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

F. Sakuma, RIKEN
This talk is based on the LoI submitted in June, 2009.

Letter of Intent for J-PARC

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

dated on 17 / 06 / 2009

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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.
Contents

- (brief) Introduction of “Kaonic Nuclear Cluster”
- Possibility of “Double-Kaonic Nuclear Cluster” by Stopped-$p^\text{bar}$ Annihilation
- Experimental Approach
- Summary
Kaonic Nuclear Cluster (KNC)

the existence of deeply-bound kaonic nuclear cluster is predicted from strongly attractive $K^{\text{bar}}N$ interaction

the density of kaonic nuclei is predicted to be extreme high density

<table>
<thead>
<tr>
<th></th>
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</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>
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<tr>
<td>$K^-ppn$</td>
<td>118</td>
<td>21</td>
<td>$8.8\rho_0$</td>
</tr>
</tbody>
</table>


we will open new door to the high density matter physics, like the inside of neutron stars
### 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>ATMS</td>
<td>48</td>
<td>61</td>
</tr>
<tr>
<td>Faddeev</td>
<td>55-70</td>
<td>90-110</td>
</tr>
<tr>
<td>Faddeev</td>
<td>79</td>
<td>74</td>
</tr>
<tr>
<td>chiral SU(3)</td>
<td>19+/-3</td>
<td>40-70 (πΣN-decay)</td>
</tr>
</tbody>
</table>

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

---

**Koike, Harada**


DWIA

\[ ^3\text{He}(K^-,p) \]
Experimental Situation of KNC

E549@KEK-PS

$^4$He (stopped K-,p)

Proton Momentum (MeV/c)

Resolution (MeV/c^2)

missing mass resolution

12C(K-,p)

E548@KEK-PS

12C(K-,n)


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

$^4$He (stopped K-,ΛN)

K^-pnn?

K^-pp/

K^-pnn?

K^-pn/

K^-ppn?

K^-pnn?

deep K-nucleus potential of ~200MeV

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

We need conclusive evidence with observation of **formation** and **decay**!
Experimental Principle of J-PARC E15

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

Formation

$K^-$ $^3\text{He}$

Decay

$K$-pp cluster

neutron

Missing mass Spectroscopy via neutron

Mode to decay charged particles

$\Lambda$ $p$ $\pi^-$ $p$

exclusive measurement by

Missing mass spectroscopy

and

Invariant mass reconstruction

Invariant mass reconstruction
E15 will provide the conclusive evidence of $K^-pp$
What will happen to put one more kaon in the kaonic nuclear cluster?

Possibility of “Double-Kaonic Nuclear Cluster” by Stopped-$p\bar{p}$ 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>
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</thead>
<tbody>
<tr>
<td>K-K-ppn</td>
<td>-221</td>
<td>37</td>
<td>17\rho_0</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>14\rho_0</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
- p\(^{\bar{}}\)A annihilation


We use p\(^{\bar{}}\)A annihilation
Double-Strangeness Production with $p^\text{bar}$

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

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

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

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

\[ \bar{p} + {}^3\text{He} \rightarrow K^+ + K^+ + K^-K^- \text{pn} + B_{KK}^{pn} \quad -106\text{MeV} \]
\[ \bar{p} + {}^3\text{He} \rightarrow K^+ + K^0 + K^-K^- \text{pp} + B_{KK}^{pp} \quad -109\text{MeV} \rightarrow \text{B.E.}=117\text{MeV} \quad \Gamma=35\text{MeV} \]
\[ \bar{p} + {}^4\text{He} \rightarrow K^+ + K^+ + K^-K^- \text{pnn} + B_{KK}^{pnn} \quad -126\text{MeV} \rightarrow \text{B.E.}=221\text{MeV} \quad \Gamma=37\text{MeV} \]
\[ \bar{p} + {}^4\text{He} \rightarrow K^+ + K^0 + K^-K^- \text{ppn} + B_{KK}^{ppn} \quad -129\text{MeV} \]

**theoretical prediction**
Production Mechanism of K⁻K⁻pp with p^{bar} + ^3He?

For example, the possible K⁻K⁻pp production mechanisms are as follows:

**with stopped p^{bar}**

① direct K⁻K⁻pp production with 3N annihilation
② Λ⁺Λ⁺ production with 3N annihilation followed by K⁻K⁻pp formation

**with in-flight p^{bar}**

in addition above 2ways,
③ elementally p^{bar} + p → KKKK production followed by K⁻K⁻pp formation

● Some theorist’s comment: If the K⁻K⁻pp bound system can be exist, such system could be Λ⁺Λ⁺ molecular system by analogy between Λ⁺ K⁻p. Then the binding energy could be small of about from 30 to 60 MeV.

