Search for $\Lambda\Lambda$ and $\Xi^{-}p$ Exotic Dibaryon States in the $^{12}C(K^{-},K^{+})$ reaction

J-PARC E42

Jung Keun Ahn (Korea University)

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hanul Hadron & Nuclear Physics Lab

Introduction

Multiquark Hadrons

- The existence of multiquark hadrons is now firmly established in the meson sector.
- Belle has shown proof for several meson+meson ("4-quark") tetraquarks.
- LHCb has shown proof for meson+baryon ("5-quark") pentaquarks.
- The existence of baryon+baryon ("6-quark") dibaryons is predicted by theory.

Perhaps a Stable Dihyperon

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Perhaps a Stable Dihyperon*

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(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

- MIT bag model predicts di-hyperon state (H) with

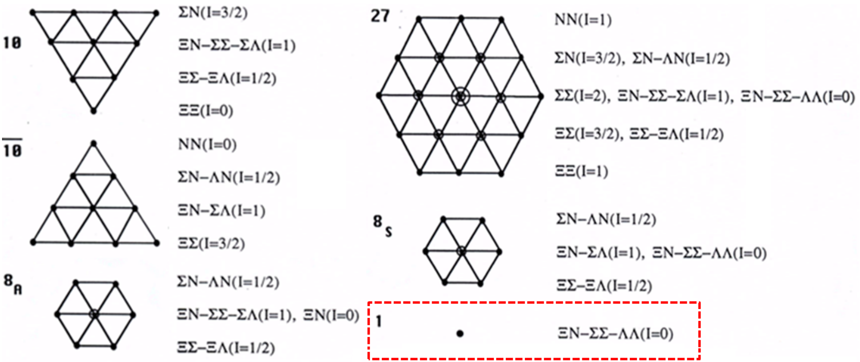
$$I = 0, \quad S = -2, \quad J^p = 0^+$$

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

- H^* with $J^p = 1^+$ appears as a 2335-MeV bump in $\Lambda\Lambda$ mass distribution.

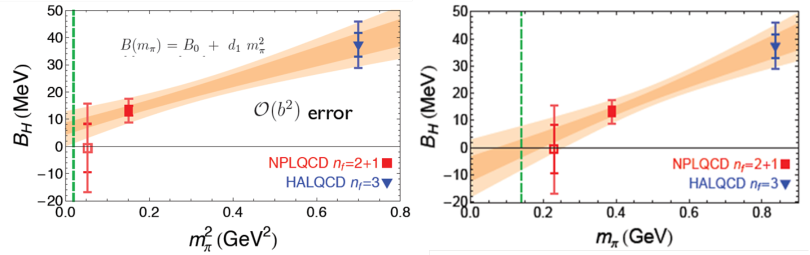
H-Dibaryon (Hexaquark State)

- A stable $SU(3)_f$ singlet hexaquark state consisting of $uuddss$ quarks due to QCD color magnetic force : H-Dibaryon.



H-Dibaryon from Lattice QCD in 2011[1]

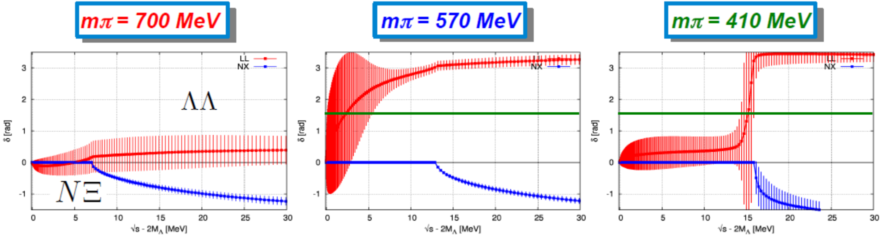
- Recent LQCD calculations seem to point to a weekly bound H or resonant state although we have got to wait for definite results with physical quark masses.



[1]HAL Collab., PRL 106 (2011)/ NPLQCD Collab. PRL 106 (2011)/ Shanahan, Thomas, Young, PRL 107 (2011)

H-Dibaryon from Lattice QCD[2]

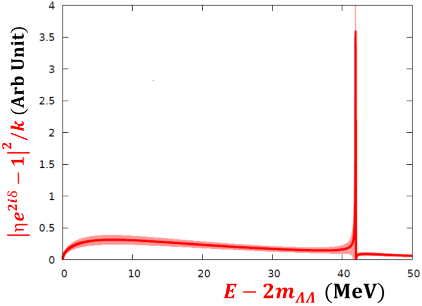
- Lattice QCD calculations predict the H appears closer to $N\Xi$ mass threshold with physical quark masses, yielding a bound $N\Xi$ system at m_π = 410 MeV.

