Decay of the $\Lambda(1405)$ to $\Sigma^0\pi^0$ measured at GlueX

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On behalf of the GlueX Collaboration
• $\Lambda(1405)$ - just below $\bar{K}N$ threshold (1.432 GeV)

• In quark model $\Lambda(1405)$ can be considered as spin-orbit partner of $\Lambda(1520)$

• Invariant mass ("line shape") of $\Lambda(1405)$ from experiments distorted from Breit-Wigner form (E.g. K. Moriya, et al, Phys. Rev. C 87, 035206 (2013))

• $\Lambda(1405)$ decays 100% into $\Sigma\pi$

• Assumed to couple strongly to $\bar{K}N$ channel

• Some chiral unitary models suggest $\Lambda(1405)$ to be composed of two $I=0$ poles (E.g. M. Mai, U.-G. Meissner, Eur. Phys. J. A 51, 30 (2015))

• Recent PDG has $\Lambda(1380)$ added as a two-star resonance

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### Table: Status of Resonances

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J^P$</th>
<th>Overall status</th>
<th>$NK$</th>
<th>$\Sigma\pi$</th>
<th>Other channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1116)$</td>
<td>$1/2^+$</td>
<td>****</td>
<td>**</td>
<td>**</td>
<td>$N\pi$ (weak decay)</td>
</tr>
<tr>
<td>$\Lambda(1380)$</td>
<td>$1/2^-$</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td></td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>$1/2^+$</td>
<td>****</td>
<td>**</td>
<td>****</td>
<td>$\Lambda\pi\pi, \Sigma(1385)\pi$</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$1/2^-$</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>$\Lambda\eta$</td>
</tr>
<tr>
<td>$\Lambda(1690)$</td>
<td>$3/2^-$</td>
<td>****</td>
<td>****</td>
<td>***</td>
<td>$\Lambda\pi\pi, \Sigma(1385)\pi$</td>
</tr>
</tbody>
</table>

V.D. Burkert et al., “$\Lambda$ and $\Sigma$ Resonances”, The Review of Particle Physics (2022)

Introduction

- $\Lambda(1405) \to \Sigma^0\pi^0$ decay is pure $I=0$ (no contamination from $\Sigma^0(1385)$) and data is very limited

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

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

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

- $\Sigma^0\pi^0$ decay is very useful to study the $\Lambda(1405)$ line shape

- GlueX can reconstruct neutral showers well $\implies$ ideal to reconstruct $\Sigma^0\pi^0$ decay mode

- Study of the $\Lambda(1405)$ line shape would provide more information on how the $\Sigma\pi$ and $N\bar{K}$ channels contribute to its production
Previous measurements for $\Lambda(1405) \rightarrow \Sigma^0 \pi^0$

- Early observation in bubble chamber experiments in 1961 (M. Alston et al., Phys. Rev. Lett. 6, 698 (1961))

$K^-p$ interactions at 1.15 GeV/c


$pp \rightarrow pK^+Y^0$

- 3.65 GeV/c proton beam at COSY-Jülich

- $\sigma_{tot}(pp \rightarrow pK^+\Lambda(1405)) = (4.5 \pm 0.9_{stat} \pm 1.8_{syst}) \mu b$

- $\gamma p \rightarrow K^+\Sigma\pi$ at CLAS

- $1.95 < W < 2.85$ GeV
Previous measurements for $\Lambda(1405) \to \Sigma^0\pi^0$

BGO-OD at ELSA

Comparison


- Exclusive reconstruction of $\gamma p \to K^+\pi^- p\gamma\gamma\gamma$ final state
  - Large background under the $\Sigma^0$ peak
  - Limited statistics

GlueX can exclusively reconstruct this state with use of kinematic fitting to reduce background and optimize mass resolution

GlueX Experiment

- Located in Hall D at Jefferson Lab, USA
- Photoproduction experiment

**Main goals**

- Search for hybrid mesons
- Study light quark meson spectrum
- Hyperon spectroscopy
GlueX spectrometer

