On the structure observed in the in-flight $^3\text{He}(K^- , \Lambda p)n$ reaction at J-PARC

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1. Introduction
2. Scenario I: Uncorrelated $\Lambda(1405) p$
3. Scenario II: $\bar{K}NN$ bound state
4. Summary

1. Introduction

++ Hadron-nucleus bound states ++

- Our ultimate goal: To understand completely the strong interaction between all hadrons.

- In this line, some hadrons rather than nucleons are expected to be bound with usual nucleus *by strong interaction* between them.
  - $\Lambda$ hyper nuclei. --- Existence is established.
  - How about other possibilities? (*e.g.* Mesic nuclei)
  - Kaonic nuclei ??? <-- Really exist or not?

- Motivations of studying the hadron-nucleus bound states:
  1. Exotic state of many-body systems in strong interaction.
     --- Inter-hadron interaction, many-body theory, ...
  2. Probe physics of *the strong interaction in finite nuclear density.*
1. Introduction

++ Kaonic nuclei ++

- We expect that kaonic nuclei should exist, which are bound states of $\bar{K}$ and nuclei via strong interaction between them.
- Because $\bar{K}$-nucleon ($N$) interaction is strongly attractive.
  --- So strong that the $\bar{K}N$ system can be bound to be $\Lambda(1405)$.

Kaiser-Siegel-Weise ('95);
Oset-Ramos ('98); ...

- Unfortunately, kaonic nuclei will be unstable with respect to strong interaction: pionic & non-pionic decay modes.

- There are motivations to study kaonic nuclei.
  1. Exotic state of many-body systems in strong interaction.
  2. Kaons in finite nuclear density.
1. Introduction

++ The “$K^- pp$” state ++

- The $\bar{K}NN$ ($I=1/2$) state --- so-called “$K^- pp$” state --- is the simplest state of the kaonic nuclei.

- There have been many studies on this state.

  - **Theoretical studies:**

  - **Experimental studies:**
    - Y. Ichikawa *et al.* [J-PARC E27], *PTEP* 2015 021D01; 061D01;
    - T. Hashimoto *et al.* [J-PARC E15], *PTEP* 2015 061D01; ...

--- However, this state is still controversial.

---

Strangeness and charm in hadrons and dense matter @ YITP (May 15 - 26, 2017)
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- Bayar, Yamagata-Sekihara and Oset, Phys. Rev. C84 (2011) 015209;
- Barnea, Gal and Liverts, Phys. Lett. B712 (2012) 132; ...

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1. Introduction

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\[ \gamma d \rightarrow K^+ \pi^- X \]

Tokiyasu et al. [LEPS] (2014).

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\[ \gamma d \rightarrow K^+ \pi^- X \]

\[ \pi^+ d \rightarrow K^+ X \]

\( \Sigma^0 p \) decay branch

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1. Introduction

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  - Experimental studies:
    - M. Agnello et al. [FINUDA], *Phys. Rev. Lett.* 94 (2005) 212303;
    - T. Yamazaki et al. [DISTO], *Phys. Rev. Lett.* 104 (2010) 132502;
    - A. O. Tokiyasu et al. [LEPS], *Phys. Lett.* B728 (2014) 616;
    - Y. Ichikawa et al. [J-PARC E27], PTEP 2015 021D01; 061D01;
    - T. Hashimoto et al. [J-PARC E15], PTEP 2015 061D01;...

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++ J-PARC E15 data ++

- Recently, the J-PARC E15 collaboration has observed a structure near the $\bar{K}NN$ threshold in the in-flight $^3$He ($K^-$, $\Lambda p$) $n$ reaction.

Y. Sada et al., PTEP 2016 051D01.

Reaction mechanism:

$K^-\to p n p$

$k_{lab} = 1$ GeV/$c$

Fast neutron

$p$

$n$

$p$

Slow kaon

$\Lambda$
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- Recently, the J-PARC E15 collaboration has observed a structure near the $\overline{KNN}$ threshold in the in-flight $^3\text{He} (K^-, \Lambda p) n$ reaction.