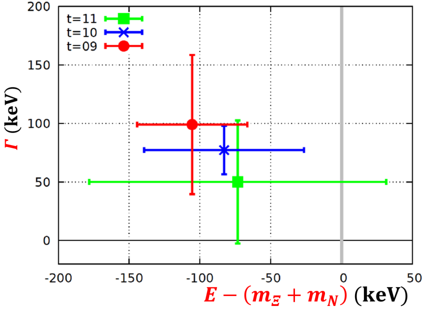


[2]S. Aoki (HAL Collab.), Nuclear Physics from Lattice QCD, March 21-May 27, 2016.

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 [3]





- Deuteron-like $N\Xi$ bound system from ESC model.[4]

[3] K. Sasaki for the HAL Collab., Reimei 2016, Inha (2016).

[4] Y. Yamamoto, NSMAT2016

Baryon-Baryon System [5]

- The flavor-singlet two-baryon state:

$$|H\rangle \approx \frac{\mathscr{A}}{\sqrt{8}}\Big(|\Lambda\Lambda\rangle + \sqrt{4}|N\Xi\rangle - \sqrt{3}|\Sigma\Sigma\rangle\Big),$$

  where $\mathscr{A}$ is the antisymmetrization operator for the six quarks.
- H couples most strongly to $N\Xi$ and that a $N\Xi$ bound state will appear in the $\Lambda\Lambda$ spectrum as a sharp resonance state.

[5] M. Oka, *QCD analysis of the H-dibaryon* arXiv:hep9510354v1 (1995).

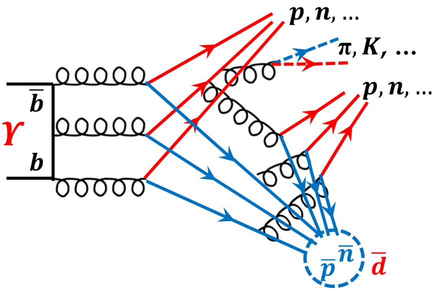
Experimental Review

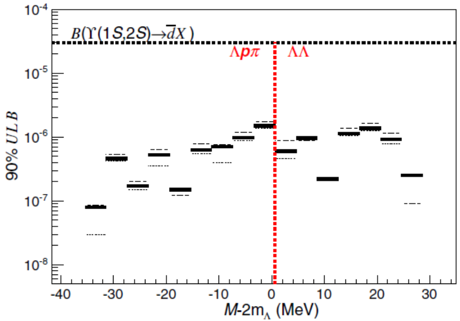
40 Year History since the H-Dibaryon Prediction

- 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 $^{6}_{\Lambda\Lambda}$He (E373)
- 1998,2007 — Enhanced $\Lambda\Lambda$ production near threshold was
- reported from E224 and E522 at KEK-PS.
- 2013-2015 — No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$
- in high-energy e^+e^-, pp and AA experiments
- 2011 — LQCD calculations predict the H-dibaryon
- to appear near (just above) threshold
- Present — **J-PARC E42 under preparation**

H-Dibaryon Search at Belle [6]

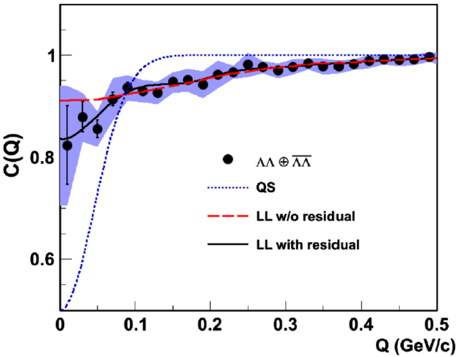
- The Belle searched for the H-dibaryon in Υ decays ($\mathrm{Br}(\Upsilon \to HX)/\mathrm{Br}(\Upsilon \to \bar{d}X) < 10^{-2}$).
- Six-quarks should be produced and correlated to form the H-dibaryon from nothing in the intial state.

