonance
  - $L = 1$ SU(3) singlet in constituent quark model
  - molecular $N\bar{K}$ bound state
  - $uds$ singlet coupled to $S$-wave meson-baryon systems
  - $udsg$ hybrid, $qqq\bar{q}$
  - dynamically generated resonance in unitary coupled channel approach
unitary coupled channel approach
dynamically generate $\Lambda(1405)$

\[ \gamma p \rightarrow K^+\pi \Sigma \]
\[ E_\gamma = 1.7 \text{ GeV} \]

difference in lineshape

\[
\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)})
\]

\[
\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)})
\]

\[
\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3} |T^{(0)}|^2 + O(T^{(2)})
\]

J. C. Nacher et al., Nucl. Phys. B455, 55

- difference in lineshapes is due to interference of isospin terms in calculation ($T^{(I)}$ represents amplitude of isospin $I$ term)
goals of $\Lambda(1405)$ analysis

- measure the lineshape in the three $\Sigma\pi$ channels ($\Sigma^+\pi^-, \Sigma^0\pi^0, \Sigma^-\pi^+$)
- determine the differential cross section (what kind of angular/Mandelstam $t$ dependence?)
- if distortion of lineshape is observed, this could be the first observation of a non-$qqq$ baryonic structure
- determine the spin and parity
the g11a data set taken at CLAS

- ran from May to July 2004
- photoproduction experiment on a proton target
- photon energies from below $\Lambda(1405)$ threshold to 3.84 GeV
- large dataset with $\sim$ 20 billion triggers
- current estimates of reconstructed $\Lambda(1405)$ events: $\sim$ 272K (from fits shown later)

Data is binned in:

- 10 bins of 100 MeV wide $W$ bins
- $\sim$ 20 bins of $t$ in each $W$ bin
- 3 Σπ decay channels (2 decay modes for Σ⁺π⁻)
- This will be the first experimental result to compare all 3 Σπ decay modes
decay channel selection cut

example in 1 bin:

- $\gamma + p \rightarrow K^+\pi^+\pi^-(n)$
- detect $K^+, \pi^+, \pi^-$, reconstruct missing neutron
- fit to Gaussian and select $\pm 3\sigma$ around neutron peak
intermediate ground state hyperon

example in 1 bin:

- neutron combined with $\pi^{\pm}$ reconstructs $\Sigma^{\pm}$
- project on each axis, select $\pm 2\sigma$, exclude other hyperon
- diagonal band ($K^0$ from $\pi^+\pi^-$) is also excluded

\[ M^2(\pi^+, n) \]
\[ M^2(\pi^-, n) \]
background (1) – $\Sigma(1385)$

- close in mass and width to $\Lambda(1405)$
- decays primarily to $\Lambda\pi^0$ (B.R. $\sim 88\%$)
- small B.R. to $\Sigma^\pm\pi^\mp$: $\sim 6\%$ each

$\Rightarrow$ calculate $\Sigma(1385)$ cross section in each bin from $\Lambda\pi^0$ channel, then scale down by B.R. to extract yield in $\Sigma\pi$ channels
background (1) – Σ(1385)

- close in mass and width to Λ(1405)
- decays primarily to Λπ⁰ (B.R. ∼ 88%)
- small B.R. to Σ±π∓: ∼ 6% each

⇒ calculate Σ(1385) cross section in each bin from Λπ⁰ channel, then scale down by B.R. to extract yield in Σπ channels
background (2) – $K^*0\Sigma^+$

- $\Gamma \sim 50$ MeV
- strong overlap with $\Lambda(1405)$ in lower $W$ bins, separated at higher energies

⇒ generated MC and subtract off incoherently (checks need to be done for interference)
example of fit to lineshape

reaction:
\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow \Sigma^+ + \pi^- \]
\[ \rightarrow n + \pi^+ \]

"nominal" \( \Lambda(1405) \)

- Monte Carlo generated with PDG values of mass, width
- all Monte Carlo was processed through detector simulation
example of fit to lineshape

reaction:

\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow \Sigma^+ + \pi^- \rightarrow n + \pi^+ \]

**Σ(1385)**

- strong overlap with Λ(1405) due to close mass and width
- Λπ⁰ decay mode was used to fix yield in Σπ decay modes
- Monte Carlo generated with PDG values of mass, width
example of fit to lineshape

reaction:
\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow \Sigma^+ + \pi^- \]
\[ \rightarrow n + \pi^+ \]

\[ \Lambda(1520) \]

- Monte Carlo generated with PDG values of mass, width
- well-established Breit-Wigner lineshape
example of fit to lineshape

reaction:

\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow \Sigma^+ + \pi^- \rightarrow n + \pi^+ \]

\[ K^{*0} \]

- strong kinematic overlap with \( \Lambda(1405) \)
- Monte Carlo generated with PDG values of mass, width
reaction:
\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow \Sigma^+ + \pi^- \rightarrow n + \pi^+ \]

⇒ after fitting with the above templates, we subtracted off contributions from the Σ(1385), Λ(1520), K*0, and assigned the remaining contribution to the Λ(1405).
acceptance correction

