Spectroscopic study of the $\Lambda(1405)$ resonance via the $d(K^-,n)$ reaction at J-PARC

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for the J-PARC E31 collaboration
Investigation of the $\Lambda(1405)$

The lightest negative parity baryon: $1405^{+1.3}_{-1.0}$ MeV (PDG2018), $J^P=1/2^-$

3 quark

$\bar{K}$N bound state

chiral unitary model:
2 pole structure of the $\Lambda(1405)$ with $\bar{K}N$, $\pi\Sigma$ resonant states

Lattice QCD Evidence that the $\Lambda(1405)$ Resonance is an $\bar{K}N$ molecule

PRL 114, 132002 (2015)

The s quark contribution to the magnetic moment of $\Lambda(1405)$ is vanished! @ $\sim$ physical pion mass

Study of $\bar{K}N$ scattering below the $\bar{K}N$ threshold is important.
J-PARC E31 experiment

measuring an $\overline{K}N \rightarrow \pi \Sigma$ scattering below the $\overline{K}N$ threshold in the $d(K^-, n)\pi \Sigma$ reactions

1 GeV/c

- 2 step process
- Producing $\Lambda(1405)$ by virtual $K$

ChiralUnitary Model:
D. Jido et al., NPA725(03)181
J-PARC E31 experiment

measuring an $\bar{K}N \rightarrow \pi\Sigma$ scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions

1 GeV/c

1 GeV/c

Identifying all final states to decompose the $l=0$ and $l = 1$ amplitude

<table>
<thead>
<tr>
<th>$\pi^\mp \Sigma^\pm$</th>
<th>$l = 0, 1$</th>
<th>$\Lambda(1405)$ $l=0$ S-wave, non-resonant $\Sigma(1385)$ $l=1$ P-wave</th>
</tr>
</thead>
</table>
| $\pi^-\Sigma^0 [\pi^-\Lambda]$ | $l=1$ | $d(K^-,p)\pi^-\Sigma^0 [\pi^-\Lambda]$  

Charged mode

<table>
<thead>
<tr>
<th>$\pi^0\Sigma^0$</th>
<th>$l=0$</th>
<th>$\Lambda(1405)$ ($l=0$, S wave) non-resonant</th>
</tr>
</thead>
</table>

Neutral mode
# E31 Run Summary

<table>
<thead>
<tr>
<th>E31 RUN</th>
<th>Beam power</th>
<th>Beam Time</th>
<th>Executed/Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre</td>
<td>May 2015</td>
<td>27 kW</td>
<td>2.2d ~5%</td>
</tr>
<tr>
<td>1st</td>
<td>May-June 2016</td>
<td>43 kW</td>
<td>7d ~30%</td>
</tr>
<tr>
<td>2nd</td>
<td>Jan.- Feb. 2018</td>
<td>33.5-51.1kW</td>
<td>20d 100% !!</td>
</tr>
</tbody>
</table>
J-PARC K1.8BR beam line

Cylindrical Detector System (CDS) (Solenoid Field 0.7T)

Beam Sweeper (Ushiwaka)

Neutron Counter (NC)

Proton Counter (PC)

Beam Sweeper

TOF~15m
Achievement of E31-1\textsuperscript{st}

d(K^-,n)''X'' \pi^\mp \Sigma^\pm \text{ spectra}

\[
\frac{d\sigma}{d\Omega}(\pi^\pm \Sigma^\mp) = \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3} Re(f_{I=0}f_{I=1}^*)
\]
I =0 dominance

- average of $d(K^{-},n)\Sigma^{-}\pi^{+}$ and $d(K^{-},n)\Sigma^{+}\pi^{-}$
- $d(K^{-},p)\Sigma^{0}\pi^{-} \times 1/2$

Assuming the similarity of the reaction mechanism of $d(K^{-},n)$ and $d(K^{-},p)$, the amplitude of I =0 in the $d(K^{-},n)$ reaction is dominant below the threshold.
What we learned from E31-1st

- The preliminary results of the \( d(K^-,n)\Sigma^-\pi^+ \) and the \( \Sigma^+\pi^- \) spectra were obtained.
  - The Interference between \( \Sigma^-\pi^+ \) and \( \Sigma^+\pi^- \)
    - The \( d(K^-,p)\Sigma^0\pi^- \) spectrum \((I = 1)\) were obtained
      → The \( I = 0 \) amplitude is dominant below the \( KN \) threshold in the \( d(K^-,n)\Sigma^-\pi^+ \) and \( \Sigma^+\pi^- \) spectra
- The \( d(K^-,n)\Sigma^0\pi^0 \) spectrum \((I = 0)\)
  - Analysis procedure was established
  - Need more statistic to discuss line shape
    (~25 events @ region of interests.....)
Recent theoretical development

- studied within a Faddeev-type approach
- good agreement with data

- dynamical coupled-channels (DCC) model
  - Full
  - w/o JP=1/2- Λ resonant amplitude
E31 - 2nd

- Beam time request
- Detector Upgrade for \( \Sigma^0 \pi^0 \)
  - New Backward Proton Chamber (BPC)
    -- event vertex
    -- tracking backward scattered particle

1.7 times enlarged in diameter
E31- 2nd

- Successfully finished in Feb. 2018
- $3.92 \times 10^{10}$ Kaons impacted on the deuteron target

- Detector performance
- Analysis procedure
- Consistency check
Detector Performance

Particle ID by CDS

Solenoid Magnet

CDH

CDC

Target

BPC

Charge x momentum [GeV/c]

Mass^2 [(GeV/c)^2]

Beam
Detector performance

Neutron Counter (NC)

Quasi-elastic scattering: \( K^- n \rightarrow K^- n \)
Charge exchange: \( K^- p \rightarrow K^0 n \)