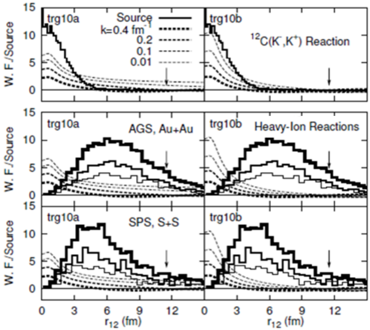




[6]B.H. Kim et al., Phys. Rev. Lett. 110 (2013)

$\Lambda\Lambda$: Recent Results from STAR [7]





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

[7] STAR Collab., Phys. Rev. Lett. 114, 022301 (2015); A. Ohnishi, HHI (2012).

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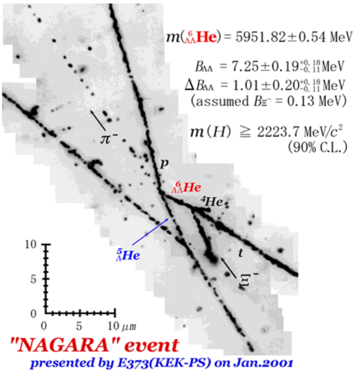
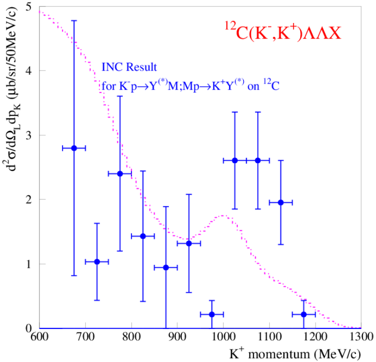
Double-Λ Hypernuclei and ΛΛ Production





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

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

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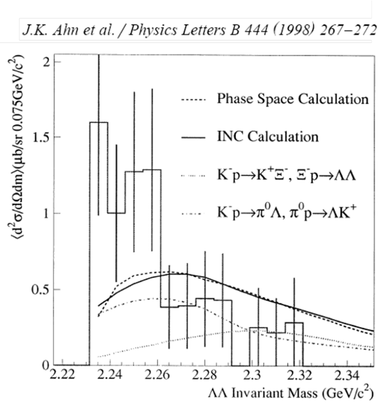
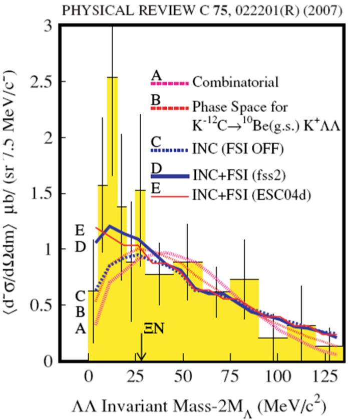
H-Dibaryon as a ΛΛ Resonance?





- Indications to the enhanced ΛΛ production from KEK-PS E224 and E522 beyond prediction from INC calculations.[8]

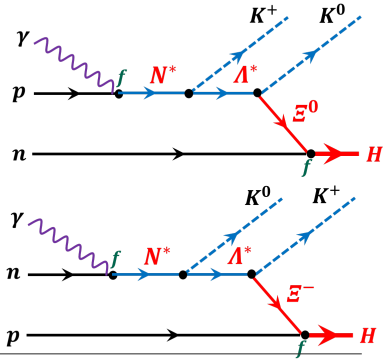
[8] Y. Nara *et al.*, Nucl. Phys. A614 (1997) 433.

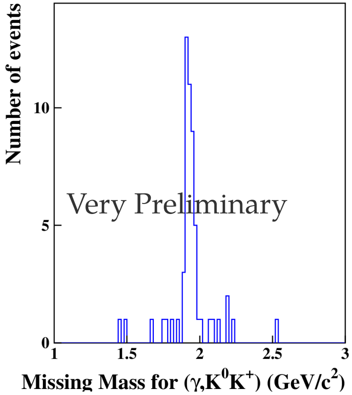
Hunting the H-Dibaryon...

1. H search in (K^-, K^+) reactions from J-PARC E42.
2. Long-lived H search in the $H \to \Lambda n \pi^0$ decay at J-PARC E14 (KOTO).
3. H search in the $\gamma d \to K^+ K^0 H$ reaction at SPring-8 ($E_\gamma^{\mathrm{th}} = 1.83$ GeV for $m_H = 2m_\Lambda$).
4. H search in QCD vacuum and gluons from Upsilon decays at Belle-II.

