A search for double anti-kaon production in antiproton-\(^3\)He annihilation at J-PARC

Fuminori Sakuma, RIKEN

Strangeness in Nuclei @ ECT*, 4-8, Oct, 2010.
Letter of Intent for J-PARC

Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation

dated on 17 / 06 / 2009

M. Iwasaki\textsuperscript{1}, P. Kienle\textsuperscript{2,3}, H. Ohnishi\textsuperscript{1}, F. Sakuma\textsuperscript{1,*}, and J. Zmeskal\textsuperscript{2}

\textsuperscript{1}RIKEN, Japan
\textsuperscript{2}Stefan Meyer Institut für subatomare Physik, Austria
\textsuperscript{3}Technische Universität Munchen, Germany

Abstract

We propose to search for double strangeness production by $\bar{p}$ annihilation on helium nuclei at rest. The proposed experiment will provide significant information on double strangeness production and double strangeness cluster states.
Possibility of "Double-Kaonic Nuclear Cluster" by Stopped-\(p^{\text{bar}}\) Annihilation

Experimental Approach

Summary
What will happen to put one more kaon in the kaonic nuclear cluster?

Possibility of “Double-Kaonic Nuclear Cluster” by Stopped-$p^{\text{bar}}$ Annihilation
The double-kaonic nuclear clusters have been predicted theoretically.
The double-kaonic clusters have much stronger binding energy and a much higher density than single ones.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K-K-ppn</td>
<td>-221</td>
<td>37</td>
<td>17ρ₀</td>
</tr>
<tr>
<td>K-K-ppp</td>
<td>-103</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>K-K-pppn</td>
<td>-230</td>
<td>61</td>
<td>14ρ₀</td>
</tr>
<tr>
<td>K-K-pppp</td>
<td>-109</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

How to produce the double-kaonic nuclear cluster?
- heavy ion collision
- (K⁻,K⁺) reaction
- p̅A annihilation

We use p̅A annihilation

Double-Strangeness Production with $p^\bar{\text{bar}}$

The elementary $p^\bar{\text{bar}}$-p annihilation reaction with double-strangeness production:

$$\bar{p} + p \rightarrow K + K + K + K \quad -98\text{MeV}$$

This reaction is **forbidden for stopped $p^\bar{\text{bar}}$**, because of a negative Q-value of 98MeV.

If multi kaonic nuclear exists with deep bound energy, following $p^\bar{\text{bar}}$ annihilation reactions **would be possible**!

$$\bar{p} + ^3\text{He} \rightarrow K^+ + K^+ + K^- K^- \ pn + B_{KK}^{pn} \ -106\text{MeV}$$

$$\bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + K^- K^- \ pp + B_{KK}^{pp} \ -109\text{MeV}$$

$$\bar{p} + ^4\text{He} \rightarrow K^+ + K^+ + K^- K^- \ pnn + B_{KK}^{pnn} \ -126\text{MeV}$$

$$\bar{p} + ^4\text{He} \rightarrow K^+ + K^0 + K^- K^- \ ppn + B_{KK}^{ppn} \ -129\text{MeV}$$

**Theoretical prediction**

- $B.E. = 117\text{MeV}$, $\Gamma = 35\text{MeV}$
- $B.E. = 221\text{MeV}$, $\Gamma = 37\text{MeV}$
K⁻K⁻pp in p^{bar} + ^3He annihilation at rest?

The possible mechanisms of the K⁻K⁻pp production are as follows:

1: direct K⁻K⁻pp production with 3N annihilation
1': Λ⁺Λ⁺ production with 3N annihilation followed by the K⁻K⁻pp formation
2: elementally p^{bar} + p → KKKK production in nuclear matter followed by the K⁻K⁻pp formation

However, there are many unknown issues, like:

1: non-resonant ΛΛ is likely to be produced compared with the K⁻K⁻pp formation!
1': how large is the Λ⁺Λ⁺ binding energy, interaction?
2: is it possible?

Anyway, if the K-K-pp exists, we can extrapolate simply the experimental results of the K⁻pp:

FINUDA@DAFNE → B.E. ~ 120 MeV, Γ ~ 70 MeV
DISTO@SATURNE → B.E. ~ 100 MeV, Γ ~ 120 MeV
then, we can assume the double binding strength:
B.E ~ 200 MeV, Γ ~ 100 MeV.
Past Experiments of Double-Strangeness Production in Stopped-\( p^{\text{bar}} \) Annihilation

A result of a search for double-strangeness productions in antiproton-nuclei annihilations was reported by using the BNL bubble chamber, in association with the H-dibaryon search.

They did NOT observe any double-strangeness event in antiproton - C, Ti, Ta, Pb annihilation (~80,000 events, \( p(p^{\text{bar}}) < 400 \text{ MeV/c} \))


<table>
<thead>
<tr>
<th>Reaction</th>
<th>Frequency (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p^{\text{bar}}A \rightarrow \Lambda^0\Lambda^0X )</td>
<td>(&lt;4\times10^{-4})</td>
</tr>
<tr>
<td>( p^{\text{bar}}A \rightarrow \Lambda^0K^-X )</td>
<td>(&lt;5\times10^{-4})</td>
</tr>
<tr>
<td>( p^{\text{bar}}A \rightarrow K^+K^+X )</td>
<td>(&lt;5\times10^{-4})</td>
</tr>
<tr>
<td>( p^{\text{bar}}A \rightarrow HX )</td>
<td>(&lt;9\times10^{-5})</td>
</tr>
</tbody>
</table>
Past Experiments (Cont’d)

Observations of the double-strangeness production in stopped $\bar{p}$ annihilations have been reported by 2 groups: DIANA@ITEP and OBELIX@CERN/LEAR.

<table>
<thead>
<tr>
<th>experiment</th>
<th>channel</th>
<th>events</th>
<th>yield ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIANA</td>
<td>$K^+K^+X$</td>
<td>4</td>
<td>0.31+/-0.16</td>
</tr>
<tr>
<td>[p$\bar{p}$+Xe]</td>
<td>$K^+K^0X$</td>
<td>3</td>
<td>2.1+/-1.2</td>
</tr>
<tr>
<td>$K^+K^+\Sigma^-\Sigma^-\rho_s$</td>
<td>34+/-8</td>
<td>0.17+/-0.04</td>
<td></td>
</tr>
<tr>
<td>OBELIX</td>
<td>$K^+K^+\Sigma^-\Sigma^+\pi^-$</td>
<td>36+/-6</td>
<td>2.71+/-0.47</td>
</tr>
<tr>
<td>[p$\bar{p}$+4He]</td>
<td>$K^+K^+\Sigma^-\Lambda n$</td>
<td>16+/-4</td>
<td>1.21+/-0.29</td>
</tr>
<tr>
<td>$K^+K^+K^-\Lambda n$</td>
<td>4+/-2</td>
<td>0.28+/-0.14</td>
<td></td>
</tr>
</tbody>
</table>

Although observed statistics are very small, their results have indicated a high yield of $\sim 10^{-4}$.
Past Experiments (Cont’d)


- $p^{\bar{p}}Xe$ annihilation
- $p=<$1GeV/c $p^{\bar{p}}$-beam @ ITEP 10GeV-PS
- **700-liter Xenon bubble chamber, w/o B-field**
- $10^6$ pictures $\rightarrow$ 7.8x10$^5$ $p^{\bar{p}}Xe$ inelastic $\rightarrow$ 2.8x10$^5$ $p^{\bar{p}}Xe$ @ 0-0.4GeV/c

<table>
<thead>
<tr>
<th>Channel</th>
<th>events</th>
<th>yield ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^+X$</td>
<td>4</td>
<td>0.31+/-0.16</td>
</tr>
<tr>
<td>$K^+K^0X$</td>
<td>3</td>
<td>2.1+/-1.2</td>
</tr>
</tbody>
</table>
Past Experiments (Cont’d)