● it has been observed that cross section of p^{bar} + p → KKKK with around 1GeV/c p^{bar}-beam is very small of less than 1μb, so it would be very difficult experimentally.

It’s worthwhile to explore these exotic system with p^{bar}, although the mechanism is NOT completely investigated!

A theoretical problem: The K⁻K⁻ interactions have been calculated in lattice QCD as strongly repulsive interaction. However, these K-K⁻ interactions are neglected simply in the PLB587,167 calculation which only shows the K-K⁻pp bound system.
Double-Strangeness Production Yield by Stopped-\(p^{\text{bar}}\) Annihilation

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

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

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

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

\(\gamma\) : reduction factor \(\sim 10^{-2}\)
Observations of the double-strangeness production in stopped $p^\bar{p}$ annihilation have been reported by only 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 [p$^\bar{p}$+Xe]</td>
<td>$K^+K^+X$</td>
<td>4</td>
<td>0.31+/-0.16</td>
</tr>
<tr>
<td>OBELIX [p$^\bar{p}$+4He]</td>
<td>$K^+K^+\Sigma^-\Sigma^+p_s$</td>
<td>34+/-8</td>
<td>0.17+/-0.04</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\Sigma^-\Sigma^+n\pi^-$</td>
<td>36+/-6</td>
<td>2.71+/-0.47</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+\Sigma^-\Lambda n$</td>
<td>16+/-4</td>
<td>1.21+/-0.29</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+K^-\Lambda nn$</td>
<td>4+/-2</td>
<td>0.28+/-0.14</td>
</tr>
</tbody>
</table>

Although observed statistics are very small, their results have indicated a high yield of $\sim10^{-4}$.
Past Experiments (Cont’d)


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

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<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>

[Diagrams showing particle interactions and annihilations.]
Past Experiments (Cont’d)

**OBELIX** (’86~’96) [Nucl. Phys., A797, 109 (2007).]
- $p^{\text{bar}}$4He annihilation
- stopped $p^{\text{bar}}$ at CERN/LEAR
- gas target ($^4\text{He}@\text{NTP}, \text{H}_2@3\text{atm}$)
- **cylindrical spectrometer w/ B-field**
- spiral projection chamber, scintillator barrels, jet-drift chambers
- 2.4x10⁵/4.7x10⁴ events of 4/5-prong in $^4\text{He}$
- $p_{\text{min}} = 100/150/300\text{MeV}/c$ for $\pi/K/p$

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they discuss the possibility of formation and decay of
$K^-K^-\text{nn}$ and $K^-K^-p\text{nn}$ bound system
The double-strangeness production yield of $\sim 10^{-4}$ makes it possible to explore the exotic systems.
How to Measure?

we focus the reaction:
\[
\bar{p} + ^3\text{He} \rightarrow K^+ + K^0 + K^- K^- pp
\]

(although $K^- K^- pp$ decay modes are not known at all,)
we assume the most energetic favored decay mode:
\[
K^- K^- pp \rightarrow \Lambda + \Lambda
\]

**final state** = $K^+ K^0 \Lambda \Lambda$

We can measure the $K^- K^- pp$ signal **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**

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

**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 Measurement

Key points of the experiment

- high intensity p^bar beam
- wide-acceptance and low-material detector

How to measure the K-K-pp signal

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

*1 because of the low-momentum kaon, it could be hard to detect all particles
*2 semi-inclusive and inclusive spectra could contain background from 2N annihilation and K⁻K⁻pp decays, respectively
We would like to perform the proposed experiment at J-PARC K1.8BR beam line (or K1.1).

\[ p^{\text{bar}} \text{ stopping-rate evaluation by GEANT4} \]

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

**Detectors**
- Carbon Degrader: 1.99*g/cm³
- Plastic Scintillator: l=1cm, 1.032*g/cm³
- Liquid He3 target: \( \phi 7 \text{cm}, l=12 \text{cm}, 0.080*\text{g/cm}^3 \)

\[ p^{\text{bar}} \] stopping-rate evaluation by GEANT4

1.3x10³ stopped \( p^{\text{bar}} \)/spill @ 0.65GeV/c, \( l_{\text{degrader}} \sim 14 \text{cm} \)

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

\[ p^{\text{bar}} \text{ produc with a Sar} \]
Detector Design

Key points
- Low material detector system
- Wide acceptance with pID

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

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

<table>
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<tr>
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<th>A</th>
<th>A'</th>
<th>A</th>
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<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>
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<tr>
<td>Layer</td>
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<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>radius</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>
Trigger Scheme

expected stopped-p$^{\text{bar}}$ yield = 1.3x10$^3$/spill

All events with a scintillator hit can be accumulated

$p^{\text{bar}}_3$He charged particle multiplicity at rest
CERN LEAR, streamer chamber exp. NPA518,683 91990).

