Search for deeply-bound $K^{\bar{\text{bar}}}$ nuclear states via the $^3\text{He}(\text{inflight-K}^-,\text{n})$ reaction at J-PARC

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Hadron2013@Nara
Nov. 8, 2013
Contents

• Introduction
  • Kaonic nuclei

• J-PARC E15 experiment
  • Setup
  • Detector performance

• Preliminary results
  • Hyperon resonance
  • Semi-inclusive 3He(K-, n)X spectrum
  • Exclusive 3He(K-, Λpn) spectrum

• Summary
Introduction

Motivation:
what will happen when anti-kaon is embedded in nucleus.

✔ Does the simplest Kaonic nuclei “K-pp” exist?
✔ How much deeply bound?


M.Agnello et al., PRL 94, 212303 (2005)


DISTO

pp\rightarrow K^+\Lambda p

B = 105\pm 2\pm 5 \text{ MeV}
\Gamma = 118\pm 8\pm 10 \text{ MeV}

FINUDA

B = 115\pm 6\pm 4 \text{ MeV}
\Gamma = 67\pm 14\pm 3 \text{ MeV}
J-PARC E15 Experiment

- Search for K⁻pp bound state by using In-flight $^3$He(K⁻,n) Reaction.
- Measuring both I. M. and M. M. of “K⁻pp”.

Theoretical calculation on $^3$He(K⁻,n)
T. Koike and T. Harada,
PLB652(2007)262

If right, we can measure the bound structure!
the completed K1.8BR spectrometer [Jun. 2012]

- beam dump
- beam sweeping magnet
- Neutron Charge Veto Proton Counter
- liquid $^3$He-target system
- CDS beam line spectrometer
- beam line
- $^3$He-target system
- CDC
- CDH
- ~15m
- K
- n
- p
- NC
- CVC
- PC
Cylindrical Detector System (CDS)

**Cylindrical Detector System (CDS)**

CDC: Drift Chamber
CDH: Hodoscope
Magnet: 0.7T
Cover 60% of the solid angle.

**π+π- invariant mass spectra**

- Peak: 497.83 MeV/c²
- DCA < 2 cm displaced Vertex > 3 mm

**ρπ- invariant mass spectra**

- Peak: 1115.58 MeV/c²
- DCA < 2 cm displaced Vertex > 3 mm

**Design performance was achieved!!**
Forward neutral particle

- Neutron Counter
  - Neutron momentum is determined by TOF method.
  - Good S/N of \(~100\) @QF neutron peak (Set threshold to 5 MeVee).
  - \(\sigma_{\text{TOF}} \approx 160\)ps \(\Rightarrow \sigma_{\text{M.M.}} \approx 10\) MeV/c\(^2\) at the region of interest.

\[\text{counts} \quad \gamma \quad n\]

\[\frac{1}{\beta} \quad \text{accidental background}\]
J-PARC E15 1st stage physics run

• Accumulated data
  ✓ w/ liquid helium-3 target: ~1% of original proposal

<table>
<thead>
<tr>
<th>period</th>
<th>Primary beam intensity</th>
<th>duration</th>
<th>Kaon on target</th>
</tr>
</thead>
<tbody>
<tr>
<td>May, 2013</td>
<td>24kw (30Tppp, 6s cycle)</td>
<td>88 hours</td>
<td>$4.0 \times 10^9$</td>
</tr>
</tbody>
</table>

• Preliminary result
  1. Hyperon production study
     • $\Lambda(1520)$ spectrum
  2. Semi-inclusive analysis
     • $^3$He(K-,n) missing mass spectrum
  3. Exclusive analysis
     • $^3$He(K-, $\Lambda p n$) exclusive
Preliminary result: Hyperon production

Λ(1520) production

- Semi–inclusive $^3$He (K-, n) missing mass
- Exclusive $^3$He (K-, Λpn)

K$^-$ 1.0GeV/c

$^3$He $\rightarrow$ spectator NN $\pi$

L(1520) $\rightarrow$ nK$^0$s $\rightarrow$ n$\pi^+$π$^-$
  - Invariant mass nK$^0$s

☑ Hyperon production on nuclear target provides the important information on the Y*N interaction.
☑ There are no data using nuclear target and this energy region (K$^-$: 1GeV/c).
**Preliminary result : Hyperon production**

\( \Lambda(1520) \) production

- **\( \Lambda(1520) \) peak is clear seen.**
  - BG: \( Kp \rightarrow n\pi K^0s(\text{non-resonant reaction}) \)
  - Peak position is consistent with PDG.