**OBELIX** (’86~’96) [Nucl. Phys., A797, 109 (2007).]

- $p^\mathrm{bar}_\mathrm{4He}$ annihilation
- stopped $p^\mathrm{bar}$ at CERN/LEAR
- gas target ($^4\mathrm{He}@\mathrm{NTP}$, $H_2@3\mathrm{atm}$)
- **cylindrical spectrometer w/ B-field**
- spiral projection chamber, scintillator barrels, jet-drift chambers
- $2.4\times10^5/4.7\times10^4$ events of 4/5-prong in $^4\mathrm{He}$
- $p_{\text{min}} = 100/150/300\mathrm{MeV/c}$ for $\pi/K/p$

<table>
<thead>
<tr>
<th>channel</th>
<th>events</th>
<th>yield ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^+\Sigma^-\Sigma^-p_s$</td>
<td>34$\pm$8</td>
<td>0.17$\pm$0.04</td>
</tr>
<tr>
<td>$K^+K^+\Sigma^-\Sigma^+n\pi^-$</td>
<td>36$\pm$6</td>
<td>2.71$\pm$0.47</td>
</tr>
<tr>
<td>$K^+K^+\Sigma^-\Lambda n$</td>
<td>16$\pm$4</td>
<td>1.21$\pm$0.29</td>
</tr>
<tr>
<td>$K^+K^+K^-\Lambda n n$</td>
<td>4$\pm$2</td>
<td>0.28$\pm$0.14</td>
</tr>
</tbody>
</table>

**they discuss the possibility of formation and decay of**

$K^-K^-nn$ and $K^-K^-pnn$ bound system
K-pp Production with $p^\text{bar}$ at rest

We can also measure K-pp production with the dedicated detector, simultaneously!

$$\bar{p} + ^3\text{He} \rightarrow K^0 + K^- \text{ pp}$$

**OBELIX@CERN-LEAR**

NP, A789, 222 (2007).

$$\bar{p} + ^4\text{He} \rightarrow K^- \text{ pp} + X$$

$$\rightarrow \Lambda + p$$

B.E. = -151.0$\pm$3.2$\pm$1.2 MeV

$\Gamma < 33.9$-$6.2$ MeV

prod. rate $> 1.2 \times 10^{-4}$

Our experiment can check the OBELIX results of the K-pp with a dedicated spectrometer
H-dibaryon search with $p^\text{bar}$ at rest

We can also search for H-dibaryon (H-resonance) by using $\Lambda\Lambda$ invariant mass / missing mass:

$$\overline{p} + ^3\text{He} \rightarrow K^0 + K^+ + H \rightarrow \Lambda + \Lambda$$

**E522@KEK-PS**

$^{12}\text{C}(K^-, K^+ \Lambda\Lambda X)$


The upper limit for the production cross section of the H with a mass range between the $\Lambda\Lambda$ and $\Xi N$ threshold is found to be $2.1 \pm 0.6$ (stat.) $\pm 0.1$ (syst.) $\mu$b/sr at a 90% confidence level.

The exclusive measurement has never been done using stopped $p^\text{bar}$ beam.
The double-strangeness production yield of $\sim 10^{-4}$ makes it possible to explore the exotic systems.

Experimental Approach
How to Measure?

we focus the reaction:

\[ \bar{p} + ^3He \rightarrow K^+ + K^0 + X \quad (X = K^-K^- pp) \]

(although K^-K^-pp decay modes are not known at all,)

we assume the most energetic favored decay mode:

\[ K^-K^- pp \rightarrow \Lambda + \Lambda \]

\textit{final state} = \( K^+K^0\Lambda\Lambda \)

We can measure the K^-K^-pp signal \textit{exclusively} by detection of all particles, \( K^+K^0\Lambda\Lambda \), using \( K^0 \rightarrow \pi^+\pi^- \) mode

We need wide-acceptance detectors.
Expected Kinematics

**K⁺K⁰X momentum spectra**

\[ \bar{p} + ^3\text{He} \rightarrow K^+ + K_S^0 + K^- K^- pp \]

**assumptions:**

- widths of K⁻K⁻pp = 0
- isotropic decay

In the K⁻K⁻pp production channel, the kaons have very small momentum of up to 300MeV/c, even if B.E. = 200MeV.

We have to construct low mass material detectors.

~200MeV/c π from K⁰, ~800MeV/c Λ, ~700MeV/c p from Λ, ~150MeV/c π from Λ
Procedure of the K⁻K⁻pp Search

Key points of the experimental setup

- high intensity $p^\text{bar}$ beam
- low mass material detector
- wide acceptance detector

Methods of the measurement

- (semi-inclusive) $K^0_S K^+$ missing-mass w/ $\Lambda$-tag
- (inclusive) $\Lambda\Lambda$ invariant mass
- (exclusive) $K^0_S K^+\Lambda\Lambda$ measurement

The E15 spectrometer at K1.8BR satisfies the above requirements
stopped-$p^{\text{bar}}+^{3}\text{He} \rightarrow K^{+}+K^{0}_{s}+K^{-}\text{pp}$,
$K^{-}\text{pp} \rightarrow \Lambda\Lambda$,
$\Gamma(K^{-}\text{pp})=100\text{MeV}$

--- $\Lambda\Lambda$ detection
--- $K^{0}_{s}K^{+}$ w/ $\Lambda$-tag detection
--- $K^{0}_{s}K^{+}\Lambda\Lambda$ detection

binding energy

- B.E. = 120 MeV
- B.E. = 150 MeV
- B.E. = 200 MeV

acceptance

- 9.0%
- 3.5%
- 0.8%
p^{\bar{b}ar} Beam @ J-PARC K1.8BR

We would like to perform the proposed experiment at J-PARC K1.8BR beam line

- 50kW, 30GeV
- 6.0 degrees
- Ni-target

p^{\bar{b}ar} production yield with a Sanford-Wang + a p^{\bar{b}ar} CS parameterization

p^{\bar{b}ar} stopping-rate evaluation by GEANT4

**Incident Beam**
- momentum bite: +/-2.5% (flat)
- incident beam distribution: ideal

**Detectors**
- Tungsten Degrader: \( \rho = 19.25\text{g/cm}^3 \)
- Plastic Scintillator: \( l = 1\text{cm}, \rho = 1.032\text{g/cm}^3 \)
- Liquid He3 target: \( \phi = 7\text{cm}, l = 12\text{cm}, \rho = 0.080\text{g/cm}^3 \)

**p^{\bar{b}ar} stopping-rate**

- \( 6.5 \times 10^3 \text{spill/3.5s} \) at 0.7GeV/c

\[ p^{\bar{b}ar} \text{ stopping-rate evaluation} \]

\[ 250 \text{ stopped } p^{\bar{b}ar}/\text{spill} \text{ at } 0.7\text{GeV/c, } l_{\text{degrader}} \sim 3\text{cm} \]
Expected double-strangeness Production Yield

- $p\bar{p}$ beam momentum: 0.7 GeV/c
- Beam intensity: $6.5 \times 10^3$/spill/3.5s @ 50kW
- $p\bar{p}$ stopping rate: 3.8%

stopped-$p\bar{p}$ yield: 250/spill/3.5s

We assume:
- double-strangeness production rate = $10^{-4}$
- Duty factors of the accelerator and apparatus = 21h/24h

Double-strangeness production yield = 540 / day @ 50kW  
[1 day = 3 shifts]
Trigger Scheme

expected stopped-$p^{\bar{\text{bar}}}$ yield = 250/spill @ 50kW

All events with a scintillator hit can be accumulated

$p^{\bar{\text{bar}}}^{3}\text{He}$ charged particle multiplicity at rest

<table>
<thead>
<tr>
<th>Nc</th>
<th>Branch (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$5.14 +/- 0.04$</td>
</tr>
<tr>
<td>3</td>
<td>$39.38 +/- 0.88$</td>
</tr>
<tr>
<td>5</td>
<td>$48.22 +/- 0.91$</td>
</tr>
<tr>
<td>7</td>
<td>$7.06 +/- 0.46$</td>
</tr>
<tr>
<td>9</td>
<td>$0.19 +/- 0.08$</td>
</tr>
</tbody>
</table>

