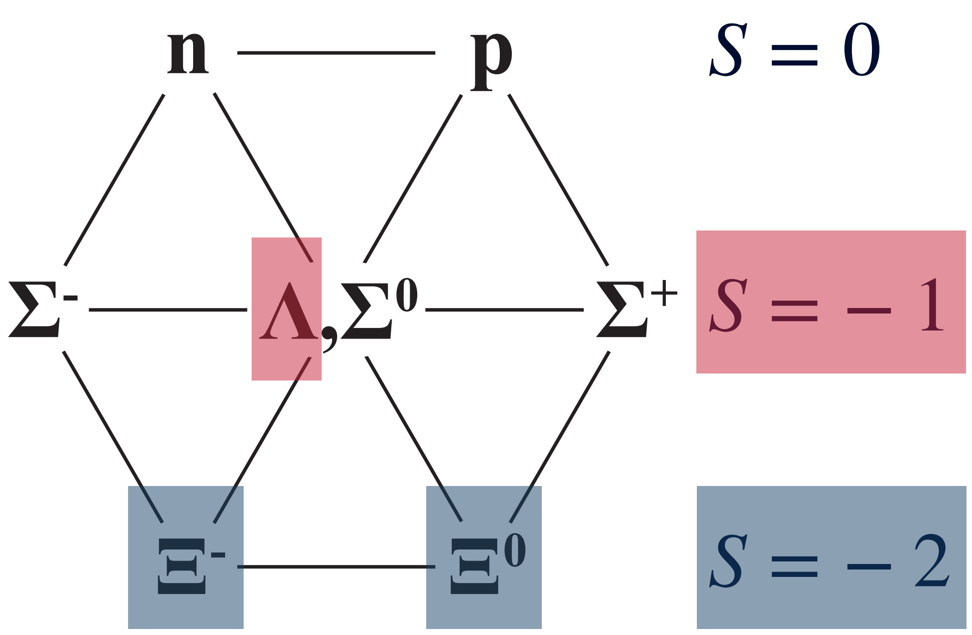
Decay Pion Spectroscopy of Double-Λ Hypernuclei at J-PARC

Hiroyuki Fujioka
(Tokyo Institute of Technology)