- **Cross section.**
  - Consistent with old data at the same order level.
  - Study of other decay channels is in progress.
Preliminary result:

Semi – inclusive $^3$He(K-, n) missing mass

Exclusive $^3$He (K-, $\Lambda$pn)

$K^-$

$^3$He

1.0 GeV/c

$\gamma$, n

NC hit

CDH hit

charge sweep out

BVC veto

CVC veto

“Semi-”: require at least 1 charged track in the CDS.
Semi-Inclusive $^3\text{He}(K^-,n)$

- w/ charged-track tag in the CDS
- $\sim 1.4 \times 10^5$ events

☑ Quasi free peak ($K^-n \rightarrow K^-n$ & $K^-p \rightarrow K^0n$) is clearly seen.

☑ The excess in the K-bound region is very interesting, it’s hard to explain by detector resolution.

$\sigma_{\text{M.M.}} : \sim 10\text{MeV/c}^2$

@ 1.0 GeV/c

$^3\text{He}(K^-,n)$ missing mass (GeV/c$^2$)
Preliminary result:

Semi–inclusive $^3$He ($K^-$, n) missing mass

Exclusive $^3$He ($K^-$, $\Lambda p n$)
Missing Mass of $^3$He($K^-$, $\Lambda p$)

- Missing neutron can be identified.
- Num. of $\Lambda pn$ (n missing) is $\sim$400 events.

To study the origin of $\Lambda pn$ events, let check Dalitz-plot in the next slide.
$^3\text{He}(K^-, \Lambda pn)$ Result: Dalitz plot of $\Lambda pn$

Selected neutron missing mass peak.

+ all events
- w/ forward n in the NC

*including $\Sigma^0 pn \rightarrow \gamma \Lambda pn$ events
$^3$He$(K^-, \Lambda pn)$ Result: Dalitz plot of $\Lambda pn$

Selected neutron missing mass peak.

Kinematical boundary region

*including $\Sigma^0 pn \rightarrow \gamma \Lambda pn$ events
\[ ^3\text{He}(K^-, \Lambda pn) \text{ Result : Dalitz plot of } \Lambda pn \]

- Events are scattered widely in phase space.
- Multi-N absorption processes exist.

☑️ It seems 3N-abs(\(\Lambda pn\)) exists

\[ p\Lambda \text{ in CDS} \]

\[ \text{Selected neutron missing mass peak.} \]

\[ + \text{ all events} \]

\[ \circ \text{ w/ forward n in the NC} \]

*including \( \Sigma^0 pn \rightarrow \gamma\Lambda pn \) events

\[ n \text{ in NC} \]

\[ p\Lambda \text{ in CDS} \]

\[ (T_p - T_n) / \sqrt{3Q} \]

\[ T_\Lambda / Q \]
$^3$He(K$^-$, $\Lambda pn$) Result: Dalitz plot of $\Lambda pn$

Selected neutron missing mass peak.

- Events are scattered widely in phase space.
- Multi-N absorption processes exist.

☑ It seems $3N$-abs($\Lambda pn$) exists

- “$\Lambda pn$” w/ forward n in the NC are a few events.

☑ We would like to carry out high statistical experiments!
2N-abs

\[ \Sigma - \Lambda \text{ conversion (2step)} \]

Kpp
$^3$He(K$^-$, Λpn) Result: Dalitz plot of Λpn

Selected neutron missing mass peak.

- Events are scattered widely in phase space.
- Multi-N absorption processes exist.

☑ It seems 3N-abs(Λpn) exists
☑ 2N-abs is very weak.