$\langle N_c \rangle = 4.16 +/- 0.06$
Backgrounds

(semi-inclusive) $K^0_S K^+$ missing-mass w/ $\Lambda$-tag

- **3N annihilation**
  - $\text{stopped-}p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + \Lambda + \Lambda$
  - $\text{stopped-}p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + \Lambda + \Lambda + \pi^0 \ldots$

- **2N annihilation**
  - $\text{stopped-}p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + K^0 + \Sigma^0 + (n)$
  - $\text{stopped-}p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + \Xi^0 + (n) \ldots$
Backgrounds (Cont’d)

(inclusive) $\Lambda\Lambda$ invariant mass

- stopped-$p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$
  $\rightarrow \Lambda + \Lambda$

  *missing 2$\gamma$*

- stopped-$p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$
  $\rightarrow \Sigma^0 + \Sigma^0$

  *missing 2$\gamma$ + $\pi^0$*

- stopped-$p^{\text{bar}} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$
  $\rightarrow \Sigma^0 + \Sigma^0 + \pi^0$

B.E. = 200 MeV
$\Gamma$ = 100 MeV
Expected Spectra

- Monte-Carlo simulation using GEANT4 toolkit
- reaction and decay are considered to be isotropic and proportional to the phase space
- energy losses are NOT corrected in the spectra
- w/o Fermi-motion
- DAQ and analysis efficiency of 0.7

expected spectra are obtained with the following assumptions:

production rate:

- $K^-K^-pp$ bound-state = $1 \times 10^{-4}$
- $(3N)$ $K^-K^-\Lambda\Lambda$ phase-space = $5 \times 10^{-5}$
- $(3N)$ $K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = $5 \times 10^{-5}$
- $(2N)$ $K^+K^0K^0\Sigma^0(n)$ phase-space = $3 \times 10^{-4}$

- total yield: upper limit of $p^{\text{bar}}A \rightarrow K\Lambda\Xi$, $5 \times 10^{-4}$
- $3N$: 20% of total yield, and $3N:2N = 1:3$
- $K^-K^-pp$ yield: 20% of total yield

These are optimistic assumptions
non-mesonic : mesonic = 1 : 1

because the \( \Sigma \Sigma \pi \pi \) decay channel expected as the main mesonic branch of the \( K^-K^-pp \) state could decrease due to the deep binding energy of the \( K^-K^-pp \)
In the $\Lambda\Lambda$ spectra, we hardly discriminate the K-K-pp $\rightarrow \Lambda\Lambda$ signals from the backgrounds clearly, but a cocktail approach could help us to explore the K-K-pp signals?
The exclusive $K^0K^+$ missing mass spectrum is attractive because we can ignore the 2N-annihilation, even though the expected statistics are small.

\[ \bar{p} + ^3He \rightarrow K^+ + K^0 + \Lambda + X \]

\[ \bar{p} + ^3He \rightarrow K^+ + K^0 + \Lambda + \Lambda (+X) \]
Sensitivity to the $K^-K^-pp$ signal

- **beam power**: 50kW, 6 weeks
- **production rate**:
  - $K^-K^-pp$ bound-state = parameter
  - $(3N) K^-K^-\Lambda\Lambda$ phase-space = 5x10^{-5} (fix)
  - $(3N) K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = 5x10^{-5} (fix)
  - $(2N) K^+K^0K^0\Sigma^0(n)$ phase-space = 3x10^{-4} (fix)

- significance [$\sigma=S/\sqrt{S+B}$] is obtained in exclusive missing-mass spectra

**ppK^-K^- rate** = 1x10^{-4}

- Integrated range: 2600 – 2760 MeV

---

**Figure**

- $S = 5.0$
- $S/\sqrt{S+B}$
- $B_{KK}$ = 200 MeV
- $B_{KK}$ = 150 MeV
- $B_{KK}$ = 120 MeV

- $4x10^{-5}$, $7x10^{-5}$, $1.1x10^{-4}$
Sensitivity to the $K^-K^-pp$ signal (Cont’d)

- **beam power**: parameter
- **production rate**: parameter
  - $K^-K^-pp$ bound-state
  - $(3N) K^-K^-\Lambda\Lambda$ phase-space = $5 \times 10^{-5}$ (fix)
  - $(3N) K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = $5 \times 10^{-5}$ (fix)
  - $(2N) K^+K^0K^0\Sigma^0(n)$ phase-space = $3 \times 10^{-4}$ (fix)

 significance [$\sigma = S/\sqrt{S+B}$] is obtained in exclusive missing-mass spectra

--- $B_{KK} = 200$ MeV
--- $B_{KK} = 150$ MeV
--- $B_{KK} = 120$ MeV
Sensitivity to the double-strangeness production

Don't forget that the double-strangeness production itself, in $p^{\text{bar}}+A$ annihilation at rest, is very interesting. (there are NO conclusive evidences)

- production mechanism (multi annihilation/cascade/...)?
- hidden strangeness?
- $\Lambda/\Xi\Lambda$?
- cold QGP? ← little bit old!

● significance $[\sigma = \sqrt{S}]$ of the $\Lambda\Lambda$ is obtained in the inclusive $K^+K^0+\Lambda+\Lambda$ event

![Graph showing the sensitivity to the double-strangeness production rate (ΛΛ production rate) vs. number of proton on target.](image)

OBELIX/DIANA
Summary
Summary

● We will search for double anti-kaon nuclear bound states by p\(\bar{p}\) annihilation on \(^3\text{He}\) nuclei at rest, using the \(p^{\bar{p}} + ^3\text{He} \rightarrow K^+ + K^0 + X (X = K^-K^-pp)\) channel.

● The produced \(K^-K^-pp\) cluster will be identified with missing mass spectroscopy using the \(K^+K^0\) channel with a \(\Lambda\)-tag, and invariant mass analysis of the expected decay particles from the \(K^-K^-pp\) cluster, such as \(\Lambda\Lambda\) by using the E15 spectrometer at the K1.8BR beam line.

● We are now improving this experiment toward the proposal submission to J-PARC.
Back-Up
### Schedule

<table>
<thead>
<tr>
<th>Year (JFY)</th>
<th>K1.8BR</th>
<th>K1.1 (φN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>beam-tune</td>
<td>proposal</td>
</tr>
<tr>
<td>2010</td>
<td>E17</td>
<td>R&amp;D, design</td>
</tr>
<tr>
<td>2011</td>
<td>E17</td>
<td>R&amp;D, design</td>
</tr>
<tr>
<td>2012</td>
<td>E15/E31</td>
<td>construction</td>
</tr>
<tr>
<td>2013</td>
<td>E15/E31</td>
<td>commissioning</td>
</tr>
<tr>
<td>2014</td>
<td>...</td>
<td>data taking</td>
</tr>
</tbody>
</table>

The proposed experiment will be scheduled in around JFY2014, whether we conduct the experiment at K1.8BR or K1.1 beam-line.

- **K1.8BR**: after E17/E15/E31
- **K1.1**: joint project with the φN experiment (E29)?
$\Lambda(1405)/K^-\text{pp production in } p^{\text{bar}}A \text{ annihilation at rest}$
the things we have learned from the past experiments are:

1. the reactions whose quark-lines vanish are minority (Pontecorvo reactions)

\[ p^{\bar{b}ar} + d \rightarrow K^0 + \Lambda + X \]
\[ \sim 10^{-3} \]

\[ p^{\bar{b}ar} + d \rightarrow K^0 + \Lambda \]
\[ \sim 10^{-6} \]


It would be too hard to investigate the \( \Lambda(1405) \) production using the simple channel in \( p^{\bar{b}ar}A \) reaction
2. \( \Lambda(1405) \) production yield in \( p^\text{bar}+A \) annihilation can be considered as

\[ \sim \frac{1}{10} \times \Lambda(\Sigma^0) \] production yield

by analogy with the \( \pi^-+p \) reaction

\[ \pi^-+p \rightarrow X, \quad p_{\pi^-} = 4.5 \text{ GeV/c} \rightarrow \sqrt{s} = 3.2 \text{ GeV} \]

\[ p^\text{bar}+d \rightarrow X, \quad \text{at rest} \rightarrow \sqrt{s} = 2.8 \text{ GeV} \]