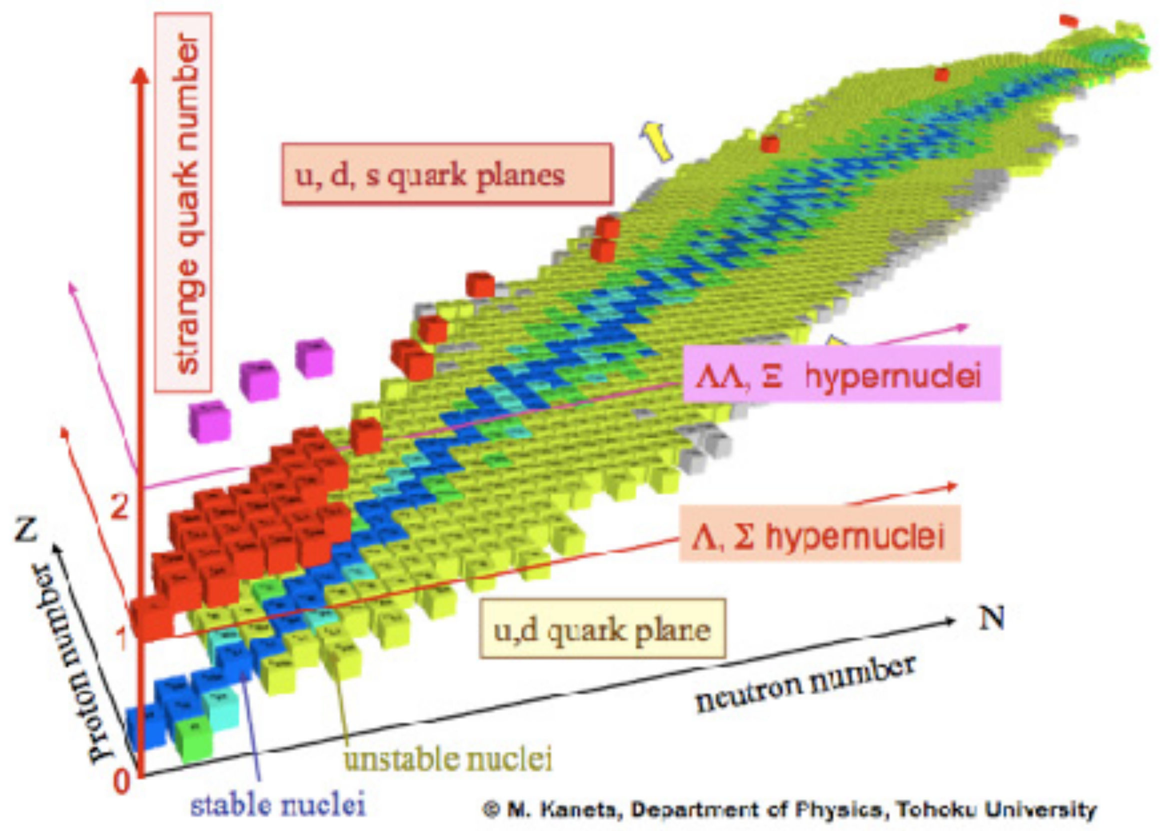
Hypernuclei with $S = -2$



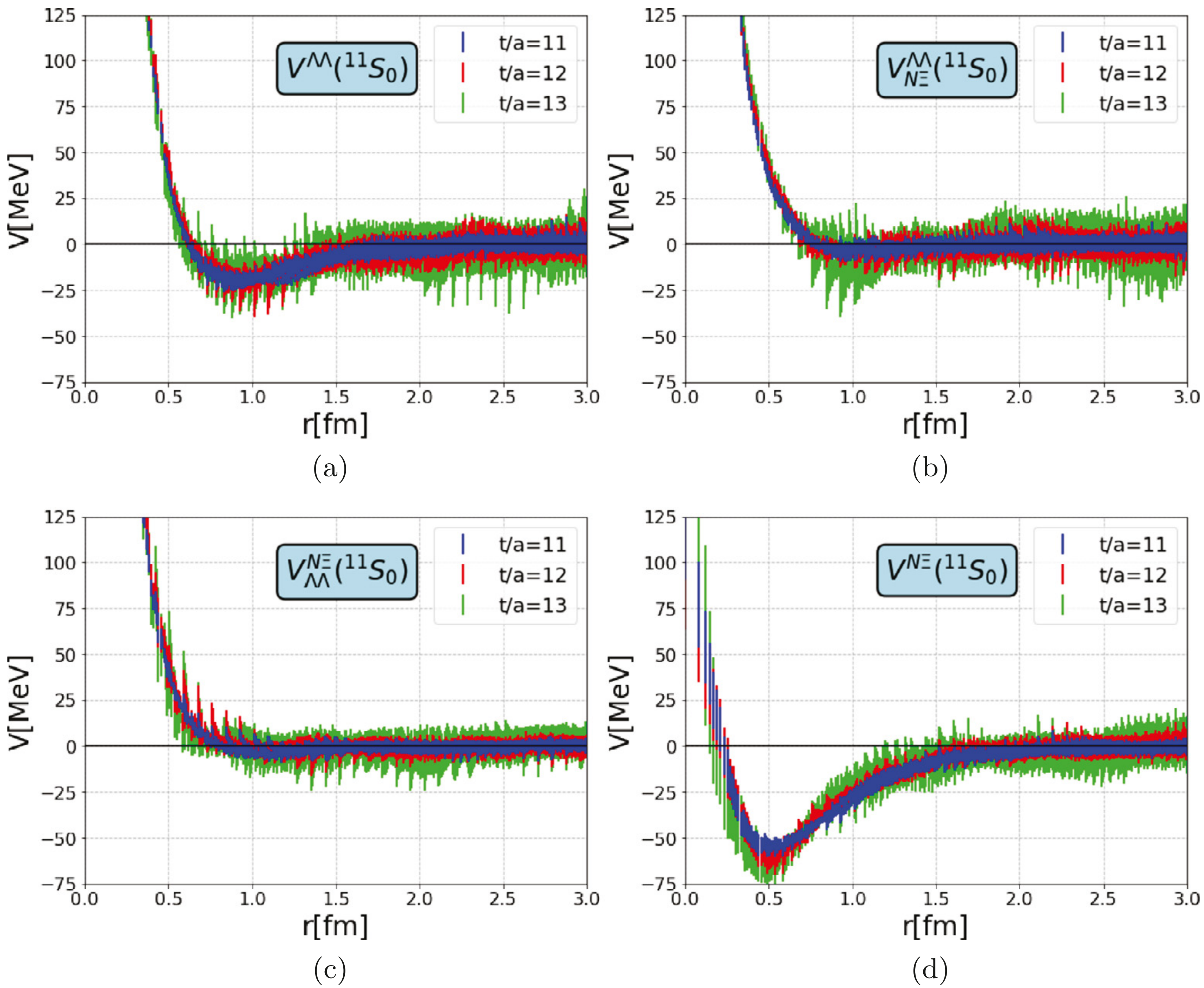
Double Λ Hypernuclei

Ξ Hypernuclei

Double Λ Hypernuclei are formed by $\Xi^- p \to \Lambda\Lambda$ conversion in nuclei, where a Ξ^- hyperon is produced in the $p(K^-, K^+)\Xi^-$ reaction.



ΛΛ, ΞN interaction



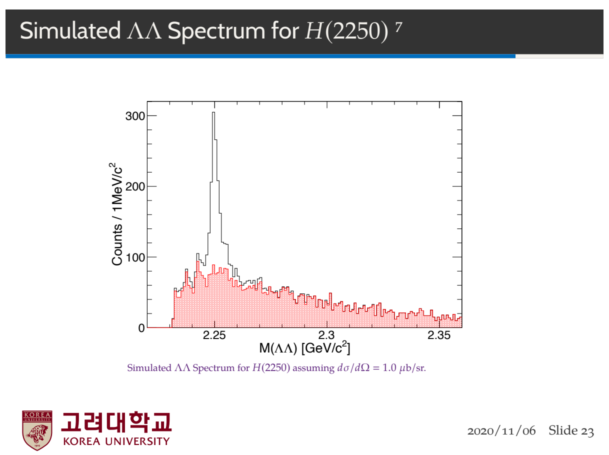
K. Sasaki et al. (HAL-QCD Collaboration) NPA 998 (2020) 121737

Study of ΞN, ΛΛ interaction

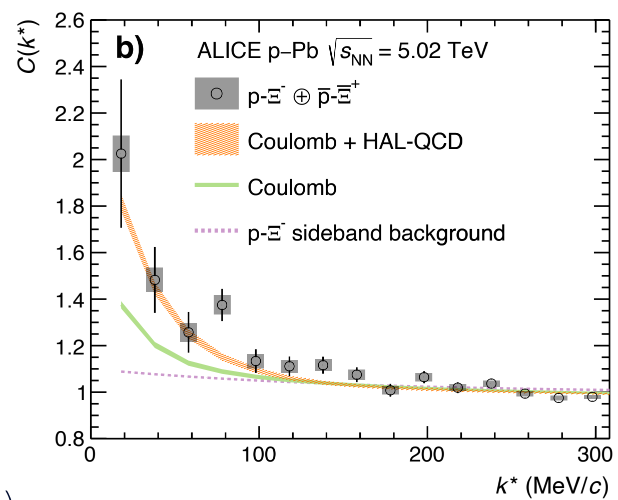
H-dibaryon

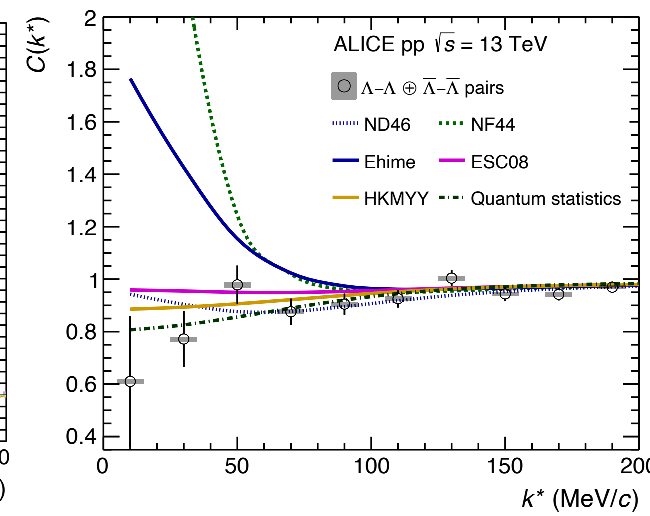
femtoscopy

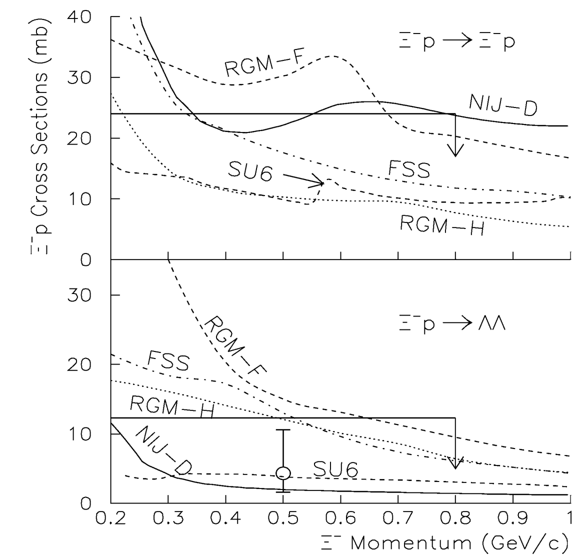
ΞN scattering



Ahn (J-PARC E42 Experiment)
http://apollo.lns.tohoku.ac.jp/workshop/c029/slides/ahn.pdf





