Strange tribaryons studied in the $^4\text{He}(K^-_{\text{stopped}}, \Lambda N)$ reaction

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Introduction - Do deeply bound kaonic nuclear states with narrow widths exist?

- No, they don’t! They must be shallow and broad
- Yes, they do.

Prediction 1: T. Kishimoto (PRL 83 4701 (1999))
BNL-AGS E930 (T. Kishimoto et. al., 2001) with $^{16}$O(in-flight K$^-$,n)
  -> narrow bound state(s)? (NPA 754 383c (2005))
KEK-PS E548 (T. Kishimoto et. al., 2005) with $^{16}$O/$^{12}$C (in-flight K$^-$,N)
  -> no narrow states! but deep potential (PTP 118 181 (2007), NPA 827 321c (2009))

KEK-PS E471 (M. Iwasaki et. al., 2002/2003) with $^4$He(stopped K$^-$,N)
  -> observation of “strange tribaryons” (nucl-ex/0310018,PLB 597 263 (2004))
FINUDA (T. Bressani et. al., 2003/2004/2006) with $^6/7$Li/$^{12}$C(stopped K$^-$,$\Lambda$p/$\Lambda$d)
DISTO (Re-analysis by T. Ymazaki et. al.) with pp->p$\Lambda$K$^+$ at 2.85 GeV
  -> indication of ppK$^-$ bound state (PRL 104 132502 (2010))
KEK-PS E549/570 (M. Iwasaki et. al./R. S. Hayano et. al., 2005) with $^4$He(stopped K$^-$,N)
  -> no narrow states! (PLB 659 107 (2008) , PLB 688 43 (2010))

Broad states with $^4$He(stopped K$^-$,$\Lambda$N)? -> This talk
(semi-)Inclusive missing mass spectroscopy of \((K_{\text{bar}} NNN)_{Z=0,T=1} : S^0 / (K_{\text{bar}} NNN)_{Z=1,T=0,1} : S^+\) via \(K^-_{\text{stopped}} + ^4\text{He} \rightarrow p + S^0_{T=1}\) \(\rightarrow M. Sato et. al., PLB 659 107\) 
\(\rightarrow n + S^+_{T=0,1}\) \(\rightarrow Y(\pi)NN\) \(Y \rightarrow \pi N\) 
\(\rightarrow H. Yim et. al., PLB 688 43\)

✓ Very strict upper limits for narrow \((\Gamma \leq 20\) MeV/c\(^2\)) states.

✓ *Insensitive to broad* \((\Gamma \geq 40\) MeV/c\(^2\)) states. *Large upper limits at \sim 3140\) MeV/c\(^2\) for \(\Gamma \geq 40\) MeV/c\(^2\).*
Semi-exclusive studies - from non-mesonic final states

Semi-exclusive missing mass spectroscopy via

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow N + ^3S_{0/1}^{0/1} \]

\[ ^3S_{0/1}^{0/1} \rightarrow Y(\pi)NN \]

Small statistics, but well resolved final states. Dibaryon?

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow ^2S_{0/1}^{0/1} + N + N \]

\[ ^2S_{0/1}^{0/1} \rightarrow YN \]

Inclusive measurement for

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow ^2S_{0}^{0} \]

Semi-exclusive measurement for

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow ^2S_{0}^{0} \]

\[ ^2S_{T=1/2}^{0} \rightarrow Yn \]

\[ \rightarrow ^3S_{T=0,1}^{+} + n \]

\[ ^3S_{T=0,1}^{+} \rightarrow Yd \]
Stopped $K^-$ Reaction on $^4$He

Only total capture rate is known.
Dynamical nature is Speculative.
The Goals of this talk

Step 1. Does the Two-Nucleon Absorption Process, \( K^- \ ‘NN’(NN) \rightarrow YN (NN) \) exist on \( A>2 \) nuclei? How is the dynamical property if it exists??

