The New Stage of $S=-2$ Hypernuclear Study
Opened with a New High-resolution Spectrometer

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Opened with a New High-resolution Spectrometer

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Motivation

• Baryon-baryon interaction in $SU_f(3)$
• Role of strangeness in dense nuclear matter

• $S=-2$ $\Xi$, $\Lambda\Lambda$
  • a few emulsion events
  • limited information

• $S=-1$ $\Lambda$, $\Sigma$
  • hypernuclear structure
    • $(K^-,\pi)$, $(\pi^+,K^+)$, $(e,e'K^+)$ etc
    • $\gamma$-ray spectroscopy
  → effective $\Lambda N$, $\Sigma N$ interactions

• $S=0$ $p$, $n$
  • a lot of $NN$ scattering data
  → realistic nuclear force
Emulsion experiment

KEK-E373

- "NAGARA" event
  - uniquely identified as $^\Lambda\Lambda^6$He
  - $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV
  - weakly attractive

  J.K. Ahn et al., PRC 88 (2013) 014003

- "KISO" event
  - $\Xi^{-}^{14}$N system
  - $\Xi^{-}+^{14}$N$\rightarrow^{10}_{\Lambda}$Be$+^{5}_{\Lambda}$He
  - $B_{\Xi^{-}} = 1.11$ or 4.38 ($\pm 0.25$) MeV $\pm \Gamma_{\text{conv.}}/2$

S=−2 hypernuclei do exist!
→ systematic study

H. Takahashi et al., PRL 87 (2001) 212502

K. Nakazawa et al., PTEP (2015) 3, 033D02
Spectroscopic Study

BNL-E885: $^{12}\text{C}(K^-,K^+)$ at 1.8 GeV/c

- missing-mass spectroscopy
- $d\sigma/d\Omega$ ($-20 < E < 0$ MeV)
  - $\theta < 14^\circ$: 67 events, 42\pm5 nb/sr
  - $\theta < 8^\circ$: 42 events, 89\pm14 nb/sr
  - "evidence" of existence of $\Xi$ bound state
- mass resolution 14 MeV FWHM
  - no clear peak
  - shape analysis $\Rightarrow V_\Xi \sim -14$ MeV?

Better resolution and more statistics $\Rightarrow$ J-PARC

P. Khaustov et al., PRC 61 (2000) 054603
Spectroscopy Experiment at J-PARC
Beam Intensity at J-PARC

Summary of the K beam intensity at K1.8 beam line and accelerator power

80kW & 1.2MK⁻/spill expected in late 2018 → exceed BNL intensity

BNL-AGS D-line $1 \times 10^6$ K/spill, $K/\pi \sim 1$, spill duration 3.6s

<table>
<thead>
<tr>
<th>K-beam rate (M/spill)</th>
<th>Acceptance</th>
<th>Path length</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS D-line</td>
<td>6.17 msr%</td>
<td>31.4 m</td>
</tr>
<tr>
<td>J-PARC K1.8</td>
<td>1.5 msr%</td>
<td>46 m</td>
</tr>
</tbody>
</table>

P.H. Pile et al., NIM A321(1992)48

K-beam experiment 2015 Apr.

K-beam experiment 2015 Nov.

Down period

1 spill 5.5s

1 spill 6s

10M $\pi$ /spill

1 spill 4s
J-PARC E05 experiment

Missing-mass spectroscopy of $\Xi$-hypernucleus via the $^{12}\text{C}(K^-, K^+)^{12}\Xi$ reaction (Nagae et al.)
- observe peaks of the bound state
  - much improved mass resolution of $<2 \text{ MeV}$
  - deduce the information of $\Xi N$ potentials

Pilot measurement: Nov. 2015
- mass resolution $\sim7 \text{ MeV}$, w/ existing SKS spectrometer
- beam: $6\times10^5 K^-$/spill (Acc. 39kW) $K/\pi \sim 0.8$

Spectrometers
- $K^-$: Beam spectrometer, $dp/p<1\times10^{-3}$
  - already working at K1.8BL
- $K^+$: S-2S spectrometer, $dp/p \ 6\times10^{-4}$
  - newly developed for $(K^-, K^+)$ reaction spectroscopy
  - magnet construction completed in 2015
to be installed in 2018 high resolution