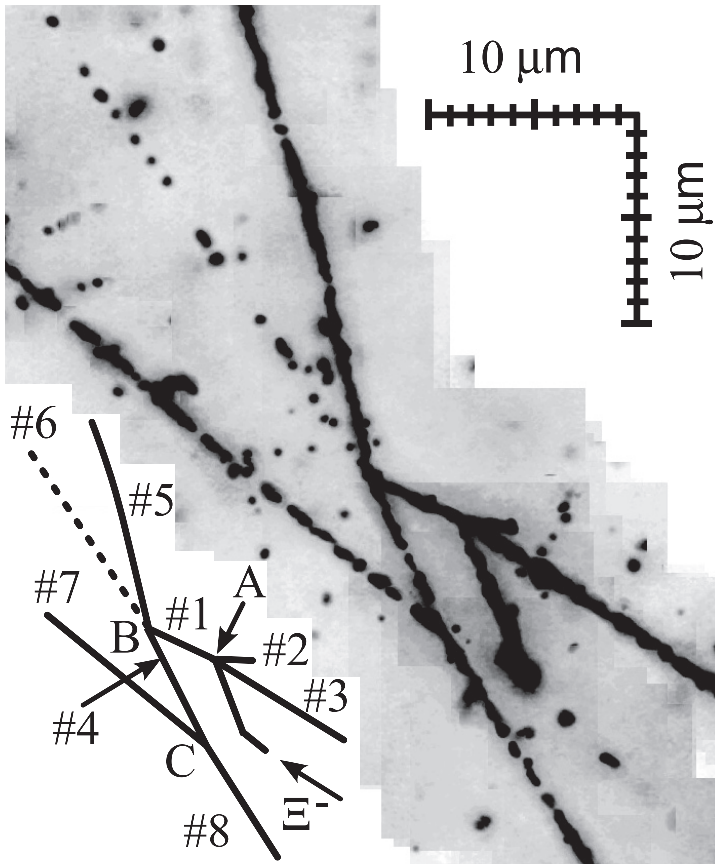


ALICE, PRL 123, 112002 (2019) ALICE, PLB 797, 134822 (2019) Ahn et al., PLB 633, 214 (2006)

Ξ Hypernuclei

Double-Λ Hypernuclei

Nagara event



captured from an atomic orbital of ^{12}C

$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$$ {}^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

$$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-} \pm 0.16\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-} \pm 0.17\,\mathrm{MeV}$$

tials. Moreover, the Ξ^- capture probability in ^{12}C from P states is a few percent at most. The most likely capture in ^{12}C, as discussed in Sec. III B, occurs from atomic D states.

C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C **59**, 295 (1999)

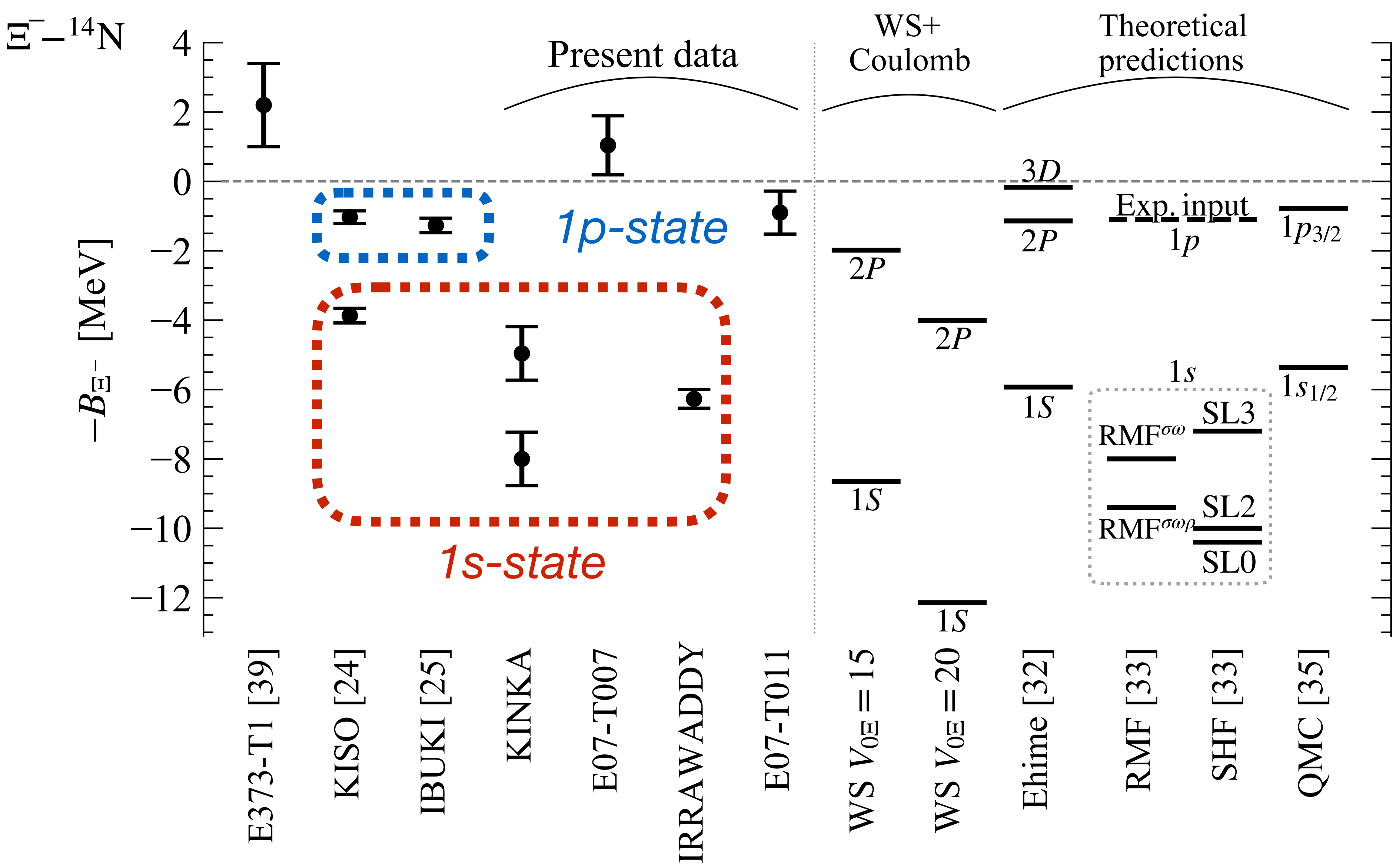
Assumption: $B_{\Xi^-}(3D) = 0.13\,\mathrm{MeV}$

$$B_{\Lambda\Lambda} = 6.91 \pm 0.16\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17\,\mathrm{MeV}$$