<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>
<tr>
<td>$&lt;N_c&gt;$</td>
<td>4.16 +/- 0.06</td>
</tr>
</tbody>
</table>

K-K-pp event
Detector Acceptance

$P^{\text{bar} + 3\text{He}} \rightarrow K^+ + K^0_S + K^- K^- p p,$
$K^- K^- p p \rightarrow \Lambda \Lambda,$
$\Gamma(K^- K^- p p) = 100\text{MeV}$

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

E15 CDS @ K1.8BR

binding energy

acceptance

B.E.=120MeV  B.E.=150MeV  B.E.=200MeV
Expected $K^-K^-pp$ Production Yield

- $\bar{p}$ beam momentum: 0.65 GeV/c
- Beam intensity: $3.4 \times 10^4$ spill/3.5s @ 270 kW
- $\bar{p}$ stopping rate: 3.9%

- Stopped-$\bar{p}$ yield: $1.3 \times 10^3$ spill/3.5s

We assume $K^-K^-pp$ production rate = $10^{-4}$

$K^-K^-pp$ production yield = $2.3 \times 10^4$ /week @ 270 kW

DAQ & ana efficiency = 0.7 & duty factor = 0.7

Expected $K^-K^-pp$ yield = $1.1 \times 10^4$ /week @ 270 kW

w/o detector acceptance
Expected $K^-K^-pp$ Detction Yield

$p^-+^3He \rightarrow K^++K^0_s+K^-K^-pp$, $K^-K^-pp \rightarrow \Lambda\Lambda$, $\Gamma(K^-K^-pp)=100$MeV

--- $\Lambda\Lambda$ detection
--- $K^0_sK^+$ w/ $\Lambda$-tag detection
--- $K^0_sK^+\Lambda\Lambda$ detection

$\sqrt{K^-K^-pp}$ production rate = $10^{-4}$
$\sqrt{Br(K^-K^-pp \rightarrow \Lambda\Lambda)} = 100\%$

excluding yield (/week@270kW)

binding energy

E15 CDS @ K1.8BR
Backgrounds

- (semi-inclusive) $K^0_S K^+$ missing-mass w/ $\Lambda$-tag
  - stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$
  - stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + \Lambda + \Lambda$

3N annihilation
- stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + \Sigma^0 + \Sigma^0 + \pi^0$
- ...$
- \text{stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + K^0 + \Sigma^0 + (n)$}

2N annihilation
- stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + \Sigma^0 + (p)$
- ...$

- (inclusive) $\Lambda\Lambda$ invariant mass
  - stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$

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

missing 2$\gamma$
  - stopped-$\bar{p} + ^3\text{He} \rightarrow K^0_S + K^+ + K^- + pp$
  $\rightarrow \Lambda + \Sigma^0$

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

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

- ...


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

**Expected spectrum with the assumptions:**

- **Production rate:**
  - $K^+K^-pp$ bound-state = $10^{-4}$
  - $(3N) K^-K^-\Lambda\Lambda$ phase-space = $10^{-4}$
  - $(3N) K^+K^0\Sigma^0\Sigma^0\pi^0$ phase-space = $10^{-4}$
  - $(2N) K^+K^0K^-\Sigma^0(n)$ phase-space = $10^{-4}$
  - $(2N) K^+K^0K^-\Sigma^0(p)$ phase-space = $10^{-4}$

- **Branching ratio of $K^-K^-pp$:**
  - $BR(K^-K^-pp \rightarrow \Lambda\Lambda) = 0.1$
  - $BR(K^-K^-pp \rightarrow \Lambda\Sigma^0) = 0.1$
  - $BR(K^-K^-pp \rightarrow \Sigma^0\Sigma^0 = 0.1$
  - $BR(K^-K^-pp \rightarrow \Lambda\Lambda\pi^0) = 0.7$

2$\Lambda$ = $\Lambda\Lambda$ detection
2$K$ = $K^+K^0$ w/ $\Lambda$-tag detection
2$\Lambda$2$K$ = $K^+K^0\Lambda\Lambda$ detection
In the $\Lambda\Lambda$ spectra, we cannot discriminate the K-K-pp going to $\Lambda\Lambda$ signals from the backgrounds, if K-K-pp has these decay modes. In contrast, the $K^0K^+$ missing mass spectroscopy is attractive for us because we can ignore the K-K-pp decay mode.
Summary
Summary

- We propose to search for double strangeness production by $p^{\bar{\text{bar}}}$ annihilation on $^3\text{He}$ nuclei at rest.