H-Dibaryon Search from Photoproduction [9]

- H-dibaryon search from SPring-8 ($E_\gamma^{th} = 1.83$ GeV for $m_H = 2m_\Lambda$). $\gamma d \to K^+ K^0 H$ followed by $K^0 \to \pi^+\pi^-$.
- $\gamma p \to K^+ \overline{K}^0 n$ $(a_0^+ \to K^+ \overline{K}^0)$; $\gamma n \not\to K^+ \overline{K}^0 X$





[9] LEPS Collaboration, SPring-8

J-PARC E42

H-Dibaryon Search at J-PARC : E42

The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

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

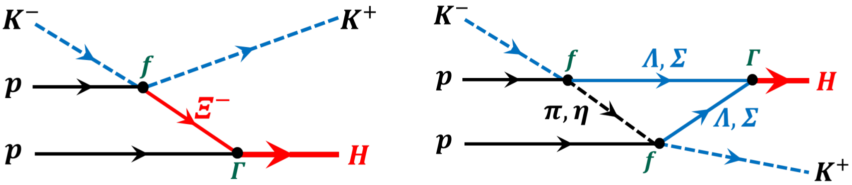
J-PARC-E42 EXPERIMENT

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!

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

$$K^- + (pp)^1S_0 \rightarrow K^+ + (\Xi^- p)^1S_0 \rightarrow K^+ + H(J^\pi = 0^+)$$

- Possible H production processes on a diproton pair via the (K^-, K^+) reaction[10] [11] :



[10] N. Aizawa and M. Hirata, Z. Phys. A 343, 103 (1992)

[11] A.T.M. Aerts and C.B. Dover, Phys. Rev. D28, 450 (1983)

The J-PARC E42 Collaboration

J.K. Ahn (*spokesperson*), W.J. Choi, W.S. Jung, S.H. Kim, M.H. Kim, Y.J. Kim, J.W. Lee, Y. Han, S. Hasegawa, R. Honda, Y. Ichikawa, K. Imai (*co-spokesperson*), H. Sako, S. Sato, H. Sugimura, K. Tanida, M. Ieiri, R. Kiuchi, M. Naruki, K. Ozawa, H. Takahashi, T. Takahashi, S.H. Hwang, S.H. Kim, H.S. Lee, S.Y. Ryu, K. Shirotori, H. Ekawa, H. Fujioka, M. Niiyama, T.J. Moon, J.Y. Lee, S. Kinbara, K. Nakazawa, M. Sumihama, J. Yoshida, B. Bassalleck, K. Hicks, C. Rangacharyulu, L. Guo, K. Miwa, S. Hayakawa, Y. Nakada

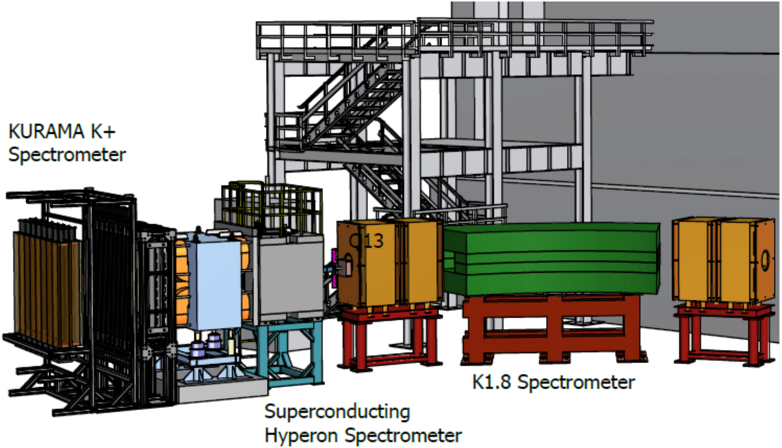
[1] *Korea University / Korea Research Institute of Standards and Science / Institute for Basic Science / Seoul National University, Korea*

[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*

Hyperon Spectrometer at K1.8 Beam Line of J-PARC



- The Hyperon spectrometer consists of a time projection chamber (HypTPC) and the superconducting Helmholtz magnet.