Y. Sada et al., *PTEP* 2016 051D01.

- Fitted by Breit-Wigner form:

\[
\frac{d^2\sigma}{dM_{\Lambda p} dq_{\Lambda p}} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{\text{inv.} \Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times \left| \exp \left( -\frac{q_{\Lambda p}^2}{2Q_X^2} \right) \right|^2 ,
\]

--- $\Lambda p$ invariant mass $M_{\Lambda p}$ and momentum transfer $q_{\Lambda p}$.

\[
M_X = 2355^{+6}_{-8} \text{ (stat.)} \pm 12 \text{ (syst.) MeV}/c^2 ,
\]

\[
\Gamma_X = 110^{+19}_{-17} \text{ (stat.)} \pm 27 \text{ (syst.) MeV}/c^2 ,
\]

- What is this peak ???

--- Is this a signal of the $\overline{KNN}$ bound state ???
1. Introduction

++ Purpose of this study ++

- We want to know what is the origin of this peak.

--> Examine 2 scenarios in which peak will appear around $\sqrt{KNN}$ Thr.

- **Scenario I:** Uncorrelated $\Lambda(1405)p$.

--- $\Lambda(1405)$ and $p$ do not make a bound state.

--- The $\Lambda(1405)p$ system makes conversion to $\Lambda p$.

- Because $\Lambda(1405)$ exists below the $\sqrt{KN}$ threshold, the uncorrelated $\Lambda(1405)p$ system may create a peak even they do not bound.
1. Introduction

++ Purpose of this study ++

- We want to **know what is the origin of this peak.**

--> Examine **2 scenarios** in which **peak will appear** around $\bar{KNN}$ Thr.

- **Scenario II:** $\bar{KNN}$ bound state.

--- $\bar{KNN}$ is indeed **bound** as a composite state after the fast neutron emission.

- If the $\bar{KNN}$ signal is strong enough, we will see a peak in the $\Lambda p$ invariant mass spectrum.
2. Uncorrelated $\Lambda(1405)\,p$

++ Reaction mechanism ++

- **Scenario I**: Uncorrelated $\Lambda(1405)p$.
  This system may create a peak in the $\Lambda p$ mass spectrum.

- Because $\Lambda(1405)$ exists below the $\bar{K}N$ threshold, the uncorrelated $\Lambda(1405)p$ system may create a peak even they do not bound.
2. Uncorrelated $\Lambda(1405)p$

++ Scattering amplitude ++

- For this process, we use the following diagrams:

\[ n(p'_n) \quad p(p'_p) \quad \Lambda(p'_\Lambda) \]

Fast neutron

\[ K^-(q) \]

Kaon absorption

\[ n(p'_n) \quad p(p'_p) \quad \Lambda(p'_\Lambda) \]

Same topology, anti-symmetrized $N$s

$\Lambda(1405)$ here!

$\kappa_{\text{lab}} = 1 \text{ GeV}/c$
2. Uncorrelated $\Lambda(1405)\ p$

+++ Scattering amplitude +++

- For this process, we use the following diagrams:

- **The $^3$He wave function** is obtained as the anti-symmetrized 3 nucleons in the harmonic oscillator potential.

- **Amplitude $T_1$** ($k=1$ GeV/c):
  
  \[
  \begin{cases}
  K^- n \rightarrow K^- n_{\text{escape}} \\
  K^- p \rightarrow \bar{K}^0 n_{\text{escape}}
  \end{cases}
  \]

- **Amplitude $T_2$**:

  \[
  \begin{cases}
  K^- p \rightarrow K^- p \\
  \bar{K}^0 n \rightarrow K^- p
  \end{cases}
  \]

--- Taken from Exp. $d\sigma/d\Omega$.

- **Amplitude $T_2$**: around $\bar{K}N$ threshold.