- \( \pi^-+p \rightarrow \Lambda+K \quad : \quad 123.5 \mu\text{b} \)
- \( \pi^-+p \rightarrow \Sigma^0+K \quad : \quad 61.5 \mu\text{b} \)
- \( \pi^-+p \rightarrow \Lambda(1405)+K^0 \quad : \quad 18 \mu\text{b} \)
\( \Lambda(1405) \) production in \( p^{\bar{\text{bar}}}A \) annihilation (Cont’d)

\[
\begin{align*}
\bar{p}d & \rightarrow \Lambda(\Sigma^0)+X : \sim 3.3 \times 10^{-3} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}d & \rightarrow \Lambda(\Sigma^0)+K^0 : \sim 4.5 \times 10^{-6} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}^3\text{He} & \rightarrow \Lambda(\Sigma^0)+X : \sim 5.5 \times 10^{-3} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}d & \rightarrow \Lambda(1405)+X : \sim 3 \times 10^{-4} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}d & \rightarrow \Lambda(1405)+K^0 : \sim 5 \times 10^{-7} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}^3\text{He} & \rightarrow \Lambda(1405)+X : \sim 5 \times 10^{-4} \text{ per stopped-} p^{\bar{\text{bar}}} \\
\bar{p}^3\text{He} & \rightarrow \Lambda(1405)+K^0+\pi^- : \sim 5 \times 10^{-7} \text{ per stopped-} p^{\bar{\text{bar}}} 
\end{align*}
\]

- taking account of the \( K^0 \) detection efficiency of \( \sim 10^{-1} \), naively, the \( \Lambda^* \) detection yield with the simple channel is the order of \( 10^{-8}/\text{stopped-} p^{\bar{\text{bar}}} \) at least.
- huge combinatorial background from involved pions could not be eliminated from \( \Lambda^* \rightarrow \pi\Sigma \rightarrow \pi\pi n \) decays, even if we can detect the neutron.
K^-pp production in p^\text{bar}A annihilation

1 nucleon annihilation (from K^-)

e.g.: \( \bar{p} + ^3\text{He} \rightarrow (\bar{p} + n) + p + p \)
\( \rightarrow K^+ + K^- + \pi^- + p + p \)
\( \rightarrow K^+ + \pi^- + (K^- + p + p) \)
\( \rightarrow K^+ + \pi^- + K^- pp \)

\( \text{yield} \sim 10^{-2} \)

p_{K^-} \sim 900\text{MeV/c}

2 nucleon annihilation (from \( \Lambda(1405) \))

e.g.: \( \bar{p} + ^3\text{He} \rightarrow (\bar{p} + pn) + p \)
\( \rightarrow K^0 + \pi^+ + \pi^- + \Lambda(1405) + p \)
\( \rightarrow K^0 + \pi^+ + \pi^- + (\Lambda(1405) + p) \)
\( \rightarrow K^0 + \pi^+ + \pi^- + K^- pp \)

\( \text{yield} \sim 10^{-4} \)

p_{\Lambda^*} \sim 500\text{MeV/c}

3 nucleon annihilation (direct production)

e.g.: \( \bar{p} + ^3\text{He} \rightarrow (\bar{p} + ppm) \)
\( \rightarrow K^+ + \pi^- + K^- pp \)
Let’s consider sticking probability $R$ of $\Lambda(1405)$ with proton as the following equation:

$$R \sim \exp(-q^2/p_F^2),$$

where $q$ is the momentum transfer and $p_F$ is the Fermi motion of $^3\text{He}$ which is $\sim 100$ MeV/c. If we assume $q$ is $\sim 500$ MeV/c, then the probability $R$ can be obtained to be $\sim 10^{-11}$.

However, if we apply their assumption of $R \sim 1\%$

K-pp yield $\sim 3 \times 10^{-4}$ ($\Lambda^*$ yield) $\times 10^{-2}$ (sticking prob.) = $3 \times 10^{-6}$ in $p^\text{bar} + ^3\text{He}$ annihilation.
K^-pp production in p^barA annihilation (Cont’d)

acceptance with the E15 CDS

\[ p^\text{bar} + ^3\text{He} \rightarrow K^+ + \pi^- + (K^-pp) \]

\[ K^-pp \rightarrow \Lambda p, \quad \Gamma = 100\text{MeV} \]
K⁻pp production in p^barA annihilation (Cont’d)

**For example**
- at rest
- p^bar^3He → K⁺π⁻(K⁻pp)
- K⁻pp → Λp
- B.E. = 100MeV,
- Γ = 100MeV

**Mass spectra**

- Mass resolution
  - Λp inv-mass : ~24MeV/c²
  - K⁺π⁻ miss-mass : ~79MeV/c²

- for example
  - at rest
  - p^bar^3He → K⁺π⁻(K⁻pp)
  - K⁻pp → Λp
  - B.E. = 100MeV,
  - Γ = 100MeV

*** Production yields are assumed to be the same for each process ***
K⁻pp production in p^barA annihilation (Cont’d)

- from the past experiment (CERN-LEAR), the Λ production yield in p^bar+^3He annihilation is known to be 5.5x10⁻³/stopped-p^bar.
- If we assume the ratio of 3NA/2NA is 10%, then the simplest BG p^bar+^3He→K⁺π⁻Λp is ~5x10⁻⁴.

- beam power: 50kW, 6weeks
- production rate:
  - K⁻pp bound-state = 1x10⁻⁴
  - (3N) Λp phase-space = 5x10⁻⁴

K⁻pp→Λp/Σ⁰p/π⁰Σ⁰p = 100/0/0

B.E.=100MeV
Γ=100MeV

25/25/50

50/50/0

from OBELIX
in-flight experiment
Detector Acceptance

\[ \bar{p} + ^3\text{He} \rightarrow K^+ + K_0^0 + K^- \bar{p} + p, \]
\[ K^- K^- + p \rightarrow \Lambda\Lambda, \]
\[ \Gamma(K^- K^- + p) = 100\text{MeV} \]

--- \( \Lambda\Lambda \) detection
--- \( K_0^0 K^+ \) w/ \( \Lambda \) tag detection
--- \( K_0^0 K^+ \Lambda\Lambda \) detection

--- stopped
--- 1GeV/c

\[ p + ^3\text{He} \rightarrow K^+ + K_0^0 + (K^- K^- + p) \]
\[ K^- K^- + p \rightarrow \Lambda\Lambda, \]
\[ \Gamma = 100\text{MeV} \]

binding energy
Expected double-strangeness Production Yield

- pbar beam momentum: 1GeV/c
- beam intensity: $7.0 \times 10^4$/spill/3.5s @ 50kW

we assume $K^-K^-pp$ production rate = $10^{-4}$ for 1GeV/c pbar+p
(analogy from the DIANA result of double-strangeness production although the result are from pbar+^{131}Xe reaction)

inelastic cross-section of 1GeV/c pbar+p is (117-45) = 72mb

$K^-K^-pp$ production CS = 7.2µb for 1GeV/c pbar+p
Expected double-strangeness Production Yield (Cont’d)

L$^3$He parameters:
* $\rho = 0.08\text{g/cm}^3$
* $l = 12\text{cm}$

\[ N = \sigma \cdot N_B \cdot N_T \]
- $N$: yield
- $\sigma$: cross section
- $N_B$: the number of beam
- $N_T$: the number of density per unit area of the target

BG rate:
- total CS = $117\text{mb}$
- $pbar = 7.0 \times 10^4 /\text{spill}$
- $BG = 1.6 \times 10^3 /\text{spill}$

Duty factors of the accelerator and apparatus = $21\text{h/24h}$

Expected double-strangeness yield = $2.1 \times 10^3 /\text{day} @ 50\text{kW}$

w/o detector acceptance
Expected Spectra @ 50kW, 6 weeks

**ΛΛ invariant mass (2Λ)**

- # of K·K·pp→ΛΛ = 716

**ΛΛ invariant mass (2K2Λ)**

- # of K·K·pp→ΛΛ = 24

**K⁺K⁰ missing mass (2KΛ)**

- # of K·K·pp = 776
- ppK⁻K⁻ rate = 1x10⁻⁴

**K⁺K⁰ missing mass (2K2Λ)**

- # of K·K·pp = 41
Expected Spectra @ 50kW, 6weeks (Cont’d)

The in-flight $K^+K^0$ missing mass spectrum looks nice, however, the backgrounds and the $K^-K^-pp$ signal are unified in case the $K^-K^-pp$ production yield is less than $\sim 0.5 \times 10^{-4}$!