- The proposed experiment will provide significant information on double strangeness production and double strangeness cluster states, $K^-K^-pp$.

- The experimental key points are high-intensity $p^{\bar{\text{bar}}}$ beam and wide-acceptance/low-material detector system. We propose to perform the experiment at K1.8BR beam-line with the E15 spectrometer.

- We are now preparing the proposal for J-PARC based on the LoI.
Back-Up
K⁻-pp Production with $p^{\text{bar}}$ at rest

Of course, we can measure K⁻-pp production!

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

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

$$R(\overline{pp} \rightarrow KK) \sim 5 \times 10^{-2}$$

Very simply, expected K⁻-pp yield is 100 times larger than the K⁻K⁻-pp production!

**OBELIX@CERN-LEAR**

NP, A789, 222 (2007)

$$\bar{p} + ^4\text{He} \rightarrow K^- pp + X \rightarrow \Lambda + p$$
Expected Spectra @ 270kW, 4weeks

$K^+ K^0 \Lambda \Lambda$ missing-mass$^2$ (2K2Λ)

stopped pbar
B.E=200MeV, $\Gamma=100$MeV
270kW, 4weeks
**Expected Spectra @ 50kW, 4 weeks**

**Γ**

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

- Number of \( K^-K^0 \rightarrow \Lambda \Lambda \) = 75

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

- Number of \( K^+K^0 \rightarrow K^+K^-pp \) = 239

### \( \Lambda \Lambda \) invariant mass (2\( K \)2\( \Lambda \))

- Number of \( K^-K^0 \rightarrow \Lambda \Lambda \) = 6

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

- Number of \( K^+K^-pp \) = 38

stopped pbar

B.E=200MeV,
\( \Gamma \)=100MeV
50kW, 4 weeks
Expected Spectra @ 50kW, 4 weeks

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

stopped pbar

\( E=200\text{MeV}, \quad \Gamma=100\text{MeV} \)

50kW, 4 weeks
in-flight experiment
$p^\text{bar} + ^3\text{He} \rightarrow K^+ + K_\Sigma^0 + K^- + p + p$,
$K^- + p + p \rightarrow \Lambda\Lambda$,
$\Gamma(K^-p + p) = 100\text{MeV}$
we assume $K^-K^-pp$ production rate $= 10^{-4}$ for $1$GeV/$c$ $\bar{p}+p$

(analogy from the DIANA result of double-strangeness production although the result are from $\bar{p}+^{131}$Xe reaction)
Expected $K^-K^-pp$ Production Yield (Cont’d)

L$^3$He parameters:

* $\rho = 0.08g/cm^3$
* $l = 12cm$

$$N = \sigma \times N_B \times N_T$$

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

K-$K^-pp$ production yield = $1.5 \times 10^5$ /week @ 270kW

BG rate:
- total CS = 117mb
- $pbar = 6.4 \times 10^5$/spill
- $BG = 1.4 \times 10^4$/spill

DAQ & ana efficiency = 0.7 & duty factor = 0.7

expected $K^-K^-pp$ yield = $7.5 \times 10^4$ /week @ 270kW
w/o detector acceptance
Expected $K^-K^+\text{pp}$ Detection Yield

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

$K^-K^\text{pp} \rightarrow \Lambda\Lambda$,

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

--- $\Lambda\Lambda$ detection
--- $K^0_sK^+ \text{ w/ } \Lambda$-tag detection
--- $K^0_sK^+\Lambda\Lambda$ detection

--- stopped
--- 1GeV/c

$E_{15 \text{ CDS @ K1.8BR}}$

Expected yield (/week@270kW)

<table>
<thead>
<tr>
<th>Binding Energy</th>
<th>Expected Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.E. = 120 MeV</td>
<td></td>
</tr>
<tr>
<td>B.E. = 150 MeV</td>
<td></td>
</tr>
<tr>
<td>B.E. = 200 MeV</td>
<td></td>
</tr>
</tbody>
</table>

--- $\Lambda\Lambda$ detection
--- $K^0_sK^+ \text{ w/ } \Lambda$-tag detection
--- $K^0_sK^+\Lambda\Lambda$ detection

Superimposed on the graph is an illustration of the experimental setup, including labeled components such as:
- L$^3$He Target
- Z-Vertex Chamber
- Kaon Decay Veto Counter
- Cylindrical Drift Chamber
- Hodoscope Counter
- Solenoid Magnet
- Charge Veto Counter
- Target Chamber
Expected Spectra @ 270kW, 4 weeks