--- Calculate in chiral unitary approach with kaon absorption width ($\epsilon \rightarrow \Gamma_K = 15$ MeV in kaon prop.).
++ Scattering amplitude ++

- For this process, we use the following diagrams:

  - The \( K^- p \Lambda \) vertex is taken from chiral Lagrangian x phenomenological FF.
  - The intermediate kaon energy is fixed as:

\[
q^0 = p^{'0}_\Lambda - \left( m_N - \frac{B_{3\text{He}}}{3} \right)
\]

\[
p^0 = p^{'0}_\Lambda + p^{'0}_p - 2 \left( m_N - \frac{B_{3\text{He}}}{3} \right)
\]

2. Uncorrelated $\Lambda(1405) p$

++ Numerical results ++

- Now we calculate the cross section and $\Lambda p$ mass spectrum of the $^3$He ($K^- , \Lambda p$) $n$ reaction in the uncorrelated $\Lambda(1405)p$ scenario.

- Our mass spectrum is compared with that from Exp. analysis: Y. Sada et al. (2016).

\[
\frac{d\sigma}{dM_{\Lambda p}} \propto \frac{p_n p_{\Lambda}^{*}}{(M_{\Lambda p} - M_X)^2 + \Gamma_X^2 / 4}
\]

\[
M_X = 2355^{+6}_{-8} \text{ (stat.)} \pm 12 \text{ (syst.) MeV}/c^2,
\]

\[
\Gamma_X = 110^{+19}_{-17} \text{ (stat.)} \pm 27 \text{ (syst.) MeV}/c^2,
\]

\[\text{ <-- Shown in blue line / band, but in arbitrary units.}\]
Now we calculate the cross section and $\Lambda p$ mass spectrum of the $^3$He ($K^−, \Lambda p$) $n$ reaction in the uncorrelated $\Lambda(1405)p$ scenario.

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\[ \frac{d\sigma}{dM_{\Lambda p}} \propto P_nP_\Lambda^*(M_{\Lambda p} - M_X)^2 + \frac{\Gamma_X^2}{4} \]

\[ M_X = 2355^{+6}_{-8} \text{ (stat.)} \pm 12 \text{ (syst.) MeV}/c^2, \]

\[ \Gamma_X = 110^{+19}_{-17} \text{ (stat.)} \pm 27 \text{ (syst.) MeV}/c^2, \]

\[ M(K^-pp) \]
**2. Uncorrelated Λ(1405) p**

++ Numerical results ++

- Now we calculate the cross section and Λp mass spectrum of the $^3$He ($K^-$, Λp) n reaction in the uncorrelated Λ(1405)p scenario.

- The peak position is inconsistent with the Exp.
  - Peak at 2355 MeV (Exp.)
  vs. 2370 MeV (this work).

- In particular, we cannot reproduce the behavior of the lower tail $\sim$ 2.3 GeV.

- Therefore, the E15 signal in the $^3$He ($K^-$, Λp) n reaction is NOT the uncorrelated Λ(1405)p state.
2. Uncorrelated $\Lambda(1405)\,p$

++ Numerical results ++

- Diff. cross section $d\sigma/d\cos\theta_n$ indicates forward neutron emission is favored.

--- Cross section of the first step,

\[
\begin{align*}
K^- n &\rightarrow K^- n_{\text{escape}} \\
K^- p &\rightarrow \bar{K}^0 n_{\text{escape}}
\end{align*}
\]

has a local maximum at $\theta_n = 0^\circ$.

--- Higher momentum in kaon propagator suppresses $d\sigma/d\cos\theta_n$ (higher $p_K$ for larger $\theta_n$ in the Lab. frame).
There is a “band” of the uncorrelated \( \Lambda(1405)p \) contribution in \( d^2\sigma/dM_{\Lambda p}d\cos\theta_n \), although its strength is weak for \( \cos\theta \leq 0.9 \).

\[ \Lambda(1405) \] gets more momentum from the kaon after the first scattering.
2. Uncorrelated $\Lambda(1405)\, p$

 ++ Underlying kinematic feature ++

- We find that there is an underlying kinematic feature rather than by the $\Lambda(1405)p$ system, in addition to the “$\Lambda(1405)p$” contribution.

--- This can be seen by taking $T_2 = \text{const.} \iff \text{ignoring } \Lambda(1405)$.