- **Beam power**: $50kW$, 6 weeks
- **Production rate**:
  - $K^-K^-pp$ bound-state = parameter
  - $(3N) K^-K^-\Lambda\Lambda$ phase-space = $5 \times 10^{-5}$ (fix)
  - $(3N) K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = $5 \times 10^{-5}$ (fix)
  - $(2N) K^+K^0K^0\Sigma^0(n)$ phase-space = $3 \times 10^{-4}$ (fix)

**$K^+K^0$ missing mass (2KΛ)**

- Number of $K^-K^-pp = 776$
- $ppK^-K^-$ rate = $1 \times 10^{-4}$

**$K^+K^0$ missing mass (2KΛ)**

- Number of $K^-K^-pp = 389$
- $ppK^-K^-$ rate = $0.5 \times 10^{-4}$
Expected Spectra @ 50kW, 6weeks

$K^+K^0\Lambda\Lambda$ missing-mass$^2$ (2$K2\Lambda$)

1GeV/c $p\bar{p}$
Other backups
Double-Strangeness Production Yield by Stopped-$p^\text{bar}$ Annihilation

From several stopped-$p^\text{bar}$ experiments, the inclusive production yields are:

\[
R(\bar{p}p \rightarrow KK) \sim 5 \times 10^{-2}
\]
\[
R(\bar{p}^3He \rightarrow \Lambda(\Sigma^0)) \sim 0.6 \times 10^{-2}
\]
\[
R(\bar{p}^4He \rightarrow \Lambda(\Sigma^0)) \sim 1.1 \times 10^{-2}
\]

Naively, the double-strangeness production yield would be considered as:

\[
R(\bar{p}A \rightarrow K\bar{K}KK) = R(\bar{p}p \rightarrow K\bar{K})^2 \times \gamma \sim 10^{-5}
\]

$\gamma$: reduction factor $\sim 10^{-2}$
Interpretation of the Experimental Results

- Although observed statistics are very small, the results have indicated a high yield of $\sim 10^{-4}$, which is naively estimated to be $\sim 10^{-5}$.

- Possible candidates of the double-strangeness production mechanism are:
  - rescattering cascades,
  - exotic processes (such as $B>0$ annihilation, formation of a cold QGP, deeply-bound kaonic nuclei, H-particle, etc.)

The mechanism is NOT known well because of low statistics of the experimental results!
**K⁺K⁰ΛΛ Final State & Background**

\[ \bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + X \]

\[ \rightarrow K^+ + K^0 + \Lambda + \Lambda \]

This exclusive channel study is equivalent to the unbound (excited) H-dibaryon search!

<table>
<thead>
<tr>
<th>Q-value</th>
<th>X momentum</th>
<th>( \Lambda\Lambda ) mass</th>
<th>( \Lambda-\Lambda ) angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁺K⁻pp</td>
<td>very small</td>
<td>( M_{\Lambda\Lambda} &gt; 2M_\Lambda )</td>
<td>back to back</td>
</tr>
<tr>
<td>H-dibaryon</td>
<td>large</td>
<td>( M_{\Lambda\Lambda} \sim 2M_\Lambda )</td>
<td>( \sim 0 )</td>
</tr>
</tbody>
</table>

**Possible background channels**

- **direct** \( K^+K^0\Lambda\Lambda \) production channels, like:
  
  \[ \bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + \Lambda + \Lambda \]

- \( \Sigma^0 \rightarrow \gamma\Lambda \) contaminations, like:
  
  \[ \bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + \Lambda + \Sigma^0 \]
  
  \[ \rightarrow K^+ + K^0 + \Lambda + \Lambda + \gamma \]
Expected Kinematics (Cont’d)

\[ \bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + H \quad \bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + \Lambda + \Lambda \]

\[ M_H = 2M_\Lambda \]

\[ \text{strong correlation of } \Lambda \Lambda \text{ opening-angle in } K^-K^-\text{pp/H productions} \]
Detector Design

Key points
• low material detector system
• wide acceptance with pID

B = 0.5T
CDC resolution: $\sigma_{r\phi} = 0.2\text{mm}$
$\sigma_z$’s depend on the tilt angles (~3mm)
ZTPC resolution: $\sigma_z = 1\text{mm}$
$\sigma_{r\phi}$ is not used for present setup

<table>
<thead>
<tr>
<th>ZTPC</th>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius</td>
<td></td>
<td>92.5</td>
<td>97.5</td>
<td>102.5</td>
<td>107.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CDC</th>
<th>Type</th>
<th>A</th>
<th>A'</th>
<th>A</th>
<th>U</th>
<th>U'</th>
<th>V</th>
<th>V'</th>
<th>A</th>
<th>A'</th>
<th>U</th>
<th>U'</th>
<th>V</th>
<th>V'</th>
<th>A</th>
<th>A'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>radius</td>
<td></td>
<td>190.5</td>
<td>204.0</td>
<td>217.5</td>
<td>248.5</td>
<td>262.0</td>
<td>293.0</td>
<td>306.5</td>
<td>337.5</td>
<td>351.0</td>
<td>382.0</td>
<td>395.5</td>
<td>426.5</td>
<td>440.0</td>
<td>471.0</td>
<td>484.5</td>
</tr>
</tbody>
</table>
Expected Spectra @ 50kW, 6weeks

$K^+K^0\Lambda\Lambda$ missing-mass$^2$ $(2K2\Lambda)$
with Dipole-setup @ K1.1
Detector Design (Cont’d)

**new dipole setup @ K1.1**

- The design goal is to become the common setup for the $\phi$-nuclei experiment with in-flight $p^{\text{bar}}$-beam
- $B = 0.5\,\text{T}$
- Double Cylindrical-Drift-Chamber setup
- pID is performed with dE/dx measurement by the INC

- INC resolution: $\sigma_{r\phi} = 0.2\,\text{mm}$, $\sigma_z = 2\,\text{mm}$ (UV)
- CDC resolution: $\sigma_{r\phi} = 0.2\,\text{mm}$, $\sigma_z = 2\,\text{mm}$ (UV)
- CDC is NOT used for the stopped-$p^{\text{bar}}$ experiment

### INC (wire chamber)

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius</td>
<td>100</td>
<td>120</td>
<td>140</td>
<td>160</td>
<td>180</td>
<td>200</td>
<td>220</td>
<td>240</td>
<td>260</td>
<td>280</td>
<td>300</td>
<td>320</td>
<td>340</td>
<td>360</td>
<td>380</td>
<td>400</td>
<td>420</td>
</tr>
</tbody>
</table>

### CDC

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius</td>
<td>500</td>
<td>525</td>
<td>550</td>
<td>575</td>
<td>600</td>
<td>625</td>
<td>650</td>
<td>675</td>
<td>700</td>
<td>725</td>
<td>750</td>
<td>775</td>
<td>800</td>
<td>825</td>
<td>850</td>
</tr>
</tbody>
</table>
Detector Acceptance

\[ \text{p}^\text{bar} + ^3\text{He} \rightarrow \text{K}^+ + K^0_S + \text{K}^- \text{pp}, \]

\[ \text{K}^- \text{K}^- \text{pp} \rightarrow \Lambda\Lambda, \]

\[ \Gamma(\text{K}^- \text{K}^- \text{pp}) = 100\text{MeV} \]

--- \( \Lambda\Lambda \) detection
--- \( K^0_S K^+ \) w/ \( \Lambda \)-tag detection
--- \( K^0_S K^+ \Lambda\Lambda \) detection

