SEARCH FOR AN $H$-DIBARYON NEAR $\Lambda\Lambda$ AND $\Xi^-p$ THRESHOLDS AT J-PARC

J-PARC E42

Jung Keun Ahn (Korea University)
(HYP2018, June 24-29, 2018, Norfolk, VA)
Perhaps a Stable Dihyperon

**R. L. Jaffe†**

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science, †Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

*(Received 1 November 1976)*

- MIT bag model predicts di-hyperon state \((H)\) with
  
  \[ I = 0, \quad S = -2, \quad J^p = 0^+ \]

  and a mass of \( m_H = 2150 \text{ MeV} \) (by 80 MeV relative to \( 2m_\Lambda \)).

- This hypothesis initiated a world-wide activity in theoretical predictions and numerous experimental searches.
A stable SU(3)$_f$ singlet hexaquark state consisting of $uuuddss$ quarks due to QCD color magnetic force: H-Dibaryon ($J = 0, I = 0$)
### 40 Year History since the H-Dibaryon Prediction

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Deeply-bound di-hyperon predicted by R. Jaffe</td>
</tr>
<tr>
<td>1980-2000</td>
<td>No evidence for the deeply-bound $H$ from KEK, BNL, and CERN</td>
</tr>
<tr>
<td></td>
<td>experimental efforts by more than 80 MeV</td>
</tr>
<tr>
<td>2001</td>
<td>Mass constraint from observation of $\Lambda\Lambda$ He (E373)</td>
</tr>
<tr>
<td>1998,2007</td>
<td>Enhanced $\Lambda\Lambda$ production near threshold was reported</td>
</tr>
<tr>
<td></td>
<td>from E224 and E522 at KEK-PS.</td>
</tr>
<tr>
<td>2013-2015</td>
<td>No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$</td>
</tr>
<tr>
<td></td>
<td>in high-energy $e^+ e^-$, $p p$ and AA experiments</td>
</tr>
<tr>
<td>2011</td>
<td>LQCD calculations predict the H-dibaryon to appear near (just above)</td>
</tr>
<tr>
<td></td>
<td>threshold</td>
</tr>
<tr>
<td>Present</td>
<td>J-PARC E42 under preparation</td>
</tr>
</tbody>
</table>
Success of recent LQCD calculations in reproducing \(NN\) interactions revived the \(H\)-dibaryon search.

Lattice QCD calculations predict the \(H\) appears closer to \(N\Xi\) mass threshold with physical quark masses, yielding a bound \(N\Xi\) system at \(m_\pi = 410\) MeV.

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\[ m_\pi = 700\ \text{MeV} \]
\[ m_\pi = 570\ \text{MeV} \]
\[ m_\pi = 410\ \text{MeV} \]

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\(^1\)S. Aoki (HAL Collab.), Nuclear Physics from Lattice QCD, 2016.
Recent Lattice QCD Calculation Result

- Preliminary results with $L = 8$ fm and $m_\pi = 145$ MeV.
- $\Lambda\Lambda$ and $N\Xi (I = 0) \, ^1S_0$ phase shifts $^2$

Deuteron-like $N\Xi$ bound system from ESC model.$^3$

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$^3$Y. Yamamoto, NSMAT 2016
Double-Λ Hypernuclei and ΛΛ Production

- ΛΛ pair decays strongly to the \( H \) in a nucleus if \( H \) is lighter than ΛΛ in a nucleus.

KEK-E224 measurement for \( ^{12}\text{C}(K^{-}, K^{+})\Lambda\Lambda\chi \) (7.6 µb/sr and 3 µb/sr for the H)

\[ m(\Lambda^3\text{He}) = 5951.82 \pm 0.54 \text{ MeV} \]
\[ B_{\Lambda\Lambda} = 7.25 \pm 0.19 \text{ MeV} \]
\[ \Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20 \text{ MeV} \]
(assumed \( B_{\pi} = 0.13 \text{ MeV} \))
\[ m(H) \geq 2233.7 \text{ MeV/c}^2 \]
(90% C.L.)

\[ ^{12}\text{C}(K^{-}, K^{+})\Lambda\Lambda\chi \]
The Belle searched for the H-dibaryon in $\Upsilon$ decays ($\text{Br}(\Upsilon \rightarrow HX)/\text{Br}(\Upsilon \rightarrow \bar{d}X) < 10^{-2}$).