Accelerator power: 80kW in 2018? enough statistics
Progress of Mass Resolution

<table>
<thead>
<tr>
<th>$^{12}$C($K^-,K^+$) experiments</th>
<th>KEK-E224</th>
<th>BNL-E885</th>
<th>J-PARC E05 (pilot run w/ SKS)</th>
<th>J-PARC E05 (S–2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Omega$ (msr)</td>
<td>90</td>
<td>50</td>
<td>110</td>
<td>60</td>
</tr>
<tr>
<td>$\theta$ (deg)</td>
<td>&lt;12</td>
<td>&lt;14</td>
<td>&lt;16</td>
<td>&lt;8</td>
</tr>
<tr>
<td>$pK^+$ (GeV)</td>
<td>0.9 – 1.7</td>
<td>1.0 – ?</td>
<td>1.1 – 2.4</td>
<td>1.2 – 1.6</td>
</tr>
<tr>
<td>$\Delta M$ (MeV$_{\text{FWHM}}$)</td>
<td>22</td>
<td>14</td>
<td>7</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

First measurement optimized for MM spectroscopy

The analysis status of J-PARC E05 pilot run w/ SKS will be reported by T. Nagae on 16 Sep.
Expected spectrum

- DWIA spectrum for ESC08a interaction
- Nuclear core excitations are taken into account.

\[ {^{12}\text{C}}(K^-,K^+) \rightarrow ^{12}\text{Be} \]

(T=1)

Black line: Theoretical calculation

Colored line: calculation convoluted with experimental resolution

To resolve these peaks, high energy resolution, \( \Delta E < 2 \text{ MeV} \), is essential

2016/9/12
INPC 2016, Adelaide, S. Kanatsuki
Future Extension

Systematic studies on $S=-2$ hypernuclei

- Various targets
  - light: $^7\text{Li} \rightarrow ^7\text{H}(\alpha\alpha n\Xi)$, $^{10}\text{B} \rightarrow ^{10}\text{Li}(\alpha\alpha n\Xi)$
  - spin-isospin dependence of $\Xi N$ potential
  - heavy: $^{89}\text{Y} \rightarrow ^{89}\text{Rb}$, etc.
    - mass dependence

- Double $\Lambda$-hypernuclei
  - via $\Xi$ doorway
  - sensitive to $\Xi N$-$\Lambda$-$\Lambda$ coupling strength
  - $d\sigma/d\Omega$ is expected to be several nb/sr
  - first measurements of excited states

\[ V_{\Xi N} = V_0 + \sigma \cdot \sigma V_{\sigma \sigma} + \tau \cdot \tau V_{\tau \tau} + (\sigma \cdot \sigma)(\tau \cdot \tau)V_{\sigma \sigma \tau \tau} \]
S–2S spectrometer
Configuration

Scattered K⁺

Drift chamber 1,2
Q1: vertical focus
Q2: horizontal focus
D1: 70° bend
Drift chamber 3,4

Momentum analysis

Normal conducting magnets
Four sets of wire chambers
dp/p ~6x10⁻⁴ FWHM, ΔΩ 60 msr

K⁺ trigger = TOF ∧ ĀC ∧ WC
TOF: off-line particle identification
Aerogel: n=1.06 → Pion veto
Water: n=1.33 → Proton veto

Trigger counters

Beam = 10⁶ K⁻
• π⁺, p : 1000
• K⁺ : 1

Path Length ~9 m
→ K⁺: survival rate 40%
Performance Estimation

\[ \frac{d\rho}{\rho} \sim 6 \times 10^{-4} \text{ (FWHM)} \]

Momentum resolution

\[ \sigma_x = 250 \text{ um (rms)} \]

Solid Angle

\[ d\Omega \sim 60 \text{ msr} \]

Hypernuclear production

\[ p(K, K^+) \Xi \]

Simulation

\[ \text{INPC 2016, Adelaide, S. Kanatsuki} \]

2016/9/12
Magnets

- **Q1 (vertical focus)**
  - 8.7 T/m
  - aperture 31 cm
  - 37 ton
  - $2.4 \times 2.4 \times 0.88 \text{ m}^3$

- **Q2 (horizontal focus)**
  - 5.0 T/m
  - aperture 36 cm
  - 12 ton
  - $2.1 \times 1.54 \times 0.5 \text{ m}^3$
  - renewal one with modification of poles and coils

- **D1**
  - 1.5 T (70° bend @ 1.37 GeV/c)
  - pole gap $32 \times 80 \text{ cm}^2$
  - 86 ton
  - central trajectory 3.7 m