--- stopped
--- 1GeV/c

Graph showing the acceptance vs. binding energy for different values of binding energy (B.E. = 120MeV, B.E. = 150MeV, B.E. = 200MeV), with lines for \( \Lambda\Lambda \) detection, \( K^0_S K^+ \) w/ \( \Lambda \)-tag detection, and \( K^0_S K^+ \Lambda\Lambda \) detection.
Expected Spectra @ 50kW, 6weeks

\(\Lambda\Lambda\) invariant mass (2\(\Lambda\))

- \# of \(K^-K^-pp \rightarrow \Lambda\Lambda\) = 138

\(K^+K^0\) missing mass (2\(K\))

- \# of \(K^-K^-pp\) = 327

\(\Lambda\Lambda\) invariant mass (2\(K2\Lambda\))

- \# of \(K^-K^-pp \rightarrow \Lambda\Lambda\) = 14

\(K^+K^0\) missing mass (2\(K2\Lambda\))

- \# of \(K^-K^-pp\) = 46

stopped \(\bar{p}\)
Expected Spectra @ 50kW, 6 weeks

\[ \text{stopped pbar} \]

\[ K^+K^0\Lambda\Lambda \text{ missing-mass}^2 (2K2\Lambda) \]
Expected Spectra @ 50kW, 6 weeks

**ΛΛ invariant mass (2Λ)**

- # of KKpp → ΛΛ = 554

**K⁺K⁰ missing mass (2K)**

- # of K Kpp = 1473

**ΛΛ invariant mass (2K2Λ)**

- # of K Kpp → ΛΛ = 38

**K⁺K⁰ missing mass (2K2Λ)**

- # of K Kpp = 82
Expected Spectra @ 50kW, 6 weeks

\[ K^+K^0\Lambda\Lambda \text{ missing-mass}^2 (2K2\Lambda) \]

- sum
- \( KKpp\rightarrow\Lambda\Lambda \)
- \( KKpp\rightarrow\Sigma^0\Sigma^0 \)
- \( KKpp\rightarrow\Sigma^0\Sigma^0\pi^0 \)
- \( K^+K^0\Lambda\Lambda \)
- \( K^+K^0\Sigma^0\Sigma^0\pi^0 \)

1 GeV/c pbar

\[ K^+K^0\Lambda\Lambda \text{ missing-mass}^2 \text{ [MeV}^2\text{]} \]
Past Experiments of Stopped-$p^{\bar{\text{bar}}}$ Annihilation
charged particle multiplicity at rest


$p\bar{p}+3\text{He}$ charged particle multiplicity at rest
CERN LEAR, streamer chamber exp.

<table>
<thead>
<tr>
<th>nc</th>
<th>branch(%)</th>
<th>&lt;nc&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.14 +0.40</td>
<td>4.155 +0.06</td>
</tr>
<tr>
<td>3</td>
<td>39.38 +0.88</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>48.22 +0.91</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.06 +0.46</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.19 +0.08</td>
<td></td>
</tr>
</tbody>
</table>

$p\bar{p}+4\text{He}$ charged particle multiplicity at rest
CERN LEAR, streamer chamber exp.

[data in nuovo-ciment is listed below, which is a higher statistics than NPA465]

<table>
<thead>
<tr>
<th>nc</th>
<th>branch(%)</th>
<th>&lt;nc&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.36 +0.35</td>
<td>4.097 +0.07</td>
</tr>
<tr>
<td>2</td>
<td>5.03 +0.42</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>33.48 +0.92</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12.26 +0.63</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35.68 +0.93</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3.51 +0.36</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.24 +0.47</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.19 +0.08</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.24 +0.10</td>
<td></td>
</tr>
</tbody>
</table>

They obtained

$$\sigma^a(\bar{p}p) = 70.4 \pm 2.5\%$$
$$\sigma^a(\bar{p}n) = 29.6 \pm 2.5\%$$

$$\rightarrow \sigma^a(\bar{p}n)/\sigma^a(\bar{p}p) = 0.42 \pm 0.05$$
KKbar production-rate for pbar+p at rest


the KKbar production-rate $R$ for pbar+p annihilation at rest
(obtained from hydrogen bubble chamber data)

$$R\left( K^0 \bar{K}^0 \right) = 1.733 \pm 0.067\%$$

$$R\left( K^+ K^- \right) = 1.912 \pm 0.141\%$$

$$R\left( \bar{K}^0 K^+ \right) + R\left( K^0 K^- \right) = 1.701 \pm 0.082\%$$

$\Rightarrow$

$$R\left( K^0_s \right) = \frac{3}{4} R\left( K^0 \bar{K}^0 \right) + \frac{1}{2} \left[ R\left( \bar{K}^0 K^+ \right) + R\left( K^0 K^- \right) \right] = 2.149 \pm 0.065\%$$

$$R\left( \bar{K}K \right) = R\left( K^+ K^- \right) + R\left( \bar{K}^0 K^+ \right) + R\left( K^0 K^- \right) + R\left( K^0 \bar{K}^0 \right) = 5.35 \pm 0.18\%$$

There is a great deal of data on the production of strange particles on $^1\text{H}$ and $^2\text{H}$ but only few ones on heavier nuclei.
Λ/K₀ₛ production-rate and multiplicity for pbar+A at rest


<table>
<thead>
<tr>
<th></th>
<th>Rₐ(Λ) (%)</th>
<th>Rₐ(K₀ₛ) (%)</th>
<th>⟨nc(Λ)⟩</th>
<th>⟨nc(K₀ₛ)⟩</th>
<th>⟨nc(all events)⟩</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹H</td>
<td>2.15 +0.07</td>
<td>2.02 +0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>²H</td>
<td>0.30 +0.04</td>
<td>2.02 +0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>³He</td>
<td>0.55 +0.11</td>
<td>1.59 +0.20</td>
<td>2.76 +0.27</td>
<td>2.97 +0.14</td>
<td>4.17 +0.08</td>
</tr>
<tr>
<td>⁴He</td>
<td>1.12 +0.12</td>
<td>1.07 +0.11</td>
<td>3.03 +0.08</td>
<td>2.72 +0.07</td>
<td>4.10 +0.13</td>
</tr>
</tbody>
</table>

charge multiplicities decrease by ~1 when Λ/K₀ₛ is produced

- $p^\text{bar}Xe$ annihilation
- $p=<$1GeV/c $p^\text{bar}$-beam @ ITEP 10GeV-PS
- 700-liter Xenon bubble chamber, w/o B-field
- $10^6$ pictures $\rightarrow$ $7.8 \times 10^5$ $p^\text{bar}Xe$ inelastic $\rightarrow$ $2.8 \times 10^5$ $p^\text{bar}Xe$ @ 0-0.4GeV/c
- $p^\text{bar}Xe \rightarrow K^+K^+X$ : 4 events $\rightarrow$ $(0.31\pm0.16) \times 10^{-4}$
- $p^\text{bar}Xe \rightarrow K^+K^0\Lambda X$ : 3 events $\rightarrow$ $(2.1\pm1.2) \times 10^{-4}$