Superconducting Dipole Magnet

- Helmholtz-type dipole magnet[a]
- 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)

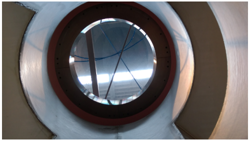
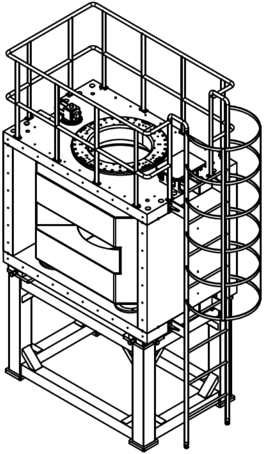


Photo of inner volume ($\phi = 800$ mm)

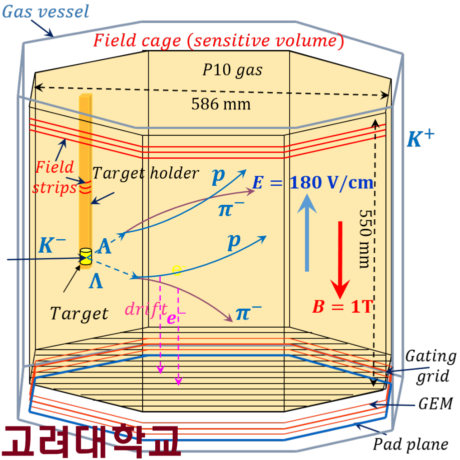
Photo of the Helmholtz magnet for field measurement

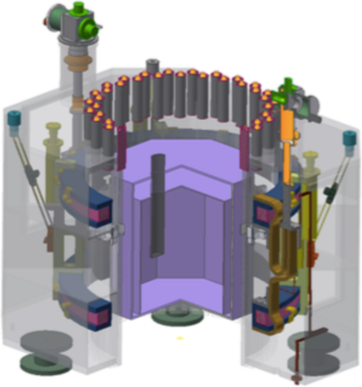


[a] KR-tech, Daegu, Korea

Time Projection Chamber

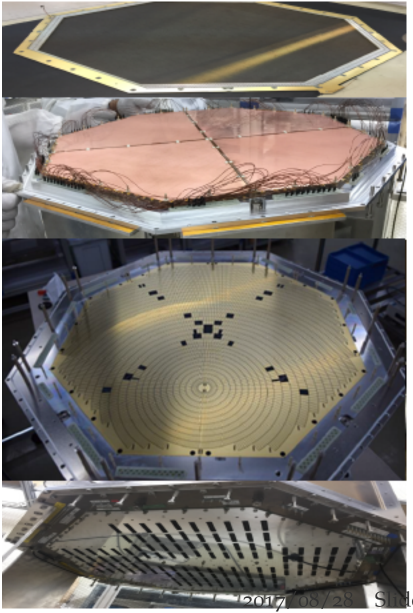
- Octagonal prism field cage and a readout chamber consisting of a gating-grid, a triple GEM layer and a concentric pad plane (5768 pads)





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.



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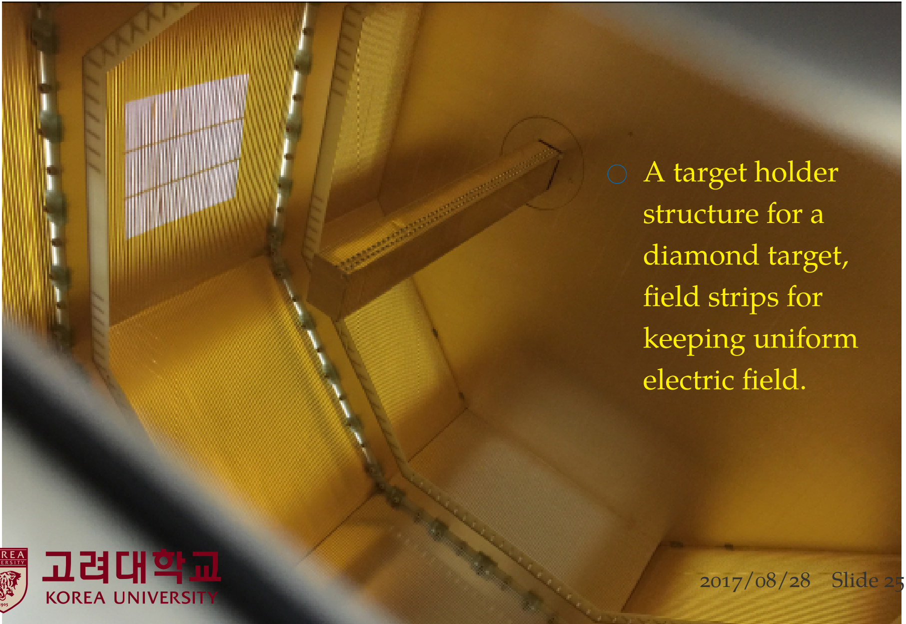
Inside the HypTPC



- A target holder structure for a diamond target, field strips for keeping uniform electric field.