- Liquid hydrogen target
- Bremsstrahlung photons tagged in the energy range 3.0 - 11.6 GeV
  - Linearly polarized tagged photons \( \sim 9 \text{ GeV} \) produced by coherent bremsstrahlung
- Nearly \( 4\pi \) angular coverage
- Detection of charged tracks and photons leads to exclusively reconstruct final state of a reaction

More info -> M. Khachatryan (Tue)

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Event selection

- GlueX Phase-I data

- Photon beam energy = 6.5 - 11.6 GeV
  - Luminosity $\sim 423\, \text{pb}^{-1}$

- Kinematic fit conserving 4-momentum and constraining event vertex
  - $\pi^0$ and $\Sigma^0$ masses constrained to improve $\Sigma^0\pi^0$ mass resolution

- Focus on $t$-channel production of $\Lambda(1405)$

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

Counts / 0.4 GeV

\[
t = (p_{\gamma(\text{beam})} - p_{K^+})^2
\]
Invariant mass of $\Sigma^0\pi^0$

- $0 \text{ GeV}^2 < -(t - t_{\text{min}}) < 1.5 \text{ GeV}^2$

$\Sigma^0\pi^0$ mass resolution from MC

- Clear peaks of $\Lambda(1405)$ and $\Lambda(1520)$

- $13351 \pm 139$ counts in the $\Lambda(1405)$ region ($M_{\Sigma^0\pi^0} < 1.47 \text{ GeV}$)  
  (Assumed background free)

- A sharp drop of yield at $\bar{K}N$ threshold seen for $\Lambda(1405)$

- Simulations indicate good resolution for $\Sigma^0\pi^0$ mass in $\Lambda(1405)$ region
• Normalization yet to be finalized

• Uncertainties are only statistical

• $\Lambda(1405)$ line shape deviates from a Breit-Wigner form

• Test two hypotheses for fitting $\Lambda(1405)$ line shape (next slide)
Two line shape ansatzes

- Single $\Lambda(1405)$
- Parameterized with one Flatté amplitude
- Incoherent $\Lambda(1520)$ and backgrounds
- $\chi^2/d.o.f$ of the fit = 5.1
- Centroid at 1407 MeV

- Compound coherent $\Lambda(1405)$’s
- Two Flatté amplitudes
  - no strong phase between them
  - a common Flatté factor
- Incoherent $\Lambda(1520)$ and backgrounds
- $\chi^2/d.o.f$ of the fit = 3.5 Better fit!
- $\Lambda(1405)$ is split into two centroids at $\sim 1387$ MeV and $\sim 1409$ MeV

- More detailed fitting is in progress
\[
\frac{d\sigma}{dM_{\pi^0\pi^0}} \text{ for different bins of } -(t - t_{\text{min}})
\]

- \(0 \text{ GeV}^2 < -(t - t_{\text{min}}) < 0.35 \text{ GeV}^2\)
- \(0.35 \text{ GeV}^2 < -(t - t_{\text{min}}) < 0.6 \text{ GeV}^2\)
- \(0.6 \text{ GeV}^2 < -(t - t_{\text{min}}) < 1.5 \text{ GeV}^2\)

- \(t\)-dependence seen in \(\Lambda(1405)\) line shape
Coherent fit to two $\Lambda(1405)$’s

Incoherent $\Lambda(1520)$ and backgrounds

Relative intensities of two $\Lambda(1405)$’s change with $-t'$

Fits describe the data well in all $-t'$ bins
Summary

- GlueX is ideally suited for exclusive reconstruction of $\Lambda(1405) \rightarrow \Sigma^0\pi^0$
  - Highest statistics obtained so far
  - $\sim 5$ MeV resolution in mass for $\Sigma^0\pi^0$ mass near $\Lambda(1405)$

- $\Lambda(1405)$ line shape clearly seems to deviate from a Breit-Wigner form

- Fits to line shape favor a composite (two coherent states) picture for $\Lambda(1405)$

- $t$-dependence observed for the $\Lambda(1405)$ line shape

- GlueX preliminary result supports previous theory and experiment suggesting the $\Lambda(1405)$ is a composite baryon state

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