<table>
<thead>
<tr>
<th>$p$ mom. interval, GeV/c</th>
<th>Events containing two $K^+$-mesons</th>
<th>Yield ($10^{-4}$)</th>
<th>Events containing $K^+K^0(K^0)$-pairs and $\Lambda$ - hyperons</th>
<th>Yield ($10^{-4}$)</th>
<th>Events containing other strange particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–0.4</td>
<td>$K^+K^+h$</td>
<td>0.31 ± 0.16</td>
<td>$K^+K^0\Lambda\Lambda$</td>
<td>2.1 ± 1.2</td>
<td>$K^+K^-\Lambda_2\pi^-\pi^+$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\pi^0h$</td>
<td></td>
<td>$K^+K^0\Lambda_p$</td>
<td></td>
<td>$K^+\Lambda\Lambda_4p$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\Lambda_2\gamma$</td>
<td></td>
<td></td>
<td></td>
<td>$K^0\Lambda\Lambda_4p$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+4\gamma$</td>
<td></td>
<td></td>
<td></td>
<td>$K^+\Lambda\Lambda_4p$</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow$ 4 events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4–0.65</td>
<td>$K^+K^+\pi^-4p\gamma$</td>
<td>0.42 ± 0.21</td>
<td>$K^+K^0\Lambda_2p$</td>
<td>3.0 ± 1.7</td>
<td>$K^+\Lambda\Sigma^-p$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\pi^0hp$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+2h$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+4p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.65–0.9</td>
<td>$K^+K^+\Lambda_2\Lambda_2p$</td>
<td>0.26 ± 0.13</td>
<td>$K^+K^0\Lambda_2p\pi^-$</td>
<td>2.4 ± 0.9</td>
<td>$K^+\Lambda\Sigma^-p$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\Lambda_2\Lambda_2p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+3p\Lambda$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\Sigma^-\Lambda p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\rightarrow$ 3 events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1
List of observed $\bar{p}Xe$ annihilation events containing two or more strange particles in the final state ($\Lambda_n$: $\Lambda \rightarrow n\pi^0$, $K^0_s(<K^0_s>)$: $K^0_s(<K^0_s>) \rightarrow \pi^0\pi^0$, $h$: ambiguously identified meson ($\pi$ or $K$)). * denotes special scanning (see text)
interpretation of the DIANA result \((p^{\text{bar}}Xe)\) from J.Cugnon \textit{et al.}, NP, \textbf{A587}, 596 (1995).

\begin{itemize}
  \item The observed double strangeness yield is explained by conventional processes described by the intranuclear cascade model, as listed in the following tables.

  \item They also show the B=2 annihilations, described with the help of the statistical model, are largely able to account for the observed yield: i.e., the branching ratio of the \(\Lambda\Lambda KK\) state in \(p^{\text{bar}}\)-NNN annihilation is equal to \(\sim 10^{-4}\) at rest (B=1 annihilations are not so helpful).

  \item However they claim the frequency of even B=1 annihilation is of the order of 3-5\% at the most [J.Cugnon \textit{et al.}, NP, \textbf{A517}, 533 (1990).] (is it common knowledge ?), so they conclude it would be doubtful to attempt a fit of the data with a mixture of B=0 and 2 annihilations.
\end{itemize}

\textit{On the other hand, the Crystal Barrel collaboration @ CERN/LEAR concludes their \(p^{\text{bar}}d \rightarrow \Lambda K^0/\Sigma^0 K^0\) measurements disagree strongly with conventional two-step model predictions and support the statistical (fireball) model.}
Table 2
Possible double strangeness production processes in $B = 0$ ($\bar{N}N$) annihilations on a nucleus

<table>
<thead>
<tr>
<th>Channel</th>
<th>Threshold $E_{cm}$, $p_{lab}$</th>
<th>Primordial state</th>
<th>Secondary reaction</th>
<th>Strange content of the final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.975, 0.646</td>
<td>$KK\bar{K}K$</td>
<td>B</td>
<td>$KK\bar{K}K$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B+B$</td>
<td>$KK\bar{K}Y$</td>
</tr>
<tr>
<td>2</td>
<td>$\bar{K}\bar{K}m$</td>
<td>A</td>
<td></td>
<td>$KK\bar{K}Y$</td>
</tr>
<tr>
<td>3</td>
<td>$m$</td>
<td>A+A</td>
<td></td>
<td>$KKYY$</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{K}^*Km$</td>
<td>A</td>
<td></td>
<td>$KK\bar{K}Y$</td>
</tr>
<tr>
<td></td>
<td>$K^*\bar{K}m$</td>
<td>A+B</td>
<td></td>
<td>$KKYY$</td>
</tr>
<tr>
<td></td>
<td>$\bar{K}^*K^*m$</td>
<td>C</td>
<td></td>
<td>$KKYY$</td>
</tr>
<tr>
<td>5</td>
<td>2.039, 0.866</td>
<td>$\phi\phi$</td>
<td>C</td>
<td>$KK\bar{K}K$</td>
</tr>
<tr>
<td>6</td>
<td>$\omega\omega$</td>
<td>A+A</td>
<td></td>
<td>$KKYY$</td>
</tr>
<tr>
<td></td>
<td>$\omega\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\omega\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Estimate of the various double strangeness yields in $\bar{p}Xe$ annihilations at antiproton momenta 0–0.4 GeV/c. The channel numbers in first row correspond to the mechanism indicated in Table 2.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$KK\bar{K}K$</th>
<th>$KK\bar{K}A$</th>
<th>$KK\bar{A}$</th>
<th>$\Xi\bar{K}K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>–</td>
<td>3.18 × 10^{-5}</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>1.6 × 10^{-4}</td>
<td>–</td>
<td>1.9 × 10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>–</td>
<td>1.29 × 10^{-7}</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>–</td>
<td>4.4 × 10^{-5}</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>–</td>
<td>3.1 × 10^{-6}</td>
<td>–</td>
</tr>
<tr>
<td>total</td>
<td>1.6 × 10^{-4}</td>
<td>7.9 × 10^{-5}</td>
<td>1.9 × 10^{-4}</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 6
Comparison of the data from Ref. [20] with our predictions. All numbers are multiplied by 10^4.

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>$K^+K^+X$</th>
<th>$K^+K^0\bar{X}$</th>
<th>Total DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp.</td>
<td>calc.</td>
<td>exp.</td>
<td>calc.</td>
</tr>
<tr>
<td>0–0.4</td>
<td>0.25 ± 0.14</td>
<td>0.16</td>
<td>1.2 ± 0.8</td>
</tr>
<tr>
<td>0.4–0.65</td>
<td>0.32 ± 0.16</td>
<td>0.19</td>
<td>2.5 ± 1.4</td>
</tr>
<tr>
<td>0.65–0.9</td>
<td>0.5 ± 0.4</td>
<td>0.22</td>
<td>2.5 ± 1.4</td>
</tr>
</tbody>
</table>

- \( p^{\bar{b}4}\text{He} \) annihilation
- stopped \( p^{\bar{b}} \) at CERN/LEAR
- liquid deuteron target
- cylindrical spectrometer w/ B-field
- SVX, CDC, CsI crystals
- \( \sim 10^6 \) events of 2/4-prong with topological triggers

\[ Br(\bar{p}d \rightarrow \Lambda K^0) = (2.35 \pm 0.45) \times 10^{-6} \]
\[ Br(\bar{p}d \rightarrow \Sigma^0 K^0) = (2.15 \pm 0.45) \times 10^{-6} \]
\[ Br(\bar{p}d \rightarrow p\pi^-) = (1.3 \pm 1.0) \times 10^{-5} \]

### Table 1

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed mode</th>
<th>Events</th>
<th>( BR ) ( [10^{-6}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda K^0 )</td>
<td>( \Lambda \rightarrow p\pi^-, K^0_L ) (noninteracting)</td>
<td>107 ( \pm 11 \pm 6 )</td>
<td>1.1 ( \pm 0.1 \pm 0.2 )</td>
</tr>
<tr>
<td>( \Sigma^0 K^-_L )</td>
<td>( \Sigma^0 \rightarrow \Lambda \gamma, \Lambda \rightarrow p\pi^-, K^0_L ) (noninteracting)</td>
<td>83 ( \pm 10 \pm 9 )</td>
<td>1.0 ( \pm 0.1 \pm 0.2 )</td>
</tr>
<tr>
<td>( 10^{-6} )</td>
<td></td>
<td></td>
<td>( R_{\Sigma^0 A} = 0.90 \pm 0.13 \pm 0.13 )</td>
</tr>
<tr>
<td>( \Lambda K^0 )</td>
<td>( \Lambda \rightarrow p\pi^-, K^0_S \rightarrow \pi^+\pi^- )</td>
<td>85 ( \pm 10 \pm 10 )</td>
<td>1.6 ( \pm 0.3 \pm 0.5 )</td>
</tr>
<tr>
<td>( \Sigma^0 K^0_S )</td>
<td>( \Sigma^0 \rightarrow \Lambda \gamma, \Lambda \rightarrow p\pi^-, K^0_S \rightarrow \pi^+\pi^- )</td>
<td>61 ( \pm 8 \pm 5 )</td>
<td>1.5 ( \pm 0.2 \pm 0.5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( R_{\Sigma^0 A} = 0.95 \pm 0.17 \pm 0.16 )</td>
</tr>
</tbody>
</table>