This is closely related to the kaonic nuclear search, as

i) it behaves as so far unknown background, and

ii) non-mesonic decay mode of kaonic nucleus, to which experimental searches are mainly performed, is no more than two(or multi)-nucleon absorption at negative energy - *therefore the decay branching ratio is bound by the spin-isospin property at 0-energy.*

Step 2. *Does the multibaryonic intensity, which is clearly separable from the contribution of multi-nucleon absorption process, exist?*
Measurement

YNN/YdN exclusive data, as well as inclusive data of d/N. Momentum decision by track detection+TOF method for $\pi/p/n$ -> remarkable momentum resolutions and PID for $p/n/d$
ΛN correlations (1)

(a_p/n): two-nucleon absorption

(c_p/n): quasi-free hyperon production (+ΣΛ conversion for Σ)

K 'N' -> Σπ/Λπ

(b_p/n): non-mesonic.

But ?? They could be the signal of multibaryon "NN' -> ΛN"
1. ‘NN’ \(_{l=0, S=1}\) dominance of \(K^-\) ‘\(NN\)’ \(_{l,s} \rightarrow \Lambda N\)

2. More intense contribution of \(B_{p/n}\)
(b_{p/n}) \rightarrow \text{broad strength peaked at } \sim 470 \text{ MeV/c.}

✓

K-NN(\text{NN}) \rightarrow \Lambda N(\text{NN}) : \text{two-nucleon absorption followed by only one of } N(\text{N}) \rightarrow N N \text{ or } \Lambda (\text{N}) \rightarrow \Lambda N : \text{elastic rescattering is } \text{unlikely, to account for } \Lambda \text{ and N momentum distributions both shifted. } \Lambda \text{ and N momenta are seen to be lower at the same time.}
\( A_{p/n} \) (Two-Nucleon-Absorption) produces continuum BG as expected at tribaryon mass \( \sim 3070 \text{ MeV}/c^2 \)

\( B_{p/n} \) peaks at tribaryon mass \( \sim 3140 \text{ MeV}/c^2 \) (B.E. 170 MeV),
dibaryon mass \( \rightarrow \Sigma^0 \) contribution must be checked.
Normalized $\Lambda p$ spectra

Condition:
$p_p > 320$ MeV/c
$p_\Lambda > 320$ MeV/c
$\cos\theta_{\Lambda p} < -0.75$

Now, spectra are comparable to any theoretical calculation. Note that $\Sigma^0$ contribution is not negligible (later).

$A_p: 0.9%/K^-$ stopped
$B_p: 1.3%/K^-$ stopped

Peak positions do not shift by the acceptance correction.

Corrected $\Lambda n$ appears soon.
Summary of Observed Properties of $a_p/a_n$: 2-nucleon- absorption (2NA)

$K^- \ 'pp' \ I=1,S=0 \ -> \ \Lambda p$ ($a_p \sim 0.9\% / K^-_{stopped}$)

$K^- \ 'pn' \ I=1,S=0/l=0,S=1 \ -> \ \Lambda n$ ($a_n \sim 3\% / K^-_{stopped}$)

*both* exist on $^4$He (the *first observation on ‘NN’ $I=1,S=0$*).

**Consequences**

1. Significantly small branch on $\Lambda p(I=0,S=1$ dominance$)$.

2. *only* $\sim 30\%$ of known $\Lambda(\Sigma^0)(pnn)(11.7 \pm 2.4)\%$ \ (PRD 1 1267 (1970))
   final states!