**ΛΛ invariant mass (2Λ)**

# of K⁻K⁺p p → ΛΛ = 1397

**ΛΛ invariant mass (2K2Λ)**

# of K⁺K⁻p p → ΛΛ = 94

**K⁺K⁰ missing mass (2K)**

# of K⁻K⁺p p = 8095

**K⁺K⁰ missing mass (2K2Λ)**

# of K⁻K⁺p p = 392

1 GeV/c pbar

B.E = 200 MeV, \( \Gamma = 100 \text{ MeV} \)

270kW, 4 weeks
Expected Spectra @ 270kW, 4weeks

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

1GeV/c pbar
B.E=200MeV, $\Gamma=100MeV$
270kW, 4weeks
with Dipole-setup @ K1.1
new dipole setup @ K1.1

- The design goal is to become the common setup for the $\phi$-nuclei experiment with in-flight $p^{\bar{b}}$-beam
- $B = 0.5T$
- Double Cylindrical-Drift-Chamber setup
- $p$ID 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-$p^{\bar{b}}$ experiment

### INC (wire chamber)

<table>
<thead>
<tr>
<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>A</th>
<th>U</th>
<th>U'</th>
<th>V</th>
<th>V'</th>
<th>A</th>
<th>A'</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<td>9</td>
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<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
</tr>
<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>
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</table>

### CDC

<table>
<thead>
<tr>
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<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>1</td>
<td>2</td>
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<td>5</td>
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<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<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

$P^\text{bar} + ^3\text{He} \rightarrow K^+ + K^0_S + K^- K^- p p,$

$K^- K^- p p \rightarrow \Lambda \Lambda \Lambda,$

$\Gamma(K^- K^- p p) = 100\text{MeV}$

--- $\Lambda \Lambda \Lambda$ detection
--- $K^0_S K^+ \ with \ \Lambda\text{-tag detection}$
--- $K^0_S K^+ \Lambda \Lambda$ detection

stopped
----- 1GeV/c

acceptance

0.10
0.05
0.00

0.10
0.05
0.00

binding energy

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

L3He Target ($\phi 70, r = 120$)
CDC (w/ pID)
STC (Scinti, t = 3mm)
CDC
TOF (Scinti or RPC)
1GeV/c beam @ 0.5T
0.68GeV/c beam @ 0.5T
Expected $K^-K_{pp}$ Detection Yield

$P^\text{bar}+^3\text{He} \rightarrow K^+ + K_0^\Sigma + K^-K_{pp}$,

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

$\Gamma(K^-K_{pp}) = 100\text{MeV}$

--- $\Lambda\Lambda$ detection
--- $K_0^\Sigma K^+$ w/ $\Lambda$-tag detection
--- $K_0^\Sigma K^+\Lambda\Lambda$ detection

\[ \text{excepted yield} \ (\text{week@270kW}) \]

- stopped
- 1GeV/c

\[ \text{binding energy} \]

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

L3He Target (d=120)
CDC (w/ pID)
STC (Scinti, t=3mm)
CDC
TOF (Scinti or RPC)

1GeV/c beam @ 0.5T
0.68GeV/c beam @ 0.5T
Expected Spectra @ 270kW, 4weeks

**ΔΔ invariant mass (2Δ)**

# of K⁻K⁻pp → ΔΔ = 282

stopped pbar
B.E=200MeV,
Γ=100MeV
270kW, 4weeks

**K⁺K⁰ missing mass (2K)**

# of K⁻K⁻pp = 1719

**K⁺K⁰ missing mass (2K2Δ)**

# of K⁻K⁻pp = 238
Expected Spectra @ 270kW, 4weeks

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

stopped p\(\bar{\text{p}}\)
B.E=200MeV,
\( \Gamma=100\text{MeV} \)
270kW, 4weeks
Expected Spectra @ 270kW, 4weeks

**ΛΛ invariant mass (2Λ)**

# of K·K·pp→ΛΛ = 1112

**K⁺K⁰ missing mass (2K)**

# of K·K·pp = 7915

**ΛΛ invariant mass (2K2Λ)**

# of K·K·pp→ΛΛ = 76

**K⁺K⁰ missing mass (2K2Λ)**

# of K·K·pp = 435

1GeV/c pbar

B.E=200MeV, Γ=100MeV

270kW, 4weeks
Expected Spectra @ 270kW, 4 weeks

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

1 GeV/c pbar
B.E=200 MeV, $\Gamma=100$ MeV
270kW, 4 weeks
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 B>0 annihilation (multi-nucleon annihilation)
- formation of a cold QGP, deeply-bound kaonic nuclei, H-particle, and so on