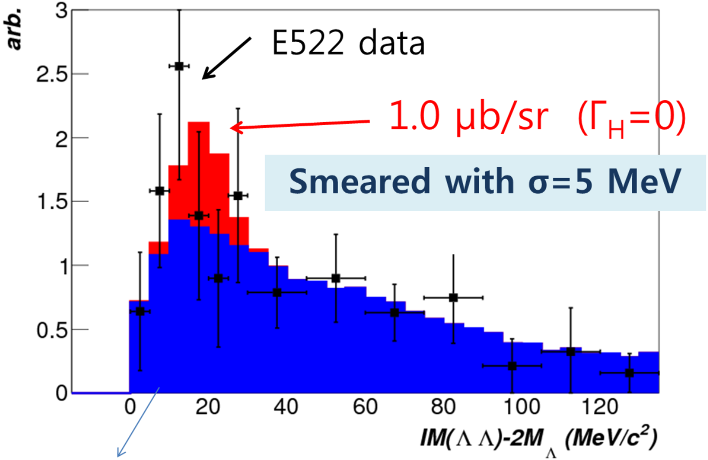
Yield Estimate

Parameters	Value
K^- beam	6×10^5 K^-/ spill (5.5 s)
Target length	20 mm
Number of nuclei	$2.65 \times 10^{23}/\mathrm{cm}^2$
$d\sigma/d\Omega_L^C(\Lambda\Lambda)$	7.6 μb/sr
$\Delta\Omega(K^+)$	0.16 sr
$\mathrm{Br}(\Lambda \to p\pi^-)^2$	0.41
K^+ Reconstruction	0.5
$\Lambda\Lambda$ Reconstruction	0.4 – 0.6
Yield	0.03 event / spill

- 1.5×10^4 $\Lambda\Lambda$ events for 100 shifts at the current beam power.

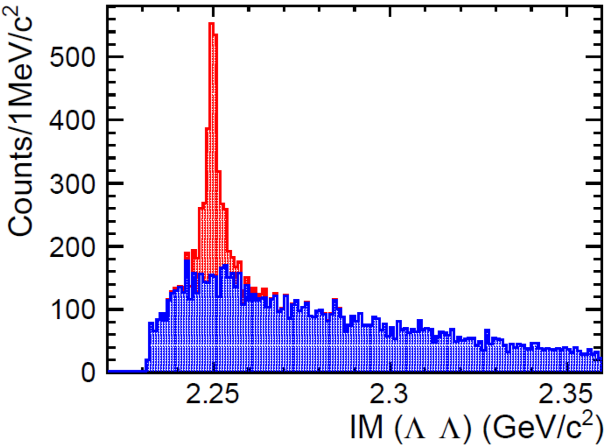
ΛΛ Mass Distribution from KEK-E522

Scintillating Fiber Target : 5 MeV ΛΛ mass resolution!



INC calculation results based on Ref (Y. Nara et al, NPA 614 (1997) 433)

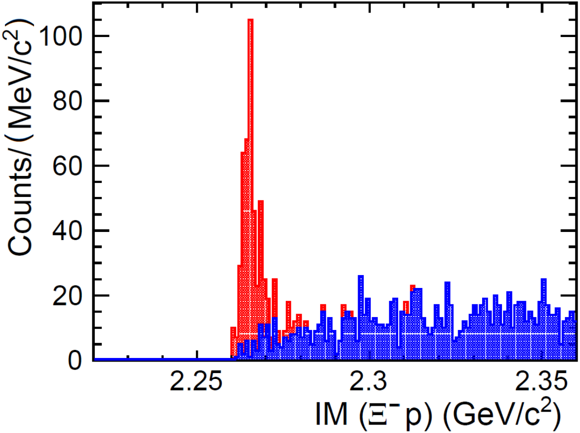
Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$ [12]



Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$ assuming $d\sigma/d\Omega = 1.0\ \mu\text{b/sr}$.

[12] Simulation on two-step processes is based on INC calculation by Y. Nara, A. Ohnishi, T. Harada and A. Engel, Nucl. Phys. A614 (1997) 433.

Simulated $\Xi^- p$ Spectrum for $H(2265)$ [13]



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

[13] Blue spectrum shows a phase-space distribution without $\Xi^- p$ final-state interactions.