- “Λpn” w/ forward n in the NC are a few events.

☑ We would like to carry out high statistical experiments!
$^3$He($K^-$, $\Lambda pn$) Result : Dalitz plot of $\Lambda pn$

Selected neutron missing mass peak.

- Events are scattered widely in phase space.
- Multi-N absorption processes exist.
- It seems 3N-abs($\Lambda pn$) exists
- 2N-abs is almost nothing.
- can not see $\Sigma$-$\Lambda$ conversion line?

- “$\Lambda pn$” w/ forward n in the NC is a few events.

☑ We would like to carry out high statistical experiments!
$^3$He(K$^-$, Λpn) Result : Dalitz plot of Λpn

- Events are scattered widely in phase space.
- Multi-N absorption processes exist.
- It seems 3N-abs(Λpn) exists
- 2N-abs is almost nothing.
- Can not see Σ-Λ conversion line?
- “Λpn” w/ forward n in the NC is a few events.
- We would like to carry out high statistical experiments!

Finally, will be confirmed in I. M. of Λp w/ missing n.
\( ^3\text{He}(K^-, \Lambda pn) \) Result

\( \Lambda p \) invariant mass

It seems that

☑ 2N abs is very weak.
☑ 3N abs may be dominant.
☑ careful studies are in progress.

\( \text{MC} \)

Kpp
B.E. \( =50 \) MeV
\( \Gamma = 50 \) MeV

2N abs
3N abs

\( \text{2N abs} \)
\( \text{3N abs} \)
Summary

• We have performed 1\textsuperscript{st} physics run of the J-PARC E15 experiment to search for deeply-bound K-pp state.
  ✓~4 x 10\textsuperscript{9} kaons were irradiated on \(^3\text{He}.
  ✓\(^3\text{He} (K^-, n): \sim 1.4 \times 10^5\) events

• We presented preliminary results.
  ✓Hyperon production(\(\Lambda(1520)\)) spectrum
  ✓Semi inclusive \(^3\text{He}(K^-, n)\) spectrum
  ✓Exclusive \(^3\text{He}(K^-, \Lambda\text{pn})\) spectrum
Thank you for your attention!
1: Semi-Inclusive $^3\text{He}(K^-,n)$

- Known $K\cdot N$ interactions are considered from babble chamber data [CERN-HERA-83-02]

Simple assumptions: $\sigma_{\text{tot}} = 2*\sigma_{K-p} + \sigma_{K-n}$ for one-nucleon induced reactions, almost background free
  - $2N$ abs.: $K^- \cdot ^3\text{He} \rightarrow \Lambda n p_s$
    - $\sigma/d\Omega=1\text{mb/sr}$,
  - $K^-\cdot pp$ prod.: $K^- \cdot ^3\text{He} \rightarrow K^-\cdot pp n$
    - $d\sigma/d\Omega=1\text{mb/sr}$
    - $K^-\cdot pp \rightarrow \Lambda p(25\%), \Sigma^0 p(25\%), \pi\Sigma p(50\%)$

$\Rightarrow$ if cross section is over $\sim1$ mb/sr, We have sensitivity of signal.

Expected spectrum from MC (Geant4)

$^3\text{He}(K^-,n)$ M.M. spectrum w/ 1-charged tag in the

\[ \text{Bound} \rightarrow K^-p \rightarrow K^0 n \]

$K^-n \rightarrow K^-n$

<table>
<thead>
<tr>
<th>B.E</th>
<th>50MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>50MeV</td>
</tr>
</tbody>
</table>

2N abs

K-pp

$\Delta K$

$\Delta K\pi$

$\Delta K(1405)\pi$

$\Delta K(1520)\pi$

$\Delta K(1690)\pi$

$\Delta K(1385)\pi$

$\Sigma\pi$

$\Sigma\pi\pi$

$\Sigma\pi\pi\pi$

$\Delta\pi$

$\Delta\pi\pi$

$\Delta\pi\pi\pi$

$\Lambda\pi$

$\Lambda\pi\pi$

$\Lambda\pi\pi\pi$

$\Lambda(1405)\pi$

$\Lambda(1520)\pi$

$\Lambda(1690)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

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$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$