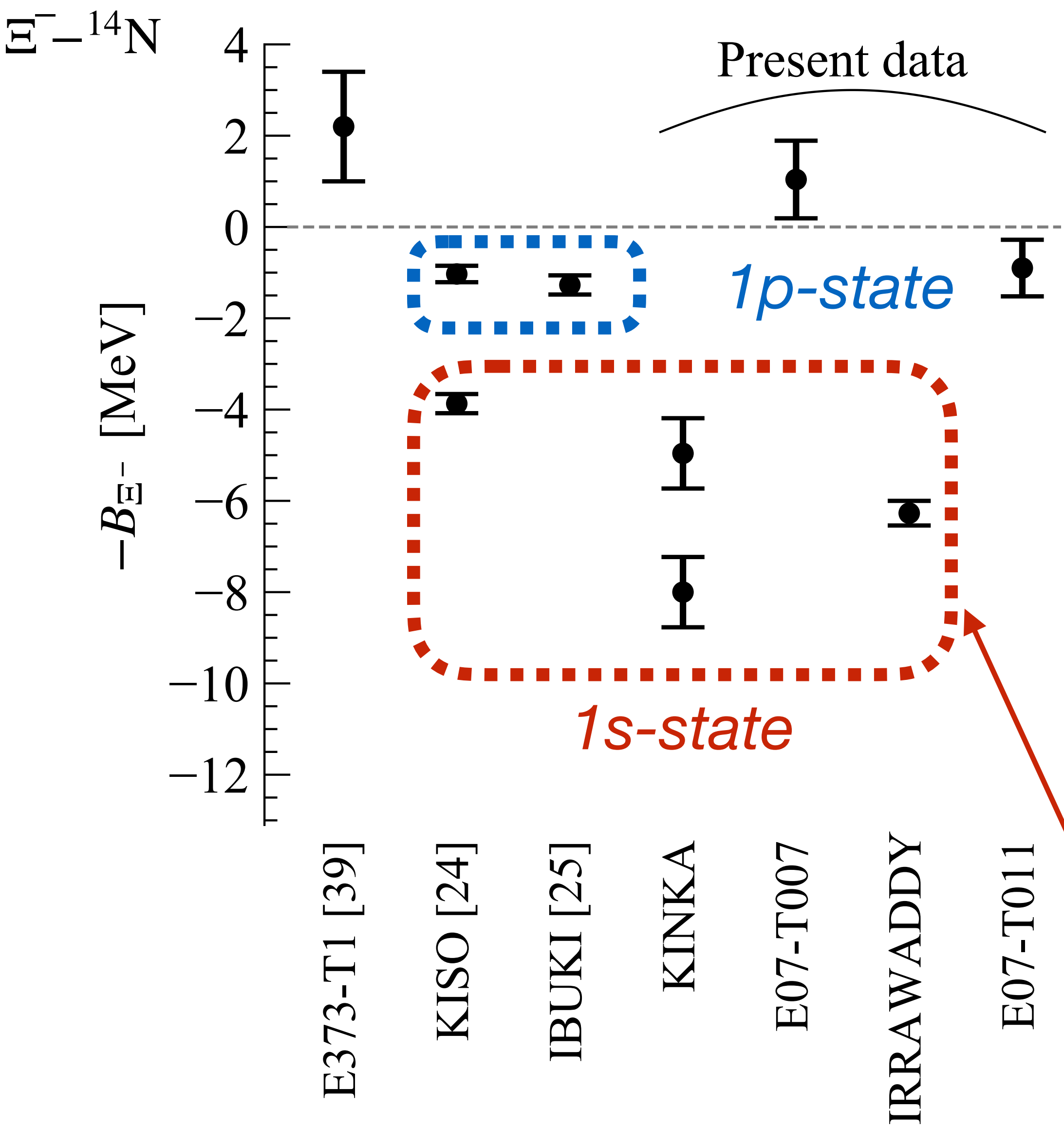
H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)

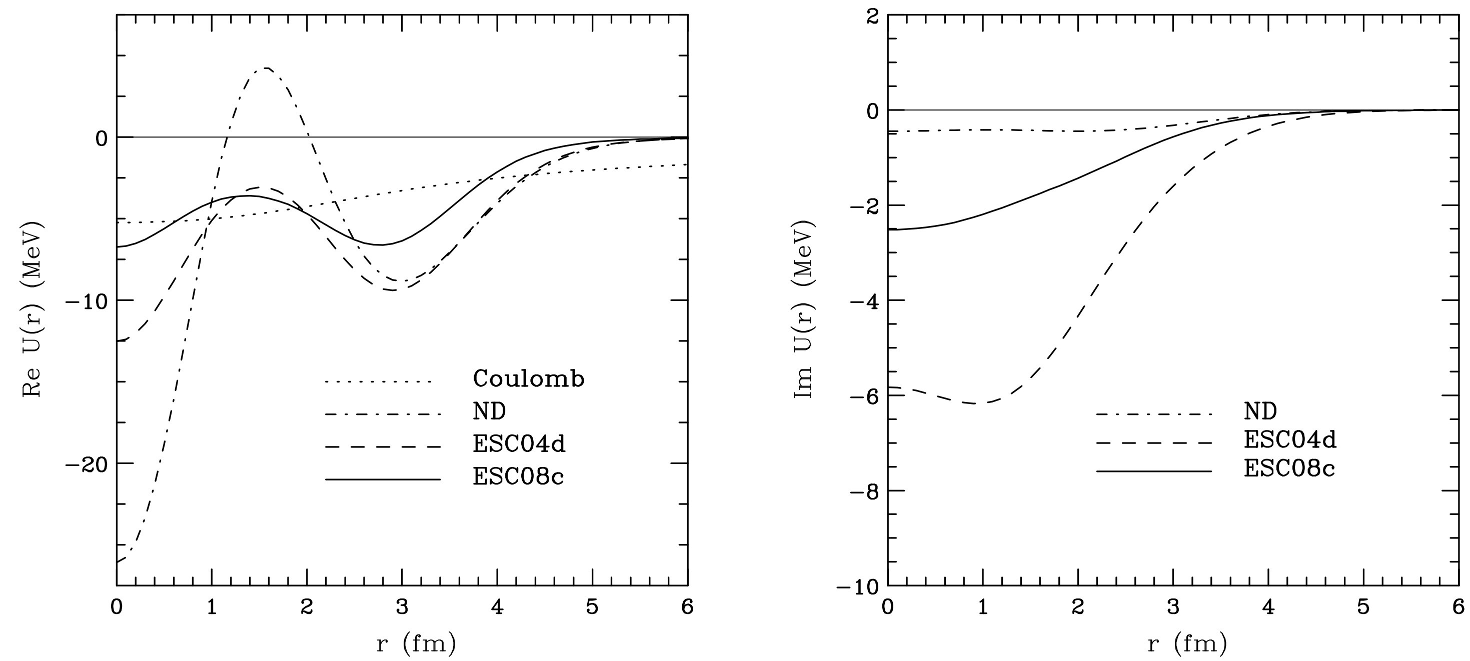
Ξ^--^{14}N system



arXiv:2103.08793

Ξ^--^{14}N system





inconsistent? Implying small |Im U(r)| …

Table II. The calculated Ξ^- nuclear absorption probability (in % per stopped Ξ^-) from each atomic state. The weak decay of Ξ^- during the cascade is 8.2% for any potentials.

