Search for the “KNN” bound state produced via in-flight $d(K^-, \Lambda p)\pi^-$ reaction

Rie MURAYAMA
RIKEN

For the J-PARC E31 collaboration
Kaonic nuclei “KbarNN”

- Nuclear system with Kbar mesons.
- Based on Strong KbarN (I=0) attraction.

*Excited hyperon Λ(1405) as KbarN quasi-bound state*

- Kbar meson should bound in a nucleus with large binding energy.
- “KbarNN” is the simplest Kaonic nucleus to investigate.

Expected as

- “Cold and Dense” state.
- Anti-quark in matter.

Good probe for low energy QCD.

\[ \text{Density (fm}^3\text{)} \]

[Images of density plots: ppn and ppnK]
Theories and experiments on “KNN”

- E15 at K1.8BR J-PARC
  \(^3\)He(K; \(\Lambda p\))n
- E27 at K1.8 J-PARC
  \(d(\pi^+, K^+)\Lambda p / \Sigma^0 p\)
  Inverse reaction \(dK^- \rightarrow \Lambda p\pi^-\) has been taken at K1.8BR.

- DISTO
  Intermediate \(N^+ \rightarrow pK^+\)?
  \(pp \rightarrow p\Lambda K^+\)

- FINUDA
  Multi-NA processes?
  \((K_{stop}^+, \Lambda p)\)
**Result of J-PARC E15**

J-PARC E15 exp. \(^3\text{He}(K^-,\Lambda p)n\)  
S. Ajimura et. al., PLB 789, 620 (2019)  

![Graph showing \(q - M\) distributions for different channels.

J-PARC E15 exp. \(^3\text{He}(K^-,\Lambda p)n\)  
T. Yamaga et. al., PRC 102, 044002 (2020)

![Graph showing \(q_{X}(\text{GeV/c}) - m_{X}(\text{GeV/c}^2)\) distributions.

- Momentum transfer \(q\)  
  \[ q(\Lambda p) = p_k - p_n \]

0.35 < \(q_{X}\) < 0.65  
Projection

**The advantage is the \(q\) dependence to understand background processes.**
\( d(K^-, \Lambda p)\pi^- \) reaction

J-PARC E15

\[ \text{J-PARC E15} \quad d(K^-, \Lambda p)\pi^- \text{ reaction} \]

Tracking and time-of-flight.

Missing.

J-PARC E31

1 GeV/c

\[ 1 \text{ GeV/c} \quad K^- \quad d \quad K^- pp \quad \pi^- \quad \Lambda \quad \text{CDS} \]

0.6 GeV/c

\[ 0.6 \text{ GeV/c} \quad K^- pp \quad \pi^- \quad \Lambda \quad p \quad \text{CDS} \]

This talk.

Tracking and time-of-flight.
Experimental Setup at K1.8BR

Liquid d-target system

Beam sweeping magnet

Beam dump

Neutron counter
Charge veto counter
Proton counter

Beam line spectrometer

CDS

(Modified Partially)

K. Agari et al., PTEP 2012, 02B011
Event selections

- ppπ event selection in CDS.

- Λ→pπ⁻ pairs selection:
  Likelihood method on closest distance approach.

- Missing pion selection:
  χ² method on kinematical refit to conserve energy-momentum.

Square of Λp missing mass after applying all the event selections
$\Lambda p$ distribution

**Data**

Acceptance $<1\%$

**MC (“KbarNN” E15)**

Number of events

<table>
<thead>
<tr>
<th>$m$ [GeV/c$^2$]</th>
<th>Count sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2200</td>
</tr>
<tr>
<td>2.2</td>
<td>2000</td>
</tr>
<tr>
<td>2.4</td>
<td>1800</td>
</tr>
<tr>
<td>2.6</td>
<td>1600</td>
</tr>
<tr>
<td>2.8</td>
<td>1400</td>
</tr>
</tbody>
</table>

Diagram showing distributions of $m$ and $q$ with $q$ in GeV/c and $m$ in GeV/c$^2$.
Event distribution of $\Lambda p\pi^-$ final state

kinematical Degree-of-Freedom = 5

9 (3 on-shell particles) - 4 (energy-momentum conservation and $\phi$ symmetry)

3 $(m, q)$-plots are more than sufficient to identify the event kinematics

We can specify reaction dynamics by these 3 plots

$m$: invariant mass of a pair  
$q$: momentum transfer to the pair

$(m, q)_{\Lambda p}$  
$(m, q)_{\Lambda \pi^-}$  
$(m, q)_{p\pi^-}$
To know reaction dynamics, we need to expand the acceptance on \((m, q)\).

When we require \(\Lambda\) detection, there are three possible event geometries to identify \(\Lambda p\pi^-\) final state.
$\Lambda p$ detect

$\Lambda p\pi$ detect

$\Lambda \pi$ detect

Sum

Shaded Systematical & statistical Error > 30 %
Knowledge from reaction dynamics \((m, q)\)

**\(\Sigma - \Lambda\) conversion**

- Not significant.

**\(K^- d \rightarrow \Sigma(1385)p\)**

- Clearly identified.

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**Data**

- \((m, q)_{\Lambda p}\)
- \((m, q)_{\Lambda \pi^-}\)
- \((m, q)_{\rho \pi}\)
Knowledge from reaction dynamics \((m, q)\)

**Σ-Λ conversion**
- Not significant.

**K- d \rightarrow Σ(1385)p**
- Clearly identified.
- Case) angle
  - Flat: \(\cos^2 θ = 0.7 : 0.3\)

**K N \rightarrow Λπ**
- Seems dominant.

**Data**
- \((m, q)_Λp\)
- \((m, q)_Λπ^-\)

**Two step**
- Not dominant.
- Not just angle of elementary processes.
One nucleon reaction: $K^- n \rightarrow \Lambda \pi^- \ (1/2)$

- Spectator-proton w/ large $p$ fires trigger. Tail component of Fermi-motion affect the distribution.

Effect of large Fermi-momentum tail on $\Lambda \pi$ distribution

MC w/o D-state

$\Lambda \pi$ distribution

MC w/ D-state

$\Lambda \pi$ distribution
One nucleon reaction: $K^- n \rightarrow \Lambda \pi^-$ (2/2)

IM of “$\bar{K}NN$” region
- MC Cross-section: $(4.8\pm0.34)\mu b$

$N_{PB129,253}$

\[ K^- n \rightarrow \Lambda \pi^- (2/2) \]

$\Lambda p$ detect

$m(\Lambda p) [GeV/c^2]$ (2/2)

Number of low-momentum protons are corrected to match data, currently.

- W/ Correction of spectator-proton momentum, data of interested region is mostly explained w/ 1N reaction.
- Difference of proton momentum is under investigation.
Summary

• E3I collaboration is investigating “KbarNN” bound state using \( d(K^-, \Lambda p)\pi^- \) reaction with the confirmation of all the kinematical freedoms.

• Reaction dynamics are determined by the momentum transfer and invariant mass of \( \Lambda p, \Lambda\pi^- \) and \( p\pi^- \) systems. The reaction processes, one nucleon reaction \( Kn \rightarrow \Lambda\pi^- \), two nucleon reaction \( Kp \rightarrow Kp, Kn \rightarrow \Lambda\pi^- \), none-mesonic \( Y^* \) production \( Kd \rightarrow \Sigma(1385)p \), are clearly identified.

• “KbarNN” interested region is mostly explained with one nucleon reaction \( Kn \rightarrow \Lambda\pi^- \) including large momentum Fermi-motion tail and correction of spectator-proton momentum distribution. Difference of proton momentum is under investigation.