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Proposed Timeline for E42

2017	Sep	Superconducting Magnet Tests
	Nov	HypTPC Test with the Magnet
2018	Feb	Proton Beam Test of HypTPC at HIMAC
	Nov	Installation of Hyperon Spectrometer
2019		
	April	Commissioning of Hyperon Spectrometer
....	.....	....
		E42 Physics Run

E42 Physics

1. *H*-dibaryon search in $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels.
2. $\Lambda\Lambda$ production cross sections from $^{12}\mathrm{C}(K^-, K^+)$ reaction (Lineshape analysis for $\Lambda\Lambda - \Xi^- p$ interaction).
3. Cascade weak decays from Ξ-hypernuclei (Charged pions and protons can be reconstructed).
4. $\Xi^- p$ or $\Xi^{-12}\mathrm{C}$ scattering from a laminated target.

- E45 looks for missing baryon resonances in $\pi\pi N$ channels.
- Study of Ξ^* resonances is viable in the $K^- p \rightarrow \Lambda K^- K^+$ reaction.

$S = -2$ Dibaryons in Particle Data Book (1982)

S=−2 DIBARYON Status: *

108 BARYON NUMBER 2, STRANGENESS -2 STATES

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

LLIM	LAMBDA-LAMBDA INVARIANT MASS
LLPI	LAMBDA-LAMBDA-PI INVARIANT MASS
XPIM	XI-P INVARIANT MASS

108 B=2, S=-2 -- MASS (MEV)

M	A	(2367.0)	(4.0)	BEILLIERE 72 LLIM Q=0 GAUSSIAN FIT
M	B	(2365.3)	(9.6)	SHAHBAZIA 73 LLIM Q=0
M	C	(2480.0)		GOYAL 80 XPIM Q=0
M	B	(3568.3)		SHAHBAZIA 82 LPPI Q=1

M
M A K- D TO XI- P K0.
M B N P TO LAMBDA LAMBDA X AND PI- P TO LAMBDA LAMBDA X FOR P IN C12.
M C GOYAL 80 ALSO SEES A SHOULDER AT 2360 MEV.

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

W	A	(15.0)	(4.0)	BEILLIERE 72 LLIM Q=0 GAUSSIAN FIT
W	B	(47.0)	(15.7)	SHAHBAZIA 73 LLIM Q=0

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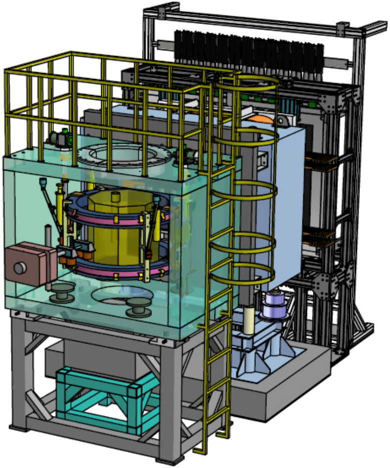
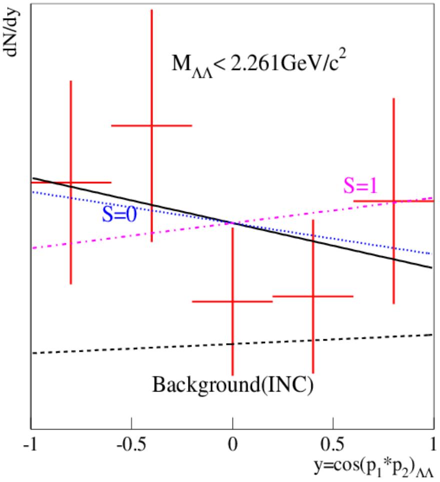
Summary

- We welcome you to join us on the journey for hunting the H-dibaryon (E42) and also for studying baryon resonances (E45) with the HypTPC at J-PARC.



Schematic view of the E42 setup

Spin Analysis



- Spin correlation measurement from E224:

$$\frac{dN}{d\cos\theta^*}\Big|_{S=0} = 1 - \alpha_\Lambda^2 \cdot \cos\theta^*$$

$$\frac{dN}{d\cos\theta^*}\Big|_{S=1} = 1 + \frac{1}{3}\alpha_\Lambda^2 \cdot \cos\theta^*,$$

where θ^* is the angle between the two decay protons in the $\Lambda\Lambda$ rest frame.