Accidental hits

\[ \frac{1}{\beta} \]
Analysis of $d(K^-, n)X \pi^\pm \Sigma^\pm$

Event topology

$\Upsilon^* \rightarrow \pi^+ \Sigma^- \rightarrow \pi^+ \pi^- n_{\text{miss}}$

$\rightarrow \pi^- \Sigma^+ \rightarrow \pi^- \pi^+ n_{\text{miss}}$
Missing mass \( d(K^-, \pi^+\pi^-n)" X" \)

\[ \gamma^* \rightarrow \pi^+\Sigma^- \rightarrow \pi^+\pi^- n_{\text{miss}} \]

\[ \rightarrow \pi^-\Sigma^+ \rightarrow \pi^-\pi^+ n_{\text{miss}} \]

Accepted as neutron
Signal/Background process

**Signal**

- **CDS**
  - **K^-** → **Σ^+** → **π^-** → **n** → **NC**
  - **CDS**
  - **K^-** → **Σ^-** → **π^+** → **n** → **NC**

**BG**

- **CDS**
  - **K^-** → **K^0** → **π^-** → **n** → **CDS**
  - **CDS**
  - **K^-** → **Σ^+** → **π^-** → **n** → **CDS**
  - **CDS**
  - **K^-** → **Σ^-** → **π^+** → **n** → **CDS**
Background 1: $K^0 + n + n$

π⁺ π⁻ invariant mass

Accept as $K^0$ event
Consistency check: CDS resolution

\[ \pi^+ \pi^- \text{ invariant mass} \]

- E31-2\textsuperscript{nd} Gaussian fit values
  - mean: 498 MeV
  - Sigma: 6 MeV

- E31-1\textsuperscript{st} (~x 2.8 Scaled)
Background 2: Forward $\Sigma$ production

$\pi^+ +$ forward n invariant mass

$\pi^- +$ forward n invariant mass

\[ \Sigma^+ \]

\[ \Sigma^- \]
\(d(K^-,n)X \pi^\mp \Sigma^\pm \) spectrum

- \(\pi^+ \Sigma^-/\pi^- \Sigma^+\) mode separation: needs template fitting on spectra
- Acceptance to be obtained

* Statistical error only
$d(K^-,n)\Sigma^0\pi^0$ Analysis

$\gamma^* \rightarrow \pi^0\Sigma^0 \rightarrow \pi^0\gamma\Lambda \rightarrow \pi^0\gamma p\pi^-$

$\Lambda(1405)$ is recoiled at a backward angle. The decay proton emitted is detected by backward detectors.

1. Reconstruction of $\Lambda$ from $p\pi^-$
2. Separate "$\Lambda\pi^0\gamma$" events from $\Lambda\pi^0\pi$ and $\Lambda\pi^0\pi^0$ by $d(K^-,'n\Lambda')$“X” missing mass analysis
Backward Lambda reconstruction

Backward detectors

Invariant mass ($\pi^- p$)

mean = 1.115
sigma = 0.003

$\Lambda$ is reconstructed as designed!

preliminary
\[ d(K^-, n\Lambda)"X" \] missing mass

- \( \pi^0 \Lambda \quad (I = 1) \)
- \( \pi^0 \Sigma^0 \rightarrow \pi^0 \gamma \Lambda \quad (I = 0) \)
- \( \pi^0 \pi^0 \Lambda \)

- \( d(K^-, n)"\Sigma^0 \pi^0" \) spectrum to be obtained
New proposed analysis – “q” dependence

Invariant mass reconstruction of “πΣ” by CDS

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{\text{point-like}}} \left| \exp\left(\frac{-q^2}{Q_X^2}\right) \right|^2
\]

Form factor

Cross section vs momentum transfer “q” will be analyzed!

Inspired by J-PARC E15 analysis
Y. Sada et al., PTEP 2016 (2016) no.5, 051D01
M. Iwasaki et al., arXiv:1805.12275
New proposed analysis – “q” dependence

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CDS

neutron detection with thin scintillation counter (t=3cm)

n detection efficiency ~ 3%

π^− \rightarrow n \rightarrow \Sigma^- \rightarrow \pi^+

K^− \rightarrow \Sigma^- \rightarrow \pi^+

\theta n

~54 cm from beam axis

t = 3cm

10cm 79cm

Not a point-like reaction if momentum transfer “q” is small
Summary

- measuring an $\bar{K}N \rightarrow \pi\Sigma$ scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions

- E31-2$^{nd}$ has been completed.
  -- missing mass spectra of $d(K^-,n)\Sigma^-\pi^+$ and the $d(K^-,n)\Sigma^+\pi^-$ with larger statistic ($\approx x3$)
  -- line shape of missing mass spectra of $d(K^-,n)\Sigma^0\pi^0$, obtained enough statistic
  -- new analysis of cross section vs momentum transfer to discuss form factor
Needs Kaon induced reaction

\[ \gamma p \rightarrow K^+ \pi^- \Sigma^+, K^+ \pi^0 \Sigma^0, K^+ \pi^+ \Sigma^- \]

\[ pp \rightarrow K^+ p \pi^- \Sigma^+, K^+ p \pi^+ \Sigma^- \]

- $\gamma/p$ induced experiments
- How these spectra couple to the $K\bar{N}$ pole or the pole is still controversial.

CLAS collaboration: Phys Rev C87, 035206

HADES collaboration: Phys Rev C87, 025201
- NC eff 30% by H2 target
- 150 psec. -> d(K-,n)X spectrum 10 MeV reso.
$d(K^-, n)^"X"$ missing mass spectra

- $K^0$ produced event
- Forward $\Sigma^-$ produced event
- Forward $\Sigma^+$ produced event

BG to excluded
Detector Performance