$\Sigma(1385)\pi$
Dalitz plot

Dalitz plot of Λpn

+ all events

● w/ forward n in the NC

*including Σ° → γΛ events

2N abs & Σ-Λ conversion

K⁻ n He

p Λ

+ forward n in the NC

p Λ in CDS (pπ⁻)

signal

K⁻ n He

p Λ

p Λ in CDS (pπ⁻)

K⁻ n He

p Λ

p Λ in CDS (pπ⁻)

signal

K⁻ n He

p Λ

p Λ in CDS (pπ⁻)

K⁻ n He

p Λ

p Λ in CDS (pπ⁻)

K⁻ n He

p Λ

p Λ in CDS (pπ⁻)
Preliminary result: Hyperon production

- $\Lambda(1520)$ peak is clearly seen.
- Peak position is consistent with PDG.
  - Combination of CDS & NC performance is good.
- Cross section
  - Consistent with old data at the same order level.

$\Lambda(1520)$

Graph

Counts/5MeV/c$^2$

- Peak: 1516 GeV/c$^2$
- $\sigma$: 11 GeV/c$^2$

Invariant Mass of nK$^0$s [GeV/c$^2$]

Graph

Kp CM frame

Total cross section $\sim$ mb

Angular distribution of L1520[cos$\Theta$]
Beam spectrometer

beam spectrometer @ K1.8BR beam line

properties @ $p_K = 1.0$ GeV/c

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam momentum</td>
<td>1 GeV/c</td>
</tr>
<tr>
<td>momentum bite</td>
<td>$\sim 3%$</td>
</tr>
<tr>
<td>mom resolution @ 1 GeV/c</td>
<td>2.2 MeV/c</td>
</tr>
<tr>
<td>kaon / spill @ 24 kW</td>
<td>150 k</td>
</tr>
<tr>
<td>total beam / spill @ 24 kW</td>
<td>480 k</td>
</tr>
<tr>
<td>$k/\pi$ ratio</td>
<td>0.45</td>
</tr>
<tr>
<td>T1-FF length</td>
<td>31.3 m</td>
</tr>
</tbody>
</table>

Momentum analyzer
Dipole and wire drift chambers

kaon identification
✓ Aerogel Cherenkov counter
✓ ToF(BHD-T0) Flight length=7.7m
NC construction was completed in Apr. 2012
Cylindrical Detector System (CDS)

Target image

Design performance was achieved!!
Forward neutral particle

- Neutron Counter
  - Neutron momentum is determined by TOF method.
  - Good S/N of ~100@ QF neutron peak (Set threshold to 5 MeVee).
  - $\sigma_{\text{TOF}} \sim 160\text{ps} \Rightarrow \sigma_{\text{M.M.}} \sim 10 \text{ MeV/c}^2$ at the region of interest.
events: 293
S/N: 0.29
peak: 1.516 GeV/c^2
σ: 0.009 GeV/c^2
2: Inclusive \(^3\)He(K\(^-\),Λp)

**Expected (simplified) spectrum from MC (Geant4)**

- Known K\(^-\)-N interactions are considered from babble chamber data [CERN-HERA-83-02]
- Simple assumptions:
  - \(\sigma_{\text{tot}} = 2*\sigma_{K-p} + \sigma_{K-n}\)
  - 2N abs.: K\(^-\) \(^3\)He → Λ p n\(_s\)
    - \(\sigma/d\Omega=1\text{mb/sr}, \text{(isotropic)}\)
  - 3N abs.: K\(^-\) \(^3\)He → Λ p n
    - \(d\sigma/d\Omega=1\text{mb/sr} \text{ (isotropic)}\)
  - K\(^-\)pp prod.: K\(^-\) \(^3\)He → K\(^-\)pp n
    - \(d\sigma/d\Omega=1\text{mb/sr} \text{ (isotropic)}\)
    - K\(^-\)pp → Λp(25%), \(\Sigma^0\)p(25%), \(\pi^\Sigma\)p(50%)