- Indicates underlying kinematic features rather than by the $\Lambda(1405)p$. 

\[ T_2 = \text{const.} \]

\[ M(K^-pp) \]

\[ M_{\Lambda p} [\text{GeV}] \]

\[ d\sigma / dM_{\Lambda p} \text{ [Arb. units]} \]
2. Uncorrelated $\Lambda(1405)\ p$

++ Underlying kinematic feature ++

- We find that there is an underlying kinematic feature rather than by the $\Lambda(1405)p$ system, in addition to the “$\Lambda(1405)p$” contribution.

--- This can be seen by taking $T_2 = \text{const.} \iff \text{ignoring } \Lambda(1405)$.

\[ T_2 = \text{const.} \]

Actually, this is due to the quasi-elastic kaon scattering in the first step.

--- The intermediate kaon after the fast neutron emission goes almost to its on mass shell.

\[ M(K^-p) \]

The actual mass spect. is essentially the product with $|T_2|^2$.

--- They merge to be a single peak.
3. $\bar{K}NN$ bound state

++ Reaction mechanism ++

- **Scenario II**: $\bar{K}NN$ bound state.

--- \textbf{$\bar{K}NN$ is indeed bound} as a composite state after the fast neutron emission.

- If the $\bar{K}NN$ signal is strong enough, we will see a peak in the $\Lambda p$ invariant mass spectrum.
3. $\overline{KNN}$ bound state

++ Scattering amplitude ++

- For this process, we use the following diagrams:

- Fast neutron

- Slow kaon

- $k_{lab} = 1 \text{ GeV/c}$

- Same topology, anti-symmetrized $N$s

- $\overline{KNN}$ here ! + kaon abs.
For this process, we use the following diagrams:

- Fast neutron
- Slow kaon
- $KNN$ here!
- $K^-$ here!
- $K$ here!
- Same topology, anti-symmetrized

$k_{lab} = 1$ GeV/c

3. $\bar{K}NN$ bound state

$\bar{K}NN$ here!
+ kaon abs.
3. $\bar{K}NN$ bound state

++ Scattering amplitude ++

- For this process, we use the following diagrams:

--- We can use same form:

- The $^3$He wave function.
- Amplitude $T_1$ ($k=1$ GeV/c):

\[
\begin{align*}
K^- n &\rightarrow K^- n_{\text{escape}} \\
K^- p &\rightarrow \bar{K}^0 n_{\text{escape}}
\end{align*}
\]

- The $\bar{K}N\Lambda$ vertex.
- The intermediate kaon energy.

- We can use the same formula for them as in the uncorr. $\Lambda(1405)p$. 

[Diagram showing the scattering amplitude and the corresponding diagrams for the $^3$He wave function and the $\bar{K}N\Lambda$ vertex.]
3. $\bar{K}NN$ bound state

++ Scattering amplitude ++

- We have to calculate the multiple kaon scattering with two $N$s.

--> We employ the so-called fixed center approximation to the Faddeev equation. Bayar, Yamagata-Sekihara and Oset, *Phys. Rev.* C84 (2011) 015209.

- Solve the following scattering equation with a “fixed center”.

--- Open circle: $\bar{K}N \rightarrow \bar{K}N$ amplitude in chiral unitary approach.
3. **$\bar{K}NN$ bound state**

--- We have to calculate the multiple kaon scattering with two $N$s.

--- We employ the so-called fixed center approximation to the Faddeev equation.

--- FCA amplitude has a peak of $\bar{K}NN$ bound state.

--- Pole at 2354 -- 36 i MeV.

--- $\Delta E \sim 15$ MeV, $\Gamma \sim 70$ MeV.

--- Open circle: $K^0N \rightarrow K^0N$ amplitude in chiral unitary approach.

--- Solve the following scattering equation with a “fixed center”.

3. $\bar{K}NN$ bound state

++ Numerical results ++

- We calculate the mass spectrum and cross section in scenario II.