state	ND	ESC04d	ESC08c	ESC08c-A	state	ND	ESC04d	ESC08c	ESC08c-A
1s	0.02	3×10^{-4}	1×10^{-4}	0.01	total s	0.07	0.04	0.06	0.06
2p	3.9	0.25	3.8	2.4	total p	5.7	0.88	5.7	4.0
3d	35.7	23.5	34.7	34.9	total d	67.1	47.9	65.3	65.3
4f	7.8	19.0	8.6	9.4	total f	18.9	42.9	20.8	22.5
5g	0.01	0.03	0.01	0.01	total g	0.03	0.10	0.04	0.04

arXiv:2103.08793

T. Koike, JPS Conf. Proc. 17, 033011 (2017)

A possible scenario

If a Ξ hyperon was absorbed at a deeper level,
$B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ might have been underestimated by an order of 1 MeV

Table 1 Current $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ data for double-Λ hypernuclear events[a]

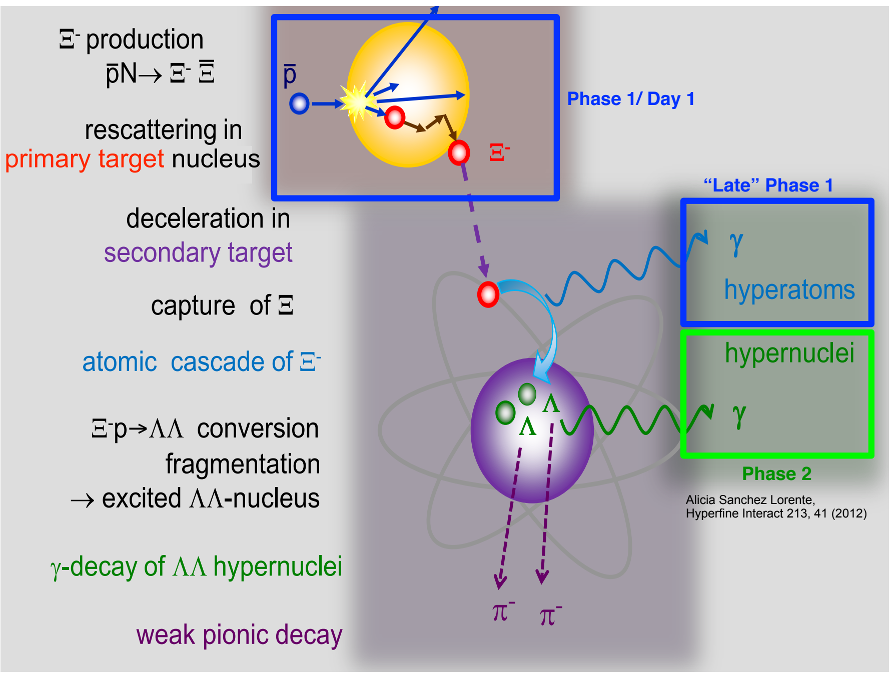
Event	$^{A}_{\Lambda\Lambda}Z$	Ξ^- hyperon captured by	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)	Comments
Nagara (33)	$^{6}_{\Lambda\Lambda}$He	$\Xi^- + {}^{12}$C (3D)	6.91 ± 0.16	0.67 ± 0.17	$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-} (\pm 0.16)$ $\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-} (\pm 0.17)$
Danysz et al. (45)	$^{10}_{\Lambda\Lambda}$Be	$\Xi^- + {}^{12}$C (–)	14.7 ± 0.4	1.3 ± 0.4	$^{10}_{\Lambda\Lambda}\text{Be} \rightarrow {}^{9}_{\Lambda}\text{Be}^* + p + \pi^-$
E176	$^{10}_{\Lambda\Lambda}$Be	$\Xi^- + {}^{14}$N (3D)	23.3 ± 0.7	0.6 ± 0.8	$^{13}_{\Lambda\Lambda}\text{B} \rightarrow {}^{13}_{\Lambda}\text{C}^* + \pi^-$
Demachi–Yanagi (33)	$^{10}_{\Lambda\Lambda}$Be*	$\Xi^- + {}^{12}$C (3D)	11.90 ± 0.13	-1.52 ± 0.15	By Danysz et al. $E_x \sim 2.8$ MeV
Hida (33)	$^{12}_{\Lambda\Lambda}$Be $^{11}_{\Lambda\Lambda}$Be	$\Xi^- + {}^{14}$N (3D) $\Xi^- + {}^{16}$O (3D)	22.48 ± 1.21 20.83 ± 1.27	 2.61 ± 1.34	
Mikage (33)	$^{6}_{\Lambda\Lambda}$He	$\Xi^- + {}^{12}$C (3D)	10.01 ± 1.71	3.77 ± 1.71	$^{6}_{\Lambda\Lambda}\text{He} \rightarrow {}^{3}_{\Lambda}\text{H} + p + 2n$
	$^{11}_{\Lambda\Lambda}$Be	$\Xi^- + {}^{12}$C (3D)	22.15 ± 2.94	3.95 ± 3.00	$^{11}_{\Lambda\Lambda}\text{Be} \rightarrow {}^{9}_{\Lambda}\text{Li} + p + n$
	$^{11}_{\Lambda\Lambda}$Be	$\Xi^- + {}^{14}$N (3D)	23.05 ± 2.59	4.85 ± 2.63	$^{11}_{\Lambda\Lambda}\text{Be} \rightarrow {}^{9}_{\Lambda}\text{Li} + p + n$