Six-quarks should be produced and correlated to form the H-dibaryon from nothing in the initial state.

Only small fraction of $\Lambda\Lambda$ or $\Xi N$ pairs will be produced close enough in space and with their relative momenta small enough to interact via $H$-formation.

Production from \((K^-, K^+)\) Reactions

\[
K^- + (pp)^1S_0 \rightarrow K^+ + (Ξ^- p)^1S_0 \rightarrow K^+ + H(J^π = 0^+)
\]

Possible \(H\) production processes on a diproton pair via the \((K^-, K^+)\) reaction\(^6\) \(^7\):


H-dibaryon search from photoproduction ($E^\text{th}_\gamma = 1.83$ GeV for $m_H = 2m_\Lambda$) is viable at SPring-8 and J-Lab.

- $\gamma d \rightarrow K^+ K^0 H$ followed by $K^0 \rightarrow \pi^+ \pi^-$.
- $\gamma p \rightarrow K^+ \bar{K}^0 n$ ($a_0^+ \rightarrow K^+ \bar{K}^0$); $\gamma n \rightarrow K^+ \bar{K}^0 X$
Background from a charge-exchange reaction $K^- p \rightarrow K^0 n$

A liquid $^3$He target could provide a $pp$ pair, but a solid denser target is better suited for an effective di-proton target such as $^{12}$C and $^{63,65}$Cu.
The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

- Weakly-bound: $H \rightarrow \Lambda p \pi^-$
- Virtual state: $\Lambda\Lambda$ threshold effect
- Resonance: Breit-Wigner peak in the $\Lambda\Lambda$ mass spectrum

**J-PARC-E42 EXPERIMENT**

1. in $(\Sigma^- p), \Lambda p \pi^-, \Lambda\Lambda$ and $\Xi^- p$ channels
2. by tagging the $S = -2$ system production
3. via $(K^-, K^+)$ reactions at 1.7 GeV/c with a diamond target.
4. Hyperon Spectrometer: 1 MeV $\Lambda\Lambda$ mass resolution!
The J-PARC E42 Collaboration


1 Korea University / Korea Research Institute of Standards and Science / Institute for Basic Science / Seoul National University, Korea
2 Japan Atomic Energy Agency (JAEA) / High Energy Accelerator Research Organization (KEK) / RCNP, Osaka University / Kyoto University / Gifu University / Tohoku University / Osaka University, Japan
3 Ohio University / University of New Mexico / Florida International University, USA
4 University of Saskatchewan, Canada
The Hyperon spectrometer consists of a time projection chamber (HypTPC) and the superconducting Helmholtz magnet.
Superconducting Dipole Magnet

- Helmholtz-type dipole magnet<sup>a</sup>
- $B$ field at center: 1.5 T (1.0 T for E42)
- Conduction cooling with two GM refrigerators
- Field uniformity $B_r/B_y < 1\%$ over the inner volume ($\phi = 500$ mm)

<sup>a</sup>KR-tech, Daegu, Korea
Octagonal prism field cage and a readout chamber consisting of a gating-grid, a triple GEM layer and a concentric pad plane (5768 pads).
HypTPC Structure

- Four GEM (250 × 250 mm$^2$) sheets per layer
- Triple GEM layers (100 μm (top) + 50 μm + 50 μm)
- Gain ~ $10^4$
- 10 inner pad rows with 2.1-2.7 × 9 mm$^2$.
- 22 outer pad rows with 2.3-2.4 × 12.5 mm$^2$.
- Position resolution < 300 μm
- $\Delta p/p = 1-3\%$ for π and p.
Inside the HypTPC

- A target holder structure for a diamond target, field strips for keeping uniform electric field.
Proton Beam Test at HIMAC
S.H. Kim, Development of the Hyperon Spectrometer for Hadron Physics Experiments at J-PARC, Poster Presentation, June 27.
### Yield Estimate