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*Scattered K*⁺

INPC 2016, Adelaide, S. Kanatsuki
Q1, Q2 magnet

- Field Measurement
  - with Hall probe
  - field gradient
    - Q1: 8.7 T/m, Q2: 5.0 T/m
    - enough to achieve large acceptance

- Field Calculation
  - 3D electromagnetic field calculation software Opera-3d/TOSCA
D1 magnet

- **Field Measurement**
  - Excitation curve is measured by using NMR

  - By ~1.5 T at the center of the gap

- **Field distribution**
  - Will be measured by using Hall probe
  - Study is ongoing at KEK

- **Leak field**
  - Measured by using gaussmeter: ~5 Gauss
  - Active cancellation of leak field by using a bucking coil for PMT on the trigger counters
Summary

• $\Xi$ hypernuclei
  – the last piece of baryon-baryon interaction in $SU_f(3)$
  – $\Xi$ in neutron star?

• J-PARC E05 experiment
  – missing-mass spectroscopy via the $^{12}\text{C}(K^-, K^+)^{12}\Xi\text{Be}$ reaction
  – with a new magnetic spectrometer S–2S
    • magnets and detectors are almost completed
    • to be installed in J-PARC in 2018 $\rightarrow$ E05 Run starts!
  – mass resolution of <2 MeV and $d\Omega$ ~60 msr $\rightarrow$ 250 events in 20 days

• Systematic study of S=−2 hypernuclei
  – high-resolution measurement of $\Xi$- & $\Lambda\Lambda$-hypernuclei with intense $K^-$ beam
  – so far, only confirmation of the existence of bound states
    $\rightarrow$ investigation of the details of the $\Xi N$, $\Lambda\Lambda$ interaction
Backup
Interaction Model Dependence

The shapes of spectra depend on the properties of spin-dependent term of interaction models.
Double $\Lambda$ hypernuclei

(a) $\sim 0.1$ nb/sr

(b) $7 \sim 12$ nb/sr

Sensitive to $\Xi N$-$\Lambda \Lambda$ coupling strength

Double Λ hypernuclei

- $^{16}\text{O}\ (K^-, K^+) \Lambda \Lambda^{16}\text{C}$

- $[^{15}\text{N}(1/2^-, 3/2^-)\times s_{\Xi}]_1^- \rightarrow [^{14}\text{C}(0^+, 2^+)]\times s_{\Lambda p}\Lambda_1^-$

- $[^{15}\text{N}(1/2^-, 3/2^-)\times p_{\Xi}]_2^+ \rightarrow [^{14}\text{C}(0^+, 2^+)]\times p_{\Lambda^2}^2_2^+$

\[\Delta E_{\text{exp}} = 1.5 \text{ MeV}\]

\[\Delta E_{\text{exp}} = 3 \text{ MeV}\]

Cross section of $p(K^-, K^+)\Xi^-$

Mass Resolution

**High-Res Spec. “S-2S”**

\[
\Delta M^2 = \left( \frac{\partial M}{\partial p_B} \right)^2 \Delta p_B^2 + \left( \frac{\partial M}{\partial p_S} \right)^2 \Delta p_S^2 + \left( \frac{\partial M}{\partial \theta} \right)^2 \Delta \theta^2 + \Delta E_{\text{strag.}}^2
\]

$^{12}\text{C}(K^-,K^+) \rightarrow ^{12}\text{Be}$, $\theta=5^\circ$, $E_{\text{hyp}}=0$ MeV, $\Delta \theta=2$ mrad  [MeV]

<table>
<thead>
<tr>
<th></th>
<th>Beam</th>
<th>Scat</th>
<th>$\theta$</th>
<th>$\Delta M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design value</td>
<td>0.84</td>
<td>0.62</td>
<td>0.04</td>
<td>1.0</td>
</tr>
<tr>
<td>Realistic?</td>
<td>1.67</td>
<td>3.74</td>
<td>0.04</td>
<td>1.8</td>
</tr>
<tr>
<td>Pilot run</td>
<td></td>
<td></td>
<td>0.04</td>
<td>4.1</td>
</tr>
</tbody>
</table>

$\Delta E_{\text{strag}} \leftarrow$ Target thickness

1 MeV $\leftarrow$ 3 g/cm$^2$
2 MeV $\leftarrow$ 6 g/cm$^2$
3 MeV $\leftarrow$ 10 g/cm$^2$

- Momentum resolution $\Delta p/p$ (FWHM)
  - Beam: (design) $<5 \times 10^{-4}$
  - (realistic?) $1 \times 10^{-3}$ $\leftarrow$ evaluation in other experiments at J-PARC
  - Scat: SKS (used in pilot run) $3 \times 10^{-3}$
  - S-2S $5 \times 10^{-4}$
Kinematics

\[ p_{K^-} = 1.8 \text{ GeV/c} \quad \leftrightarrow \quad p_{K^+} = 1.2 \sim 1.4 \text{ GeV/c} \]