3. $K^- [pn]_{l=0,S=1} \rightarrow \Lambda n \sim 0.4\%$ at $E_{Kbar}=0$ \ (PRD 1 1883 (1970))
   and $0.9\%/3\% \sim 30\%$ reaction rate of $K^- [NN]_{l=1,S=0} \rightarrow \Lambda N$ leads

   $K^- [pp]_{l=1,S=0} \rightarrow \Lambda p \sim 0.12\%$ at $E_{Kbar}=0$

   $\rightarrow \ K^- [pp]_{l=1,S=0} \rightarrow \Lambda p \ is \ unlikely \ for \ any \ E_{kbar} > \ Y\pi N$ decay threshold
Summary of Observed Properties of \( \Lambda p/\Lambda n \):

**Multi-baryon candidates**

- **Intense** (~70% of \( \Lambda N NN \) final states) so far unknown non-mesonic components exist on both \( \Lambda p/\Lambda n \).

- \( \Lambda p \) cannot be explained by the elastic re-scattering effect.

- \( \Lambda n \) could be partly explained by that.

\( \Rightarrow \) **\( \Lambda p \) is extremely peculiar.**

- The strength, which is likely to be the tribaryon signals, peaks at ~3140 MeV/c\(^2\) (B.E. 170 MeV)

- **Dibaryon** (\( M \sim 2230 \) MeV/c\(^2\)) interpretation is unlikely, except for unpredicted \( K^-[pn]_{I=0,S=1} \)
Three- and Four-Nucleon Absorption

The existence of three- and four-nucleon absorption processes of $K^-$ were also established in KEK E549...

Condition:
$P_d > 550\text{ MeV/c}$
$P_\Lambda > 350\text{ MeV/c}$
$\cos \theta_{\Lambda d} < -0.8$

$3\text{NA}(\Lambda d \text{ Br.}) : \sim 0.1\% / K^-_{\text{stopped}}$

$4\text{NA}(\Lambda t \text{ Br.}) : 0.03\% / K^-_{\text{stopped}}$

Three- and four-nucleon absorption processes do exist, but too rare to account for intense "B" components.
**ΔN+n semi-exclusive analysis 1**

– separation of $\Sigma^0$ and $\Lambda$ final states

✓ By detecting an additional neutron in coincidence with back-to-back $\Lambda N$, we can separate $\Lambda NN$/$\Lambda_\gamma N$NN/$\Lambda_\pi N$NN final states.

•~30% of Bp component is now found to be occupied by $\Sigma^0$pnn events.

• Study of $\Sigma^0$pnn events allows us more unambiguous search of multibaryon intensity (we can forget the possibility of $\Sigma\Lambda$ conversion).
ΔN+n semi-exclusive analysis 2  
– observation of multibaryon strength

Green : Σ^0 NNN
Red : Δ NNN

- No 2NA strength is seen for Σ^0 p events !!
- Peak of tribaryon mass spectrum by Σ^0 p final state is shifted from expectation of 2NA process by ~40 MeV/c^2 !!
- All conventional explanations are unlikely to account for the peak at 3170 MeV/c^2 !!

Observation of Σ^0 nn decay mode of ^3S^0 tribaryon.

12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon, Williamsburg, Virginia
Conclusions

1. The spin-isospin dependence of 2NA process of negative kaon has been observed for the first time.
2. The 2NA process accounts for only $\sim 30\%$ of non-mesonic $\Lambda$ branch.
3. A large fraction of the remaining $\sim 70\% (7\sim 9\%/K_{\text{stopped}})$ does not allow any interpretation except for multibaryon formation.
4. The $K^- [pp]_{I=1,S=0}$ hypothesis of $\Lambda p$ spectrum (FINUDA interpretation) is, however, unlikely from observed spin-isospin property of the 2NA process at 0-energy.
5. The $\Lambda p$ spectrum suggests $^3S^0_{T=1}$, while the $\Lambda n$ suggests $^3S^+_T=0/1$. The $\Lambda n$ spectrum would be interpreted as an unpredicted dibaryon $K[pn]_{I=0,S=1}$.
6. *Observed* tribaryon mass is $\sim 3140$ MeV/c$^2$ ($\Sigma^0$ and $\Lambda$ modes overlap). The dependence of the peak position on the decay mode was now observed.