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$ beam</td>
<td>$6 \times 10^5$ $K^-$/spill (5.5 s)</td>
</tr>
<tr>
<td>Target length</td>
<td>20 mm</td>
</tr>
<tr>
<td>Number of nuclei</td>
<td>$2.65 \times 10^{23}$/cm$^2$</td>
</tr>
<tr>
<td>$d\sigma/d\Omega_C^{\Lambda\Lambda}$</td>
<td>$7.6 , \mu$b/sr</td>
</tr>
<tr>
<td>$\Delta\Omega(K^+)$</td>
<td>0.16 sr</td>
</tr>
<tr>
<td>$\text{Br}(\Lambda \to p\pi^-)^2$</td>
<td>0.41</td>
</tr>
<tr>
<td>$K^+$ Reconstruction</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Lambda\Lambda$ Reconstruction</td>
<td>$0.4 - 0.6$</td>
</tr>
<tr>
<td>Yield</td>
<td>0.03 event / spill</td>
</tr>
</tbody>
</table>

- $1.5 \times 10^4$ $\Lambda\Lambda$ events for 100 shifts at the current beam power.
ΛΛ Mass Distribution from KEK-E522

Scintillating Fiber Target: 5 MeV ΛΛ mass resolution!

E522 data

1.0 μb/sr ($\Gamma_H=0$)

Smeared with $\sigma=5$ MeV

INC calculation results based on Ref (Y. Nara et al, NPA 614 (1997) 433)
Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$ \(^9\)

Simulated $\Xi^- p$ Spectrum for $H(2265)$ \(^{10}\)

Simulated $\Xi^- p$ Spectrum for $H(2265)$ assuming $d\sigma/d\Omega = 0.3 \ \mu b/sr.$

\(^{10}\)Blue spectrum shows a phase-space distribution without $\Xi^- p$ final-state interactions.
Simulated $\Lambda p \pi^-$ Spectrum for $H(2200)$

- $\Lambda p \pi^-$ decays are almost free from background in $(K^-, K^+)$ reaction at 1.8 GeV/$c$. 
Anticipated Timeline for E42

2018

June

Proton Beam Test of HypTPC at HIMAC

Jul

HypTPC Test with the Magnet

Nov

Installation of Hyperon Spectrometer

2019

Commissioning of Hyperon Spectrometer

E42 Physics Run

2020

E42 Physics Run
**S = −2 Dibaryons in Particle Data Book (1982)**

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**S = −2 DIBARYON**

**Status:** *

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108 BARYON NUMBER 2, STRANGENESS −2 STATES

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**IN THIS SECTION WE USE THE FOLLOWING ABBREVIATIONS FOR MEASURED QUANTITIES**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLIM</td>
<td>LAMBDA–LAMBDA INVARIANT MASS</td>
</tr>
<tr>
<td>LLPI</td>
<td>LAMBDA–LAMBDA–PI INVARIANT MASS</td>
</tr>
<tr>
<td>XPIM</td>
<td>XI–P INVARIANT MASS</td>
</tr>
</tbody>
</table>

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**108 B = 2, S = −2 -- MASS (MEV)**

<table>
<thead>
<tr>
<th>M</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(2367.0)</td>
<td>(2365.3)</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td>(9.6)</td>
</tr>
</tbody>
</table>

- Beillerie 72 LLIM Q=0 GAUSSIAN FIT
- Shahbazia 73 LLIM Q=0
- Goyal 80 XPIM Q=0
- Shahbazia 82 LPPI Q=1

**M M A K– D TO XI– P K0.**

**M M B N P TO LAMBDA LAMBDA X AND PI– P TO LAMBDA LAMBDA X FOR P IN C12.**

**M M C Goyal 80 also sees a shoulder at 2360 MEV.**

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**108 B = 2, S = 0 -- WIDTH (MEV)**

<table>
<thead>
<tr>
<th>W</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(15.0)</td>
<td>(47.0)</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td>(15.7)</td>
</tr>
</tbody>
</table>

- Beillerie 72 LLIM Q=0 GAUSSIAN FIT
- Shahbazia 73 LLIM Q=0

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1. *H*-dibaryon search in $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels.

2. Cascade **weak decays** from $\Xi$-hypernuclei (Charged pions and protons can be reconstructed).

3. $\Xi^- p$ or $\Xi^-^{12} C$ **scattering** from a laminated target.

- E45 looks for missing baryon resonances in $\pi\pi N$ channels.
- E72 looks for $\Lambda(1665)$ near $\eta\Lambda$ threshold.\(^{11}\)
- Study of $\Xi^*$ resonances is viable in the $K^- p \rightarrow \Lambda K^- K^+$ reaction.

\(^{11}\)K. Tanida, in Session B2
We welcome you to join us on the journey for hunting the H-dibaryon (E42) with the HypTPC at J-PARC.