Recoil Momentum

Momentum of \( K^+ \)

*Fig. 2.3. The momentum \( q_\gamma \) transferred to the hyperon \( \gamma \) as a function of the projectile momentum \( p_{\text{proj}} = p_s \) in the reaction \( aN \rightarrow \gamma \gamma \) at \( \theta_{\gamma \gamma} = 0^\circ \).*

2016/9/12

INPC2016, Adelaide, S. Kanatsuki
Momentum Resolution

\[ \frac{dp}{p} \approx 6 \times 10^{-4} \text{ (FWHM)} \]

Magnet condition
Q1, Q2, D1 = 2500A (max)
Solid Angle

Magnetic field ← TOSCA calculation
Q1,Q2,D1 = 2500A (max)

Particles just passing through the magnets
= not including detector configuration
1. Various products off targets
   • Reaction rate: \( \sim 10\% \)

2. Decay of beam \( K^- \)
   - \( K^- \rightarrow \pi^- \pi^- \pi^+ \) (B.R. 5.6%)
   - \( K^- @ 1.8 \text{ GeV/c: } \beta \gamma c \tau \sim 13.5 \text{ m} \)

3. Reactions on the D1 yoke
   • \( K^- + \text{Fe} \rightarrow \text{many particles} \)
Backgrounds not from the Target

- Decay of beam $K^- \&$ Reactions on the D1yoke

![Graph showing beam-induced background and Geant4 simulation]

- Beam $K^- = 10^6$
  - Only neutrons can reach the counters at the exit
  - A few tens of $\pi^+$ from $K^-$ decay

- Most charged particles stop inside of the D1
Reactions in target

• Background estimation
  – JAM v1.210 : Jet AA Microscopic transport model


\[ K^+ p \rightarrow \bar{\Xi} - K^+ \]
\[ K^- p \rightarrow \bar{\Xi}^* K^- \]
\[ K^- p \rightarrow p K^- \]
\[ K^- p \rightarrow p \pi K^- \]
\[ K^- n \rightarrow p \pi^- K^- \]
\[ K^- p \rightarrow \bar{\Lambda} \pi^+ \pi^- \]
\[ K^- p \rightarrow \Sigma^+ \pi^+ \]

\[ 3.2 \pm 0.05 \text{ GeV/c} \]

\[ S_{2S} : 0 < 18^\circ \]

Out of Acceptance!

*Compilation of Cross-Sections : K+ induced reactions*, CERN-Library(1983)
Background Distributions

JAM simulation
$10^6 K^- @ 1.8 \text{GeV/c}, \ 3 \text{g/cm}^2, ^{12}\text{C target}$
Field Calculation of D1

• Calculation by Opera/TOSCA-3d
  – Input model will be tuned after field measurement

1.49 Tesla

20~50 Gauss @Counters
Status summary

Magnets
- Q1, Q2: Ready
- D1: Field measurement is ongoing

Existing Detectors
- DC 1
- DC 3, 4
  - 1 m × 1 m Drift chambers
  - Need some repairments
- AC
  - Ready

New Detectors
- TOF
  - Plastic scintillator
- DC 2
  - 2.5mm-pitch, vertically large size
- Water Cherenkov
  - T. Gogami, et al., NIM A, 817 (2016) 70
Active Fiber Target

- Scintillating fiber
  - scintillation light yield → correction of the energy of kaons event-by-event

Energy losses of
- Beam $K^-$
- Scat. $K^+$
- Decay particles from hypernucleus
  should be measured separately → Target must be segmented
Active Fiber Target

- Scintillating fiber bundle
  - 3x3 mm square or 3 mm Φ (→ 50×18+16×18 ≡ 1000)
  - MPPCs attached on the both ends of each fiber
Expected spectrum

**12 C(K^-, K^+)\text{^{12}Be}**  \( E_K = 1.7 \) GeV/c  \( (\theta_{\text{lab}} = 0) \)

**Hypernuclear Energy**  \( E_{\Xi} \) (MeV)

Three \( 1^- \) states with widths of 2.5 MeV\text{FWHM}

20 days  60 days