Theoretical analysis on the peak structure observed in the J-PARC E15 experiment

Takayasu SEKIHARA
(Japan Atomic Energy Agency)

in collaboration with

Eulogio OSET (Valencia Univ.)
and Angels RAMOS (Barcelona Univ.)

1. Introduction

2. Theoretical analysis for the J-PARC E15 1st run

3. Theoretical analysis for the J-PARC E15 2nd run

4. Summary
1. Introduction
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++ Kaonic nuclei ++

- Antikaon ($\bar{K}$) -nucleon ($N$) interaction is interesting!
  - The $\bar{K}N$ interaction is **strong enough to make a bound state as $\Lambda(1405)$**.
  - There should exist kaonic nuclei, which are **bound states of $\bar{K}$ and nuclei** via strong interaction between them.

- There are **several motivations** to study kaonic nuclei:
  1. **Exotic states of many-body systems** in strong interaction.
  2. **Feedback to the $\bar{K}N$ interaction**.
  3. **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:**
    
    Barnea, Gal and Liverts, *Phys. Lett.* B712 (2012) 132; ...

  - **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; ...

--- However, this state is **still controversial**.
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- T. Hashimoto et al. [J-PARC E15], *PTEP* 2015 061D01; ...

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1. Introduction

++ J-PARC E15 ++

- Recently, the J-PARC E15 Exp. was performed to search for the $\bar{K}NN$ bond state with the in-flight $K^- \ 3^\text{He} \rightarrow \Lambda p n$ reaction.

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

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1. Introduction

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2. Theoretical analysis for the J-PARC E15 1st run
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++ Peak structure of the J-PARC E15 data ++

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

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

--- From the $\Lambda p$ invariant mass $M_{\Lambda p}$ spectrum and momentum transfer $q_{\Lambda p}$:

- What is this peak ???

--- Is this a signal of the $\bar{K}NN$ bound state ???
2. For the J-PARC E15 1st run

++ Reaction for J-PARC E15 ++

- We want to \textbf{know what is the origin of this peak.}

--> **Calculate the reaction cross section**
and compare it with the Exp. data!

\[ k_{\text{lab}} = 1 \text{ GeV/c} \]
2. For the J-PARC E15 1st run

++ Reaction for J-PARC E15 ++

- We want to know what is the origin of this peak.
- First, we **pin down the reaction mechanism.**

--> Reaction diagram:

- Fast & forward neutron
- Slow kaon
- Slow kaon
- Fast & forward neutron

Some dynamics.

For the J-PARC E15 1st run

- $K^-_{lab} = 1 \text{ GeV/c}$
2. For the J-PARC E15 1st run

++ First collision ++

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

--- Fitted so as to **reproduce the Exp. $d\sigma/d\Omega$.**

- $d\sigma_{KN \rightarrow KN}/d\Omega$ favors forward neutron emission in $^3\text{He}$ $(K^-, \Lambda p)$ $n$!

--- Note: **Form factor for the $\bar{K}$ absorption** also favors forward $n$. 

---
2. For the J-PARC E15 1st run

++ Propagating kaon ++

- The slow kaon after the first collision propagates and is absorbed into two nucleons.
- The expression of the propagator:
  \[
  = \frac{1}{(p^\mu_{\text{prop}})^2 - m_K^2 + im_K \Gamma_K}
  \]

--- Two-nucleon Abs. width \( \Gamma_K = 15 \text{ MeV} \).

--> This can create a "kinematic peak", because the propagating kaon can go almost on its mass shell. ( \( 1 / \text{prop} \sim 0 \) )

- Taking the shaded box = 1. (w/o dynamics of \( \bar{K}NN \) system)

--> The quasi-elastic kaon scattering in the first step.
2. For the J-PARC E15 1st run

++ Scenario: $\bar{K}NN$ bound state ++
- We consider a scenario that $\bar{K}NN$ bound state is indeed generated.

$K^{-}$

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

Fast & forward neutron

$\bar{K}NN$
We consider a scenario that $\bar{K}NN$ bound state is indeed generated.

--- Fixed center Approx. (FCA) amplitude has a peak of $\bar{K}NN$ bound state.

--- Pole at $2354 \pm 36$ i MeV.

$|T_{\text{FCA}}| \quad [\text{MeV}^{-1}]$

$M(K^-pp)$

$K_{\Lambda p} \rightarrow K^-pp$

$\bar{K}^0np \rightarrow K^-pp$

$\bar{K}^0pn \rightarrow K^-pp$

--- $B_E \sim 15$ MeV, $\Gamma \sim 70$ MeV.
2. For the J-PARC E15 1st run

++ $\bar{K}NN$ bound state: Numerical results ++

- We calculate the mass spectrum in a scenario that $\bar{K}NN$ bound state is indeed generated.

□ 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 $\bar{K}NN$ bound state.
One more thing:

Our spectrum has a “two 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 kinematic reason: The quasi-elastic kaon scattering in the 1st step.

<-- Almost on-shell kaon.
3. Theoretical analysis for the J-PARC E15 2nd run
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++ 2nd run data ++

- Now, the 2nd run data of the J-PARC E15 are available!

Ajimura et al., arXiv:1805.12275.

- The same reaction: in-flight $^3$He ($K^-$, $\Lambda p$) $n$.

- ~30 times more data.

- “Two peak” structure.
3. For the J-PARC E15 2nd run

++ 2nd run data ++

- Now, the 2nd run data of the J-PARC E15 are available!

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□ After the cut to separate the bound-state signal and quasi-elastic kaon scattering, they found a single peak structure!
3. For the J-PARC E15 2nd run

++ Comparison with theoretical analysis ++
- We calculate the cross section in the $\bar{K}NN$ bound state scenario.
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++ Comparison with theoretical analysis ++

- We calculate the cross section in the $\bar{K}NN$ bound state scenario.

□ The same behavior for the differential cross section.

Ajimura et al.,

Ts., Oset and Ramos, in preparation.
3. For the J-PARC E15 2nd run

++ Comparison with theoretical analysis ++

- We calculate the cross section in the $\bar{K}NN$ bound state scenario.

- Perform the same cut for the momentum transfer as the Exp. data:
  $350 \text{ MeV} < q_{\Lambda p} < 650 \text{ MeV}$.

- Only the peak of the bound-state signal survives after the cut.
  --- This result supports the validity of the Exp. cut.
3. For the J-PARC E15 2nd run

++ Comparison with theoretical analysis ++

- **We calculate the cross section in the $\bar{K}NN$ bound state scenario.**

- With the cut $350 \text{ MeV} < q_{\Lambda p} < 650 \text{ MeV}$, we can reproduce the peak structure in Exp. but...

  1. **Peak height in theory is smaller** than the Exp. one.

  --- Too strong form factor?

  2. Position and width of the peak are inconsistent.

  More bound $\bar{K}NN$?
4. Summary
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- There should exist kaonic nuclei, generated by the strong interaction between antikaon and nuclei.

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

  □ If we assume the production of the $\bar{K}NN$ bound state, we can qualitatively well reproduce the data of the J-PARC E15.

  --> Our result supports the production of the $\bar{K}NN$ bound state.

  □ Making momentum transfer cut ($350 \text{ MeV} < q_{\Lambda p} < 650 \text{ MeV}$) as in the 2nd run Exp. data, only $\bar{K}NN$ bound-state signal survives.

  --> Our result supports the validity of the Exp. cut.

* * *

- Theorists have to quantitatively reproduce the peak height, position, and width of the 2nd run data, so as to extract more information on the $\bar{K}NN$ bound state.
Thank you very much for your kind attention!