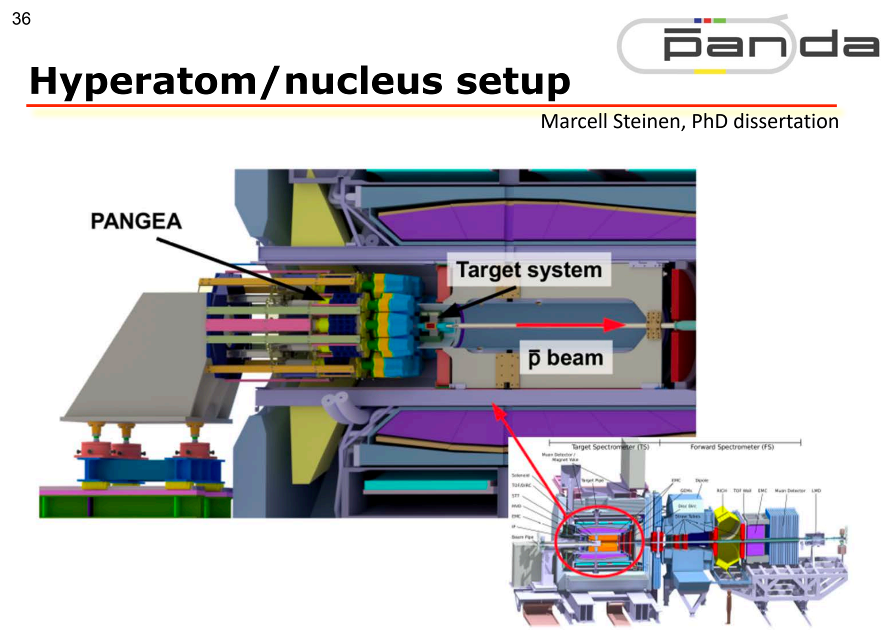
[a] Because the data were obtained with kinematics including the production process, B_{Ξ^-} values are assumed for each capture nuclei at the 3D level, except for the Danysz et al. data (50), which were independent of B_{Ξ^-} because the the analysis was made only on the decay process. For the Demachi–Yanagi event, if 2.8 MeV is used as the excitation energy (E_x) of $^{10}_{\Lambda\Lambda}$Be*, then the $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ data agree well with the Danysz et al. data. Note that the value of 2.8 MeV is similar to the value of 3.05 MeV for the E_x of the $^{9}_{\Lambda}$Be nucleus. Regarding the case of the $^{12}_{\Lambda\Lambda}$Be of the Hida event, the $\Delta B_{\Lambda\Lambda}$ value was not obtained, because there are no data for the B_{Λ} value of the $^{11}_{\Lambda\Lambda}$Be nucleus.

K. Nakazawa and E. Hiyama, Annu. Rev. Nucl. Part. Sci. 68, 131 (2018)

Projects in GSI/FAIR and HIAF

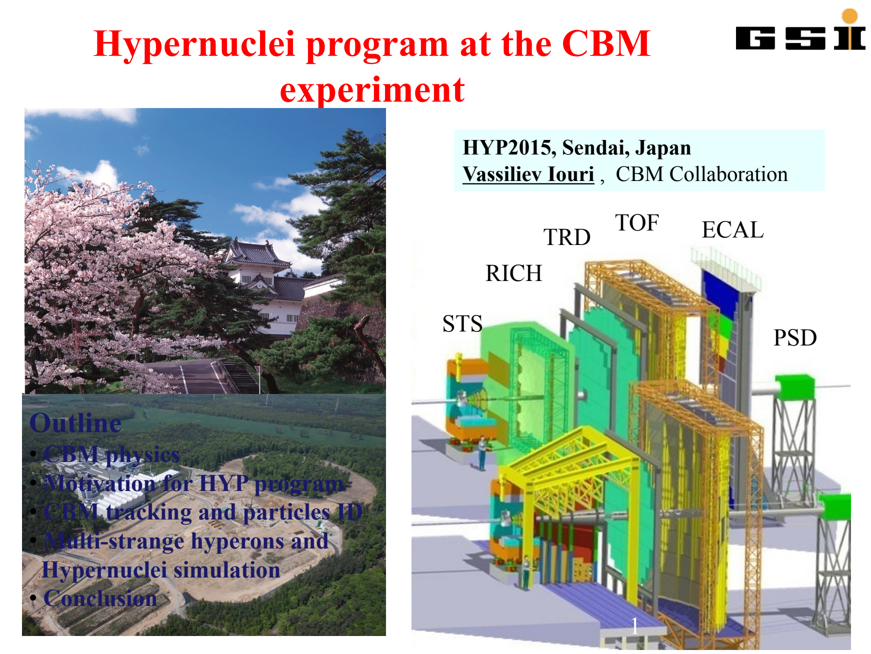
Ξ⁻ capture in a target nucleus
$\Rightarrow \Xi^{-}p \rightarrow \Lambda\Lambda$ conversion





J. Messchendorp's Seminar (last week)

Heavy-ion collision



I. Vassiliev, HYP2015

T.R. Saito HYP2018

Various new experiments (w/o using nuclear emulsion) will begin near future in FAIR, HIAF, and J-PARC.

Proposal for J-PARC 50 GeV Synchrotron

Decay Pion Spectroscopy of $^{5}_{\Lambda\Lambda}\mathrm{H}$ Produced by Ξ-hypernuclear Decay

Hiroyuki Fujioka[1*], Tomokazu Fukuda[2,3†], Toshiyuki Gogami[4], Emiko Hiyama[5,3‡], Yuhei Morino[6], Toshio Motoba[2,7], Tomofumi Nagae[4], Sho Nagao[8], Toshiyuki Takahashi[6], Atsushi O. Tokiyasu[9]

[1] *Department of Physics, Tokyo Institute of Technology*

[2] *Osaka Electro-Communication University*

[3] *RIKEN Nishina Center*

[4] *Department of Physics, Kyoto University*

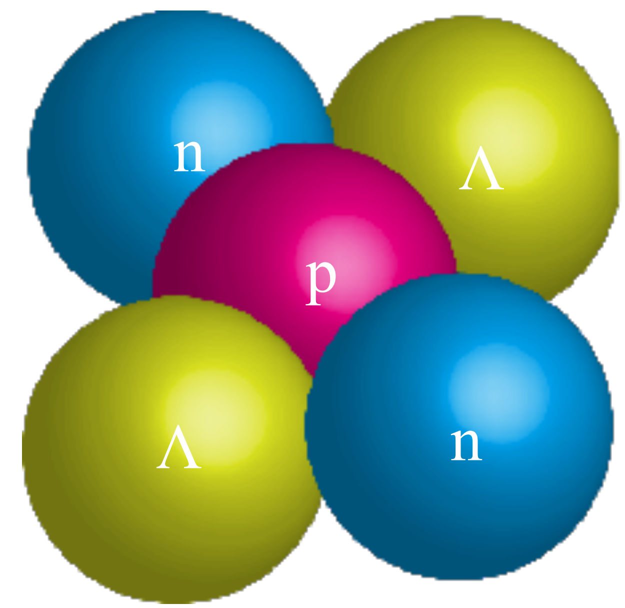
[5] *Department of Physics, Kyushu University*

[6] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization*

[7] *Yukawa Institute for Theoretical Physics, Kyoto University*

[8] *Institute for Excellence in Higher Education, Tohoku University*

[9] *Research Center for Electron Photon Science (ELPH), Tohoku University*



December 14, 2018

http://j-parc.jp/researcher/Hadron/en/pac_1901/pdf/P75_2019-09.pdf

Stage-1 approved

Phase-1 of the P75 experiment: Measurement of the formation cross section of $^{7}_{\Xi^-}\mathrm{H}$ in the $^{7}\mathrm{Li}(K^-, K^+)$ reaction