The mechanism is NOT known well because of low statistics of the experimental results!
$K^+K^0\Lambda\Lambda$ 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></th>
<th>Q-value</th>
<th>X momentum</th>
<th>$\Lambda\Lambda$ mass</th>
<th>$\Lambda$–$\Lambda$ angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\cdot K^\cdot p\pi$</td>
<td>very small</td>
<td>~ at rest</td>
<td>$M_{\Lambda\Lambda} &gt; 2M_{\Lambda}$</td>
<td>back to back</td>
</tr>
<tr>
<td>H-dibaryon</td>
<td>large</td>
<td>boosted</td>
<td>$M_{\Lambda\Lambda} \sim 2M_{\Lambda}$</td>
<td>~ 0</td>
</tr>
</tbody>
</table>

Possible background channels

● direct $K^+K^0\Lambda\Lambda$ production channels, like:

$\bar{p} + \, ^3\text{He} \rightarrow K^+ + K^0 + \Lambda + \Lambda$

be distinguished by inv.-mass only

be eliminated by the kinematical constraint, \textit{ideally}

● $\Sigma^0 \rightarrow \gamma \Lambda$ 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)

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

\[ M_H = 2M_\Lambda \]

\[ \begin{align*}
\text{Momentum} & \quad \text{Inv. Mass} \\
\Lambda^+ & \quad \Lambda^0 \\
K^+ & \quad K^0 \\
H & \quad \Lambda & \quad \Lambda
\end{align*} \]

\[ \begin{align*}
\text{\( \Lambda \Lambda \) spectra} & \\
\text{\( \Delta \) momentum} & \\
\text{\( \Lambda - \Lambda \) opening-angle} & \\
\text{\( \Lambda \Lambda \) inv. mass}
\end{align*} \]

**Strong correlation of \( \Lambda \Lambda \) opening-angle in \( K^-K^-pp/H \) productions**
<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?
Past Experiments of Stopped-$p^{\text{bar}}$ Annihilation
charged particle multiplicity at rest


<table>
<thead>
<tr>
<th>nc</th>
<th>branch(%)</th>
<th>branch(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.14 ±0.40</td>
<td>3.36 ±0.35</td>
</tr>
<tr>
<td>3</td>
<td>39.38 ±0.88</td>
<td>5.03 ±0.42</td>
</tr>
<tr>
<td>5</td>
<td>48.22 ±0.91</td>
<td>33.48 ±0.92</td>
</tr>
<tr>
<td>7</td>
<td>7.06 ±0.46</td>
<td>12.26 ±0.63</td>
</tr>
<tr>
<td>9</td>
<td>0.19 ±0.08</td>
<td>35.68 ±0.93</td>
</tr>
<tr>
<td></td>
<td>&lt;nc&gt; 4.155 ±0.06</td>
<td>&lt;nc&gt; 4.097 ±0.07</td>
</tr>
</tbody>
</table>

They obtained

\[
\sigma^a(\bar{pp}) = 70.4 \pm 2.5\%
\]

\[
\sigma^a(\bar{pn}) = 29.6 \pm 2.5\%
\]

\[
\rightarrow \sigma^a(\bar{pn})/\sigma^a(\bar{pp}) = 0.42 \pm 0.05
\]
the KKbar production-rate $R$ for $p\bar{p}+p$ annihilation at rest
(obtained from hydrogen bubble chamber data)

\[
R\left(K^0 \bar{K}^0\right) = 1.733 \pm 0.067\%
\]
\[
R\left(K^+ K^-\right) = 1.912 \pm 0.141\%
\]
\[
R\left(\bar{K}^0 K^+\right) + R\left(K^0 K^-\right) = 1.701 \pm 0.082\%
\]

\[
⇒
R\left(K_s^0\right) = \frac{3}{4} R\left(K^0 \bar{K}^0\right) + \frac{1}{2} \left[R\left(\bar{K}^0 K^+\right) + R\left(K^0 K^-\right)\right] = 2.149 \pm 0.065\%
\]
\[
R\left(\bar{K}K\right) = R\left(K^+ K^-\right) + R\left(\bar{K}^0 K^+\right) + R\left(K^0 K^-\right) + R\left(K^0 \bar{K}^0\right) = 5.35 \pm 0.18\%
\]

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/K⁰_s production-rate and multiplicity for pbar+A at rest**


