Observation of $\Lambda\Lambda$ Production in the Reaction $(K^-, K^+)$ with HypTPC at J-PARC

Double Strangeness Systems with E42 Detector

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Doubly Strange Dibaryon Systems and $H$ Particle

- **$\Lambda\Lambda$**
  - $I=0$

- **$\Xi N$**
  - $I=0, 1$

- **$\Lambda\Sigma$**
  - $I=0, 1$

- **$\Sigma\Sigma$**
  - $I=0, 1, 2$

- For $N$ quarks, the QCD color magnetic interaction can be summarized by an effective Hamiltonian acting on the quarks’ spin and color indices;

$$\mathcal{H}_{\text{eff}} \propto - \sum_{i \neq j}^{N} \{\vec{\lambda} \vec{\sigma}\}_i \cdot \{\vec{\lambda} \vec{\sigma}\}_j = 8N - \frac{1}{2} C_6^N + \frac{4}{3} S_N (S_N + 1).$$

- For 6 quarks, the color-spin interaction energies are

$$\langle \mathcal{H}_{\text{eff}} \rangle_1 = -24, \quad \langle \mathcal{H}_{\text{eff}} \rangle_8 = -\frac{28}{3}, \quad \langle \mathcal{H}_{\text{eff}} \rangle_{10} = +\frac{8}{3}, \quad \langle \mathcal{H}_{\text{eff}} \rangle_{27} = +3,$$
The History of H-Dibaryon Searches

1977  • Deeply-bound di-hyperon predicted by R. Jaffe
1980-2000 • No evidence for the deeply-bound $H$ from KEK, BNL, and CERN experimental efforts by more than 80 MeV
2001  • Mass constraint from observation of $^6_\Lambda\Lambda\text{He}$ (E373)
1998,2007  • Enhanced $\Lambda\Lambda$ production near threshold was reported from E224 and E522 at KEK-PS.
2011  • LQCD calculations predict the H-dibaryon near $m_{\Lambda\Lambda}$
2013-2015  • No evidence for $H \rightarrow \Lambda p\pi^-$ and $H \rightarrow \Lambda\Lambda$
in high-energy $e^+ e^-$, $pp$ and AA experiments
2021  • LQCD calculations point to the mass the H-dibaryon very close to $\Xi N$ threshold ($m_{\pi} \approx 146$ MeV)
2021  • J-PARC E42 has successfully completed with HypTPC.
2024  • We are about to see what we would see in the E42 dataset.

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E42 aims at searching for an $H$-dibaryon in $\Lambda p\pi^-$, $\Lambda\Lambda$, and $\Xi^- p$ from $^{12}\text{C}(K^-, K^+)$ at 1.8 GeV/$c$.

E42 has a good sensitivity over a broad range of the $H$ mass.

Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$

Simulated $\Xi^- p$ Spectrum for $H(2265)$
Nuclear Potential

- Spectral response of the $-B_\Xi$ spectrum for $^{12}\text{C}(K^-, K^+)$ provides some information on the WS potential depth $V^\Xi_0$, which $\approx -14$ MeV (DWIA) but $\approx 0$ MeV (SCDW) analyses.
- High-resolution $\Xi^-$ nuclear state measurement with E70 detector

<table>
<thead>
<tr>
<th>$p_{K^-}$</th>
<th>$\theta_{K^-}$</th>
<th>$U^0_\Xi$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.65 GeV/c</td>
<td>5.5°</td>
<td>0</td>
</tr>
<tr>
<td>1.8 GeV/c</td>
<td>0°–8°</td>
<td>-20, -10, 0, +10, fss2</td>
</tr>
</tbody>
</table>

Iijima et al. $p_{K^-} = 1.65$ GeV/c ($1.7°–15.6°$)

Khaustov et al. $p_{K^-} = 1.8$ GeV/c ($0°–8°$)
Nuclear Potential

- Ξ spectrum of $^9$Be($K^-, K^+$) within DWIA using the optimal Fermi-averaged $K^- p \rightarrow K^+ \Xi^- \rightarrow \Xi^0$ amplitude favors $V^\Xi_0 \approx -17$ MeV.

- The same study on $^{12}$C($K^-, K^+$) shows strong energy and angular dependencies.

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\( \Xi N \) Interaction with \(^{9}\text{Be}(K^-, K^+)\) and \(^{12}\text{C}(K^-, K^+)\)

**Graphs:**
- Escaping Probability
- Scattering Probability

**Equations:**
- \( \Xi^\text{Be} E_{906} \)
- \( \sigma \approx 30 \text{ mb} \) at \( \sim 0.55 \text{ GeV}/c \)
- \( \sigma(\Xi^- p \rightarrow \Xi^- n) = 24 \text{ mb} \) at 90% CL
- \( \sigma(\Xi^- p \rightarrow \Lambda \Lambda) = 4.3^{+6.3}_{-2.7} \) in \( p_{\Xi} = 0.2 \) to 0.8 GeV/c