- Our mass spectrum is compared with that from Exp. analysis: Y. Sada et al. (2016).

$$\frac{d\sigma}{dM_{\Lambda p}} \propto p'_n p^*_\Lambda \frac{\Gamma_X^2}{(M_{\Lambda p} - M_X)^2 + \Gamma_X^2/4}$$

$M_X = 2355^{+6}_{-8} \text{ (stat.)} \pm 12 \text{ (syst.) MeV}/c^2,$

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 <-- Shown in blue line / band, but in arbitrary units.
3. $\Bar{KNN}$ bound state

++ Numerical results ++

- We calculate the mass spectrum and cross section in scenario II.

- Our mass spectrum is consistent with the Exp. within the present errors.

--- Reproduce the tail at lower energy $\sim 2.3$ GeV.

- Therefore, our spectrum supports the explanation that the E15 signal in the $^3$He ($K^-$, $\Lambda p$) $n$ reaction is indeed a signal of the $KNN$ bound state.
3. $\bar{K}NN$ bound state

++ Numerical results ++

We calculate the mass spectrum and cross section in scenario II.

□ One more thing:

Our spectrum has a “double peak” structure around the $\bar{K}NN$ threshold.

--- The lower peak is the signal of the $\bar{K}NN$ bound state.

--- The higher peak comes from the quasi-elastic kaon scattering in the first step.

<-- Almost on-shell kaon.
There are two “bands” in $d^2\sigma/dM_{\Lambda p}d\cos\theta_n$.

--- One is the signal of the $\bar{KNN}$ bound state.

--- The other comes from the quasi-elastic kaon scattering in the first step.

Diff. cross section $d\sigma/d\cos\theta_n$ again indicates forward neutron emission is favored.
3. $\bar{K}NN$ bound state

++ Numerical results ++

There are two "bands" in $d^2\sigma/dM_{\Lambda p}/d\cos\theta_n$.

--- One is the signal of the KNN bound state.
--- The other comes from the quasi-elastic kaon scattering in the first step.

Diff. cross section $d\sigma/d\cos\theta_n$ again indicates forward neutron emission is favored.

Our peak gives $\sigma = 7.6 \mu b$. This is consistent with the empirical value $\sigma = 7 \pm 1 \mu b$ (pole).

Y. Sada et al. (2016).
3. $\bar{K}NN$ bound state

++ Data in 2nd run of J-PARC E15 ... ++

Exclusive $^3\text{He}(K^-,\Lambda p)n$

Sakuma-sun at MENU 2016.

- Two structures are seen around $M[K+p+p]$!?
4. Summary

++ Summary ++

- We have investigated the origin of the peak structure near the $^{3}$He $(K^{-}, \Lambda p) n$ reaction threshold observed by J-PARC E15.

--- We have considered 2 scenarios to create the peak.

1. Uncorrelated $\Lambda(1405)p$, which does not make a bound state.
2. $KNN$ bound state.

- As a result, we have found that the experimental signal is qualitatively well reproduced by the assumption that a $KNN$ bound state is generated in the reaction, while we have discarded the interpretation in terms of an uncorrelated $\Lambda(1405)p$ state.
4. Summary

++ Outlook ++

- We must “prove” the E15 peak is indeed the $K\bar{N}N$ signal.

--- We need to check consistency between experiments and theories for various quantities.

- High statistics data from Exp. & More precise calc. from theory.
- Angular dependence of the peak structure.
- Branching ratio $\Lambda p / \Sigma^0 p$.
- Spin / parity of the system for the peak. 
  ...
Thank you very much for your kind attention!
Appendix
Appendix

++ Outlook ++

- How about the difference between E15 and others?

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++ Outlook ++

- How about the difference between E15 and others?


\[ \pi^+ d \rightarrow K^+ X \]

\[ \Sigma^0 p \text{ decay branch} \]

Experiments

Thomas ('73).

\[ \pi^- p \rightarrow K^0 \pi \Sigma \]
Appendix

++ Outlook ++

- How about the difference between E15 and others?


**Exclusive \(^{3}\text{He}(K^{-},\Lambda p)n**

Sakuma-sun at MENU 2016.

* Two structures are seen around M[K+p+p]!?

E27

Hyodo and Jido (2012).

Experiments