<table>
<thead>
<tr>
<th>pbar+A experimental yields and charge multiplicities of Λ(Σ^0) and K⁰_s at rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>He data is from CERN LEAR, streamer chamber exp. NP A526, 415 (1991).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>R_a(Λ) (%)</th>
<th>R_a(K⁰_s) (%)</th>
<th>&lt;nc(Λ)&gt;</th>
<th>&lt;nc(K⁰_s)&gt;</th>
<th>&lt;nc(all events)&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹H</td>
<td></td>
<td>2.15 ±0.07</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/K⁰_s is produced

- $p^\bar{p}$Xe annihilation
- $p<1$GeV/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
- $p^\bar{p}$Xe$\rightarrow$K$^+K^+X$: 4 events $\rightarrow$ (0.31+/-0.16)x10$^{-4}$
- $p^\bar{p}$Xe$\rightarrow$K$^+K^0\Lambda X$: 3 events $\rightarrow$ (2.1+/-1.2)x10$^{-4}$

<table>
<thead>
<tr>
<th>$p^\bar{p}$ 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>$K^+\Lambda^+\Lambda^-\pi^0\pi^0$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \pi^0 h$</td>
<td></td>
<td>$K^+K^0\Lambda^+\Sigma^+ p$</td>
<td></td>
<td>$K^+\Lambda\Lambda 4p$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \Lambda\pi_\gamma$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td>$K^+\Lambda\Lambda 4h$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ 2h$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ 4\gamma$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4–0.65</td>
<td>$K^+K^+ \pi^- 4\gamma_\pi$</td>
<td>0.42 ± 0.21</td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td>3.0 ± 1.7</td>
<td>$K^+\Lambda\Sigma^- 2h$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \pi^0 4\gamma_\pi$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ 2h$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ 4\gamma$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.65–0.9</td>
<td>$K^+K^+ \Lambda\Lambda_2 p$</td>
<td>0.26 ± 0.13</td>
<td>$K^+K^0\Lambda\Lambda_2 p\pi^-$</td>
<td>2.4 ± 0.9</td>
<td>$K^+\Lambda\Sigma^- 3h$</td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \Lambda\Lambda_2$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p\pi^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \Lambda\Lambda_3 p\Lambda$</td>
<td></td>
<td>$K^+K^0\Lambda\Lambda_2 p\pi^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K^+K^+ \Lambda\Lambda_3 p\Lambda$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The observed double strangeness yield is explained by conventional processes described by the intranuclear cascade model, as listed in the following tables.

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 \( p^\text{bar}-\text{NNN} \) annihilation is equal to \( \sim 10^{-4} \) at rest (B=1 annihilations are not so helpful).

However they claim the frequency of even B=1 annihilation is of the order of 3-5\% at the most [J.Cugnon et al., NP, 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.

On the other hand, the Crystal Barrel collaboration @ CERN/LEAR concludes their \( p^\text{bar}d \to \Lambda K^0/\Sigma^0 K^0 \) 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>$\bar{K}K\bar{K}$</td>
<td>$\bar{K}K\bar{K}$</td>
<td>$KKK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>$KK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B+B</td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td>2</td>
<td>$\bar{K}\bar{K}m$</td>
<td>A</td>
<td></td>
<td>$KK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A+B</td>
<td></td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td>3</td>
<td>$m$</td>
<td>A+A</td>
<td></td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{K}^*Km$</td>
<td>A</td>
<td></td>
<td>$KK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td>$K^*\bar{K}m$</td>
<td>A+B</td>
<td></td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td></td>
<td>$\bar{K}^*K^*m$</td>
<td>C</td>
<td></td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td>5</td>
<td>2.039, 0.866</td>
<td>$\phi\phi$</td>
<td>$\bar{K}K\bar{K}$</td>
<td>$KK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>$KK\bar{K}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D+D</td>
<td>$KK\bar{Y}$</td>
</tr>
<tr>
<td>6</td>
<td>$\omega\omega$</td>
<td>$\omega\eta$</td>
<td>A+A</td>
<td>$KK\bar{Y}$</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>$KK\bar{K}$</th>
<th>$KK\bar{K}\Lambda$</th>
<th>$KK\Lambda\Lambda$</th>
<th>$\Xi\bar{K}\bar{K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$3.18 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$1.29 \times 10^{-7}$</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$4.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$3.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>total</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$7.9 \times 10^{-5}$</td>
<td>-</td>
<td>$1.9 \times 10^{-4}$</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>$K^+K^0\Lambda X$</th>
<th>Total DS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>exp.</td>
<td>calc.</td>
<td>exp.</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>

Experimental values are not final values of the DIANA data.