Shuhei Ajimura[1], Hiroyuki Fujioka[2*], Tomokazu Fukuda[3,4†], Toshiyuki Gogami[5], Emiko Hiyama[6,4‡], Yuhei Morino[7], Toshio Motoba[3,8], Tomofumi Nagae[5], Sho Nagao[9], Akane Sakaue[5], Toshiyuki Takahashi[7], Yosuke Taki[2], Atsushi O. Tokiyasu[10], Makoto Uchida[2], Masaru Yosoi[1]

[1] *Research Center for Nuclear Physics (RCNP), Osaka University*

[2] *Department of Physics, Tokyo Institute of Technology*

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[4] *RIKEN Nishina Center*

[5] *Department of Physics, Kyoto University*

[6] *Department of Physics, Kyushu University*

[7] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization*

[8] *Yukawa Institute for Theoretical Physics, Kyoto University*

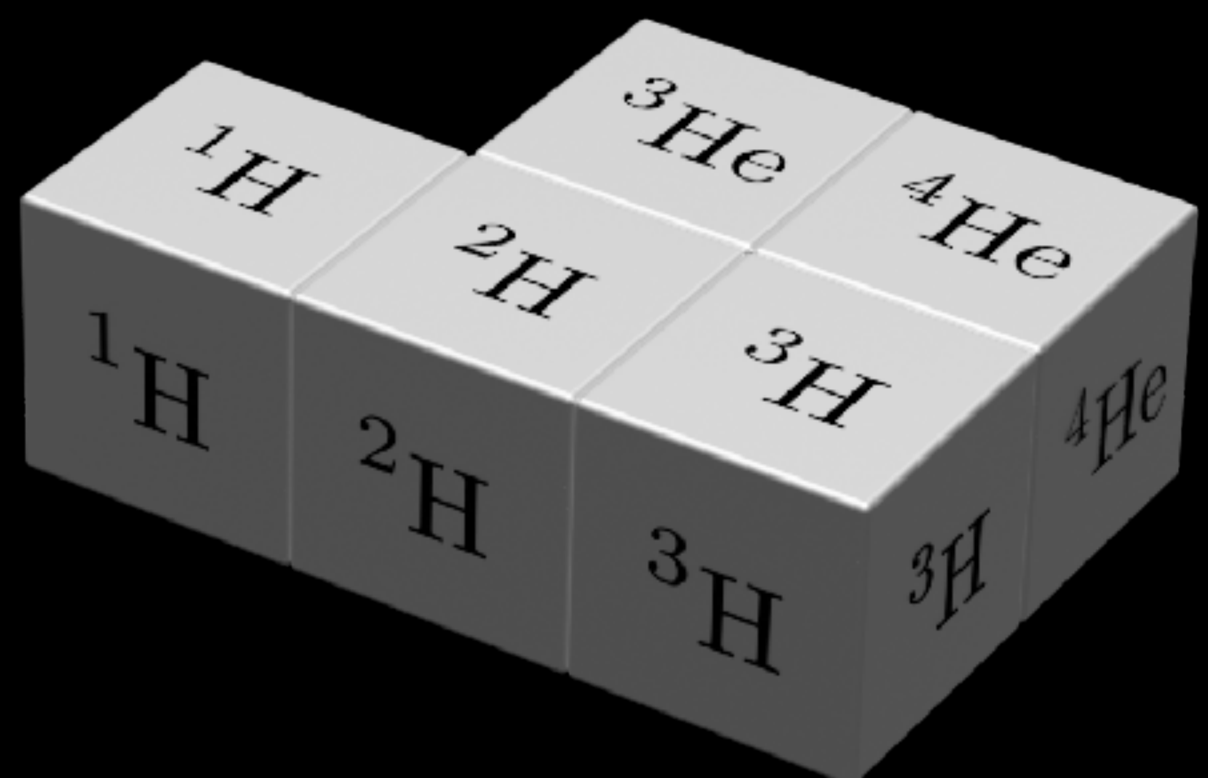
[9] *Department of Physics, Tohoku University*