- after subtracting background contributions, we are left with “residual” spectrum
- to correct for dependence of the lineshape on acceptance, we have calculated the acceptance as a function of lineshape
- our lineshape results are summed over the $t$ bins in each energy bin
different lineshapes for each $\Sigma\pi$ decay mode

- lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, most narrow
results of lineshape after acceptance correction

- different lineshapes for each $\Sigma \pi$ decay mode
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- $\Sigma^+ \pi^-$ decay mode has peak at highest mass, most narrow
theory prediction from chiral unitary approach

\[ \gamma p \rightarrow K^+\pi \Sigma \]
\[ E_\gamma = 1.7 \text{ GeV} \]

- \( \Sigma^-\pi^+ \) decay mode peaks at highest mass, most narrow
- difference in lineshapes is due to interference of isospin terms in calculation (\( T(I) \) represents amplitude of isospin \( I \) term)

\[ \frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)}) \]
\[ \frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)}) \]
\[ \frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3} |T^{(0)}|^2 + O(T^{(2)}) \]
differential cross sections

- summing over the lineshape gives differential cross section
- $\Lambda(1520)$ serves as a check of systematics
- at lower energies where lineshapes differ, differences in $\frac{d\sigma}{dt}$ are observed

\[
\frac{d\sigma}{dt}[\mu b/GeV^2] \text{ for } 2.050 < W < 2.150 (GeV)
\]
differential cross sections

- summing over the lineshape gives differential cross section
- $\Lambda(1520)$ serves as a check of systematics
- at lower energies where lineshapes differ, differences in $\frac{d\sigma}{dt}$ are observed

$$\frac{d\sigma}{dt}[\mu b/\text{GeV}^2] \text{ for } 2.350 < W < 2.450 (\text{GeV})$$

$\Lambda(1405)$

$\Lambda(1520)$
differential cross sections

- summing over the lineshape gives differential cross section
- \( \Lambda(1520) \) serves as a check of systematics
- at lower energies where lineshapes differ, differences in \( \frac{d\sigma}{dt} \) are observed

\[
\frac{d\sigma}{dt} [\mu b/\text{GeV}^2] \text{ for } 2.750 < W < 2.840 \text{ (GeV)}
\]

\( \Lambda(1405) \)  
\( \Lambda(1520) \)
no previous **direct experimental evidence** for the spin and parity of the Λ(1405) (PDG assumes $1/2^-$)

How do we measure these quantities?

- **spin** – measure distribution into $\Sigma\pi$
  - flat distribution is best evidence possible for $J = 1/2$
- **parity** – measure polarization of $\Sigma$ from Λ(1405)
  - Polarization direction as a function of $\Sigma$ decay angle will be determined by $JP$ of Λ(1405)
\[ L = 0 \text{ (s-wave)} \]
\[ \vec{P}_{\Sigma^+} = \vec{P}_{\Lambda^*} \]

\[ L = 1 \text{ (p-wave)} \]
\[ \vec{P}_{\Sigma^+} = |\vec{P}_{\Lambda^*}| \hat{n}(2\theta_{\Sigma^+}) \]

\[ \Lambda(1405) \rightarrow \Sigma\pi \text{ is s-wave} \]
\[ \iff J^P = 1/2^- \]

\[ \Lambda(1405) \rightarrow \Sigma\pi \text{ is p-wave} \]
\[ \iff J^P = 1/2^+ \]
determination of spin of $\Lambda(1405)$

fits to $J = \frac{1}{2}$ and $J = \frac{3}{2}$

distributions done to

- $\Lambda(1405) \rightarrow \Sigma^+\pi^-$
- $\Sigma(1385) \rightarrow \Lambda\pi^0$
- 3 bins of $W$ centered at 2.6, 2.7, 2.8 GeV with forward $K^+$ angles
- selected region has kinematic separation from $K^{*0}$ bg

with $J = 3/2$ fit, $\chi^2/\text{ndf}$ is reduced for $\Sigma(1385)$, but almost no reduction for $\Lambda(1405)$
determination of spin of $\Lambda(1405)$

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with $J = 3/2$ fit, $\chi^2$/ndf is reduced for $\Sigma(1385)$, but almost no reduction for $\Lambda(1405)$

$\Rightarrow$ best possible evidence for $J = 1/2$
determination of parity
polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
determination of parity

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polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)
determination of parity
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$\Rightarrow J^P = 1/2^-$ is confirmed
determination of parity
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furthermore, this measured $\Sigma^+$ polarization is the $\Lambda(1405)$ polarization
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polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)

$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured $\Sigma^+$ polarization is the $\Lambda(1405)$ polarization

$\Rightarrow \Lambda(1405)$ is produced with $\sim 40\%$ polarization
conclusion

- high statistics measurement of $\Lambda(1405)$ photoproduction has been done with CLAS at Jlab
- **difference in lineshape for different decay modes** has been observed
- **difference in cross section for different decay modes** has been observed
- spin and parity are experimentally established for the first time
- as a bonus, **polarization of $\Lambda(1405)$ is found to be $\sim 40\%$ at $W \sim 2.6$ GeV, forward $K^+$ angles**

$\Rightarrow$ best evidence to date of possible deviation from a simple $qqq$-structure.