- $p^\text{bar}4\text{He}$ annihilation
- stopped $p^\text{bar}$ @ CERN/LEAR
- liquid deuteron target
- cylindrical spectrometer w/ B-field
- SVX, CDC, CsI crystals
- $\sim10^6$ 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>$\Lambda K_L^0$</td>
<td>$\Lambda \rightarrow p\pi^-, K_L^0$ (noninteracting)</td>
<td>$107 \pm 11 \pm 6$</td>
<td>$1.1 \pm 0.1 \pm 0.2$</td>
</tr>
<tr>
<td>$\Sigma^0 K_L^0$</td>
<td>$\Sigma^0 \rightarrow \Lambda\gamma, \Lambda \rightarrow p\pi^-, K_L^0$ (noninteracting)</td>
<td>$83 \pm 10 \pm 9$</td>
<td>$1.0 \pm 0.1 \pm 0.2$</td>
</tr>
<tr>
<td>$\Sigma^0 K_S^0$</td>
<td>$\Sigma^0 \rightarrow \Lambda\gamma, \Lambda \rightarrow p\pi^-, K_S^0 \rightarrow \pi^+\pi^-$</td>
<td>$61 \pm 8 \pm 5$</td>
<td>$1.6 \pm 0.3 \pm 0.5$</td>
</tr>
<tr>
<td>$\Lambda K_S^0$</td>
<td>$\Lambda \rightarrow p\pi^-, K_S^0 \rightarrow \pi^+\pi^-$</td>
<td>$85 \pm 10 \pm 10$</td>
<td>$1.5 \pm 0.2 \pm 0.5$</td>
</tr>
</tbody>
</table>

**Table 2**

Comparison of experimental results and predictions of dynamical and statistical models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></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>$1.0 \times P_{\bar{B}=1}$ $^c$</td>
</tr>
<tr>
<td>$\Sigma^0 K^0$</td>
<td>$2.15 \pm 0.45$ $^a$</td>
<td>0.004</td>
<td>$1.0 \times P_{\bar{B}=1}$ $^c$</td>
</tr>
<tr>
<td>$p\pi^-$</td>
<td>$13.0 \pm 1.0$ $^b$</td>
<td>2–6</td>
<td>$4.7 \times P_{\bar{B}=1}$ $^c$</td>
</tr>
<tr>
<td>(ii) Relative branching ratios $R_{\Sigma^0 \Lambda} = BR(\Sigma^0 K^0) / BR(\Lambda K^0)$</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 $P_{\bar{B}=1} \lesssim 10\%$ (Ref. [6]).

Support the statistical model
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 $\bar{p}d \rightarrow \Sigma^+ K^0 \Sigma^- \rightarrow \Lambda \pi^+$, $\Lambda \rightarrow p \pi^-$, $K^0_S \rightarrow \pi^+ \pi^-$ 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).]

- $p^\text{bar}^4\text{He}$ annihilation
- stopped $p^\text{bar}$ @ CERN/LEAR
- gas target ($^4\text{He}@\text{NTP}, \text{H}_2@3\text{atm}$)
- 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 $\pi/K/p$

<table>
<thead>
<tr>
<th>Prong</th>
<th>Process</th>
<th>Events</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-prong</td>
<td>$\bar{p}^4\text{He} \rightarrow K^+ K^+ \Sigma^- \Sigma^- p_s \rightarrow K^+ K^+ \pi^- \pi^- (nnp_s)$</td>
<td>34±8</td>
<td>$(0.17±0.04) \times 10^{-4}$</td>
</tr>
<tr>
<td>5-prong</td>
<td>$\rightarrow K^+ K^+ \Sigma^- \Sigma^+ n\pi^- \rightarrow K^+ K^+ \pi^+ \pi^- \pi^- (nnn)$</td>
<td>36±6</td>
<td>$(2.71±0.47) \times 10^{-4}$</td>
</tr>
<tr>
<td>5-prong</td>
<td>$\rightarrow K^+ K^+ \Sigma^- \Lambda n \rightarrow K^+ K^+ p\pi^- \pi^- (nn)$</td>
<td>16±4</td>
<td>$(1.21±0.29) \times 10^{-4}$</td>
</tr>
<tr>
<td>5-prong</td>
<td>$\rightarrow K^+ K^+ K^- \Lambda nn \rightarrow K^+ K^+ K^- p\pi^- (nn)$</td>
<td>4±2</td>
<td>$(0.28±0.14) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

* (xx) is not observed

they discuss the possibility of formation and decay of $K^-K^-\text{nn}$ and $K^-K^-\text{pnn}$ bound system