**References:**
Superconducting Hyperon Spectrometer
Scattered Particles at Forward Angles

- We reconstructed the masses and momenta for scattered particles successfully with the forward $K^+$ spectrometer.
Charged Particles at Large Angles in HypTPC

\[ K^- \rightarrow K^+ + \pi^- \]

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Particle Identification with HypTPC

- \( \langle dE/dx \rangle_{20\% \text{ truncated}} \) vs \( p/z \) for reconstructed HypTPC tracks in the diamond target dataset (C\( (K^-, K^+) \)X reactions).
- \( \sigma_{dE/dx}/\langle dE/dx \rangle \sim 20\% \) for the range 0.40 < \( p_T \) < 0.45 GeV/c.
Missing-mass spectrum for $p(K^-, K^+)X$ reactions is reproduced by considering the reconstruction efficiencies for $\Xi^-$ decays with visible and invisible $\Lambda$ decays, which are obtained from an independent Monte Carlo simulation study.

$\Xi^* \Xi^- \Xi^* \Xi^-\ |
\text{Counts}/(5\text{ MeV}/c^2)$

$\Xi^- p(K^-, K^+)X$
$p(K^-, K^+)\Xi X / Br(\Lambda \rightarrow p\pi^-)$
$p(K^-, K^+)\pi^- / Br(\Lambda \rightarrow n\pi^0)$

$12C$ contribution subtracted from the spectrum with a $\text{CH}_2$ target.
Production in the $^{12}\text{C}(K^-, K^+)$ Reaction

- The $\Xi^- \to \Lambda\pi^-$ and its subsequent $\Lambda \to p\pi^-$ visible decays are reconstructed using HypTPC track information.

$E224 \quad p_{K^-} = 1.65 \text{ GeV/c}$

$E42 \quad p_{K^-} = 1.8 \text{ GeV/c}$
Ξ⁻N Scattering in the $^{12}\text{C}(K^-, K^+)$ Reaction

- Colinearity angle $\cos \psi = (\vec{p}_{K^-} - \vec{p}_{K^+}) \cdot \vec{p}_{\Xi}^{\text{rec}}$
- $\sigma_{\Xi^-N} = 30.7 \pm 6.7^{+3.7}_{-3.6}$ mb for $\langle p_{\Xi} \rangle = 0.55$ GeV/c and $R(\sigma_{\Xi^-p}/\sigma_{\Xi^-n}) \approx 1.1$ in the eikonal approximation\(^1\).

One and two-step processes may contribute to the $^{12}\text{C}(K^-, K^+)$ reactions but the previous intranuclear cascade model calculation$^1$ needs further improvements to reproduce the experimental data from E176$^2$.


\[
\begin{align*}
K^- p & \rightarrow K^+ \left( \begin{array}{c} \Xi^- \\ \Xi(1535)^- \end{array} \right) \\
K^- p & \rightarrow \left( \begin{array}{c} \pi \\ \eta \\ \rho \\ \Sigma \\ \Sigma^* \end{array} \right); \; \left( \begin{array}{c} \pi \\ \eta \\ \rho \end{array} \right) N \rightarrow K^+ \left( \begin{array}{c} \Lambda \\ \Sigma \\ \Sigma^* \end{array} \right) \\
K^- p & \rightarrow K^+ \Xi^-; \Xi^- p \rightarrow \left( \begin{array}{c} \Lambda \Lambda \\ \Xi^- p \end{array} \right) \\
K^- p & \rightarrow \left( \begin{array}{c} \phi \\ a_0 \\ f_0 \end{array} \right) \Lambda, \; \text{where } \phi, a_0, f_0 \rightarrow K^+ K^-
\end{align*}
\]
Cross sections $d^2\sigma/d\Omega dp_{K^+}$ for $^{12}C(K^-, K^+)$ Reaction

Preliminary Results from E42

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

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

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

$\Xi^*(1535) \rightarrow \Xi^0\pi^-/\Xi^-\pi^0$

$K^+$ momentum (GeV/c)
Binding Energy Spectrum for $^{12}\text{C}(K^-, K^+)X$

$$K^- + ^{12}\text{C} \rightarrow K^+ + (\Xi^- + ^{11}\text{B})$$

- E42 can offer critical information on individual processes involved in the $^{12}\text{C}(K^-, K^+)$ reaction with large acceptance despite moderate energy resolution.
- The processes include reactions with the emission of $\Xi^-$, $\Xi^- p$, $\Lambda\Lambda$, and hypernuclear decay particles such as two pions.
ΛΛ Production in the \((K^-, K^+)\) Reactions
E42 will soon open the box for the $H$-dibaryon search.
E42 can also offer critical information on individual processes involved in the $^{12}\text{C}(K^-, K^+)$ reactions with large acceptance despite moderate energy resolution.
Additionally, E42 has a good dataset for extensive studies of kaonic nuclei (F. Oura, Wed 14:40 M5) and $K^*$ production in $^{12}\text{C}(K^-, p)$ reactions.