### Table 2

Comparison of experimental results and predictions of dynamical and statistical models

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Dynamical model</th>
<th>Statistical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Absolute ( \bar{p}d ) branching ratios ( (BR) ) ( [10^{-6}] )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Lambda K^0 )</td>
<td>2.35 ( \pm 0.45 ) (^a)</td>
<td>0.3</td>
<td>1.0 ( \times P_{B=1} ) (^c)</td>
</tr>
<tr>
<td>( \Sigma^0 K^0 )</td>
<td>2.15 ( \pm 0.45 ) (^a)</td>
<td>0.004</td>
<td>1.0 ( \times P_{B=1} ) (^c)</td>
</tr>
<tr>
<td>( p\pi^- )</td>
<td>13.0 ( \pm 1.0 ) (^b)</td>
<td>2--6</td>
<td>4.7 ( \times P_{B=1} ) (^c)</td>
</tr>
<tr>
<td>(ii) Relative branching ratios ( R_{\Sigma^0 A} = BR(\Sigma^0 K^0) / BR(\Lambda K^0) )</td>
<td>0.92 ( \pm 0.15 ) (^a)</td>
<td>0.012</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(^a\) Weighted average of the results in Table 1 with quadratically added statistical and systematic errors.

\(^b\) Weighted average of the results of Refs. [9,10], applying charge independence to the \( n\pi^0 \) result [10].

\(^c\) Total probability [%] of forming a fireball with baryon number \( B = 1 \). Estimates yield \( P_{B=1} \leq 10\% \) (Ref. [6]).
Fig. 1. Event of the Pontecorvo type, selected from the data set. With the charged-particle multiplicities 0 in the SVX and 4 in the drift chamber, it shows the complete signature of a $\bar{p}d \rightarrow \Sigma^+ K^0 \Sigma^- \rightarrow \Lambda \rightarrow p \pi^-$, $K^0 \rightarrow \pi^+ \pi^-$ event in the transverse (a) as well as in the longitudinal projections (b). The apparent left-right ambiguity of hits in the drift chamber is resolved (full line trajectories) by the sense wire staggering [13]. Clockwise and anticlockwise curvatures in (a) correspond to negative and positive charges, respectively. Energy deposits in the barrel-shaped electromagnetic calorimeter are represented by bars of proportional lengths.
OBELIX ('86-'96) [Nucl. Phys., A797, 109 (2007).]

- $p^{\bar{p}} \text{He}$ annihilation
- stopped $p^{\bar{p}}$ @ CERN/LEAR
- gas target ($^4\text{He}@$NTP, $^2\text{H}_2@$3atm)
- cylindrical spectrometer w/ B-field
- spiral projection chamber, scintillator barrels, jet-drift chambers
- 238,746/47,299 events of 4/5-prong in $^4\text{He}$
- $p_{\text{min}} = 100/150/300\text{MeV/c}$ for $\pi/K/p$

\[ \overline{p}^4\text{He} \rightarrow K^+ K^+ \Sigma^- \Sigma^- p_s \rightarrow K^+ K^+ \pi^- \pi^- (nnp_s) \]

- 4-prong
  - 34+/−8 events $\rightarrow (0.17+/−0.04)x10^{-4}$

\[ \overline{p}^4\text{He} \rightarrow K^+ K^+ \Sigma^- \Sigma^+ n\pi^- \rightarrow K^+ K^+ \pi^+ \pi^- \pi^- (nnn) \]

- 5-prong
  - 36+/−6 events $\rightarrow (2.71+/−0.47)x10^{-4}$

\[ \overline{p}^4\text{He} \rightarrow K^+ K^+ \Sigma^- \Lambda n \rightarrow K^+ K^+ p\pi^- \pi^- (nn) \]

- 5-prong
  - 16+/−4 events $\rightarrow (1.21+/−0.29)x10^{-4}$

\[ \overline{p}^4\text{He} \rightarrow K^+ K^+ K^- \Lambda nn \rightarrow K^+ K^+ K^- p\pi^- (nn) \]

- 5-prong
  - 4+/−2 events $\rightarrow (0.28+/−0.14)x10^{-4}$

* (xx) is not observed

4+/-2 events $\rightarrow (0.28+/-0.14)x10^{-4}$

36+/-6 events $\rightarrow (2.71+/-0.47)x10^{-4}$

16+/-4 events $\rightarrow (1.21+/-0.29)x10^{-4}$

they discuss the possibility of formation and decay of $K^-K^-\text{nn}$ and $K^-K^-\text{pnn}$ bound system
Introduction
we will open new door to the high density matter physics, like the inside of neutron stars

Kaonic Nuclear Cluster (KNC)
the existence of deeply-bound kaonic nuclear cluster is predicted from strongly attractive $K^{\bar{\text{bar}}N}$ interaction
the density of kaonic nuclei is predicted to be extreme high density

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-p$</td>
<td>27</td>
<td>40</td>
<td>$3.5\rho_0$</td>
</tr>
<tr>
<td>$K^-pp$</td>
<td>48</td>
<td>61</td>
<td>$3.1\rho_0$</td>
</tr>
<tr>
<td>$K^-ppp$</td>
<td>97</td>
<td>13</td>
<td>$9.2\rho_0$</td>
</tr>
<tr>
<td>$K^-ppn$</td>
<td>118</td>
<td>21</td>
<td>$8.8\rho_0$</td>
</tr>
</tbody>
</table>

## Theoretical Situation of KNC

Theoretical predictions for kaonic nuclei, e.g., $K^-pp$

<table>
<thead>
<tr>
<th>Method</th>
<th>Binding Energy (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akaishi, Yamazaki PLB533, 70 (2002).</td>
<td>ATMS</td>
<td>48</td>
</tr>
<tr>
<td>Ikeda, Sato PRC76, 035203 (2007).</td>
<td>Faddeev</td>
<td>79</td>
</tr>
<tr>
<td>Dote, Hyodo, Weise NPA804,197(2008).</td>
<td>chiral SU(3)</td>
<td>19+/3</td>
</tr>
</tbody>
</table>

- **whether the binding energy is deep or shallow**
- **how broad is the width?**

Koike, Harada
DWIA

$^3\text{He}(K^-n)$
Experimental Situation of KNC

E549@KEK-PS

${}^4\text{He}$ (stopped $K^-,p$)

Proton Momentum (MeV/c)

missing mass resolution

E549@KEK-PS

${}^4\text{He}$ (stopped $K^-,\Lambda N$)

unknown strength between Q.F. & 2N abs.

K$^-pnn$?

K$^-pp$?

K$^-pp$?

K$^-pnn$?

K$^-pn$?

K$^-ppn$?

1$^2\text{C}(K^-,n)$

1$^2\text{C}(K^-,p)$

missing mass

$-BE$(MeV)

mb/sr/10MeV


deep $K$-nucleus potential of $\sim 200$MeV

arXiv:0711.4943
Experimental Situation of KNC (Cont’d)

We need conclusive evidence with observation of formation and decay!

peak structure $\rightarrow$ signature of kaonic nuclei?

\[ K^-pp? \]

\[ \Lambda^-p \text{ invariant mass} \]

\[ p^-\Lambda \text{ invariant mass} \]

FI NUDA@DAΦNE
PRL, 94, 212303 (2005)

OBELIX@CERN-LEAR
NP, A789, 222 (2007)

DISTO@SATUREN
PRL, 104, 132502 (2010)
Experimental Principle of J-PARC E15

search for K-pp bound state using $^3\text{He}(K^-,n)$ reaction

- **Formation**: $K^- + ^3\text{He} \rightarrow K^-\text{(pp cluster)} + \text{neutron}$
- **Decay**: $K^-\text{(pp cluster)} \rightarrow \Lambda p + \pi^-$

**Missing mass spectroscopy** and **Invariant mass reconstruction**

*exclusive measurement* by

---

81
E15 will provide the conclusive evidence of $K^{-}pp$