[10] *Research Center for Electron Photon Science (ELPH), Tohoku University*

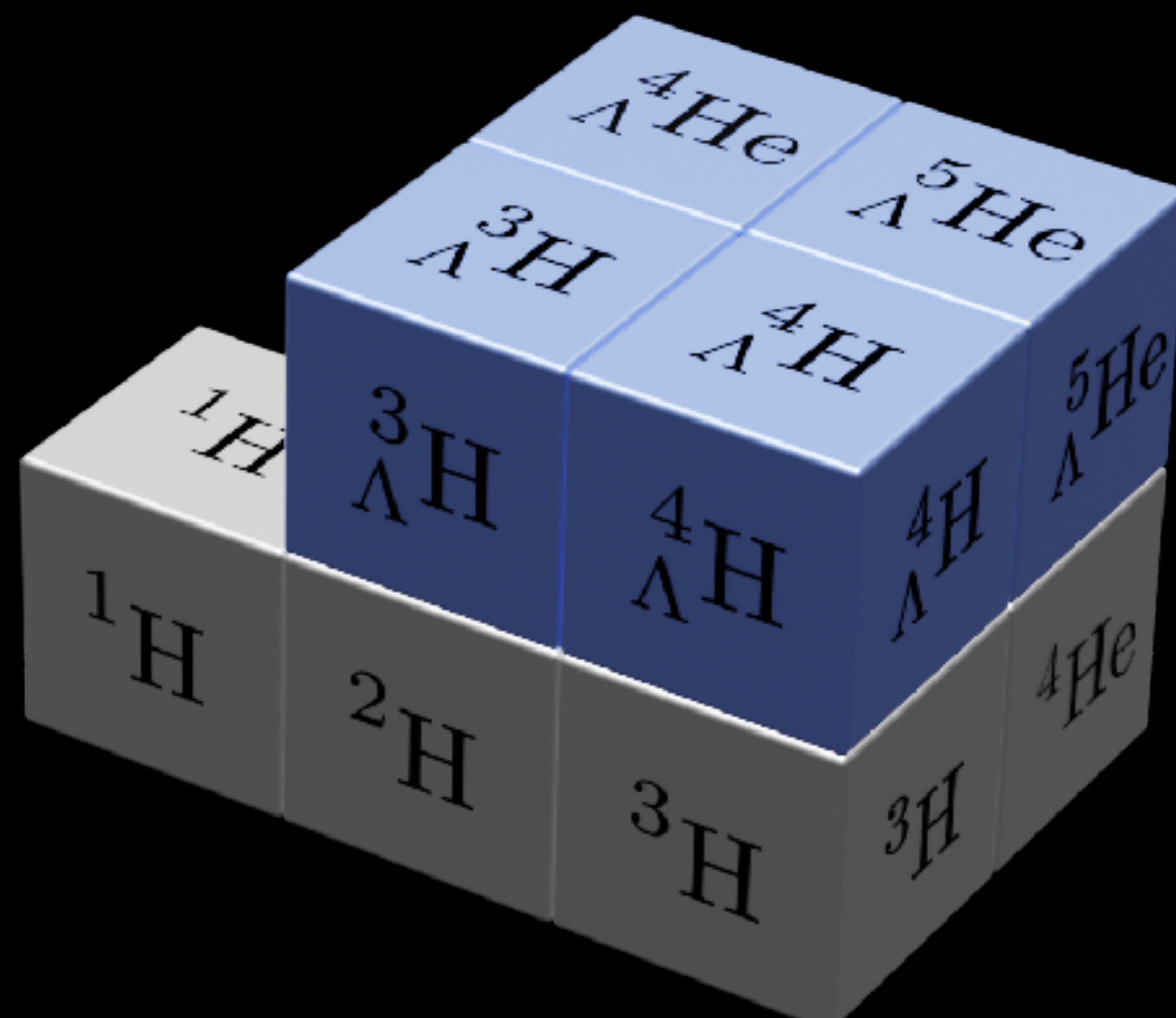
December 9, 2019

http://j-parc.jp/researcher/Hadron/en/pac_2001/pdf/P75_2020-02.pdf

s-shell nuclei



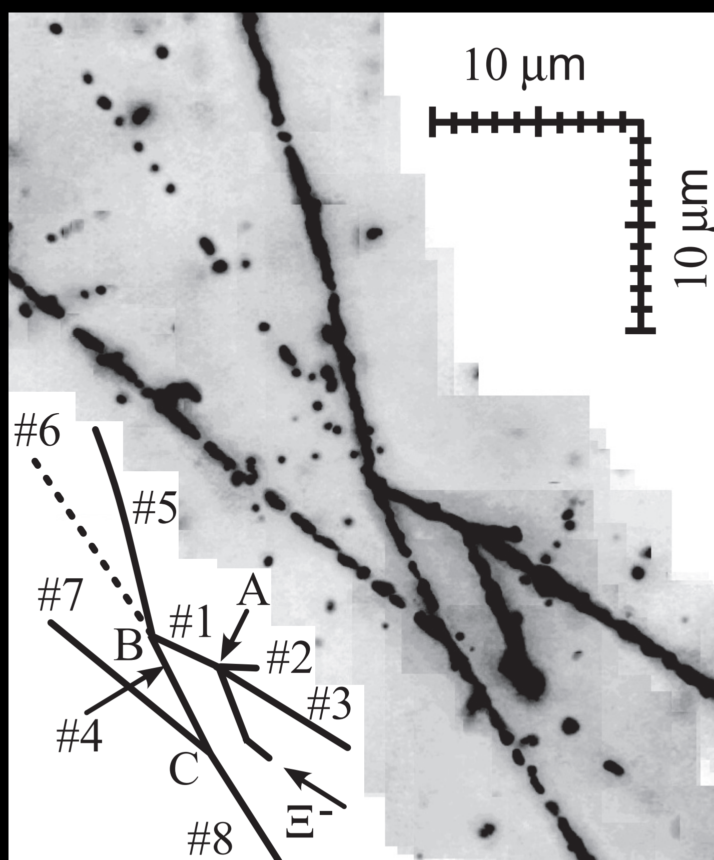
s-shell single-Λ hypernuclei



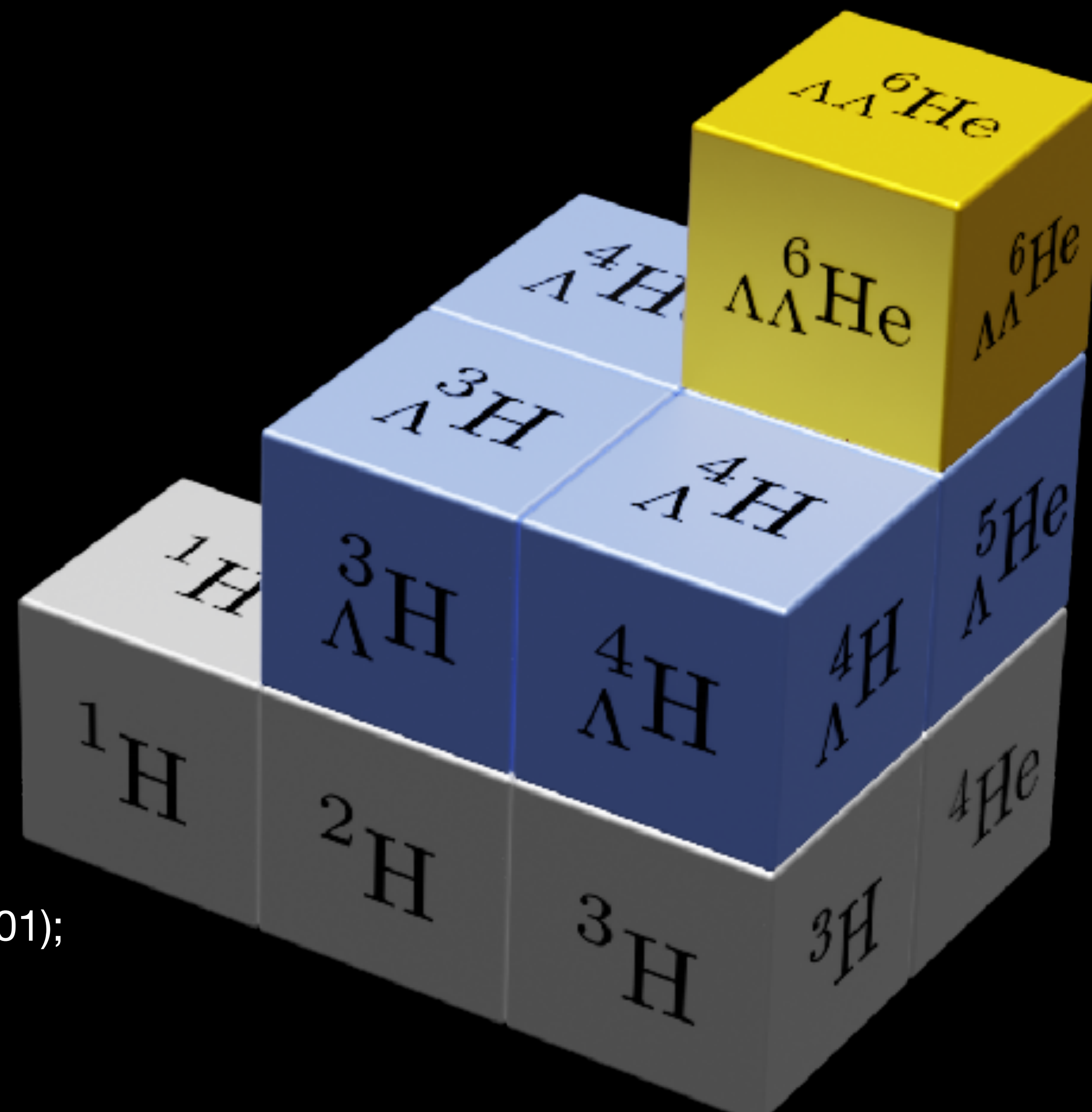
s-shell double-Λ hypernuclei

(as of March 2021)

NAGARA Event



H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)

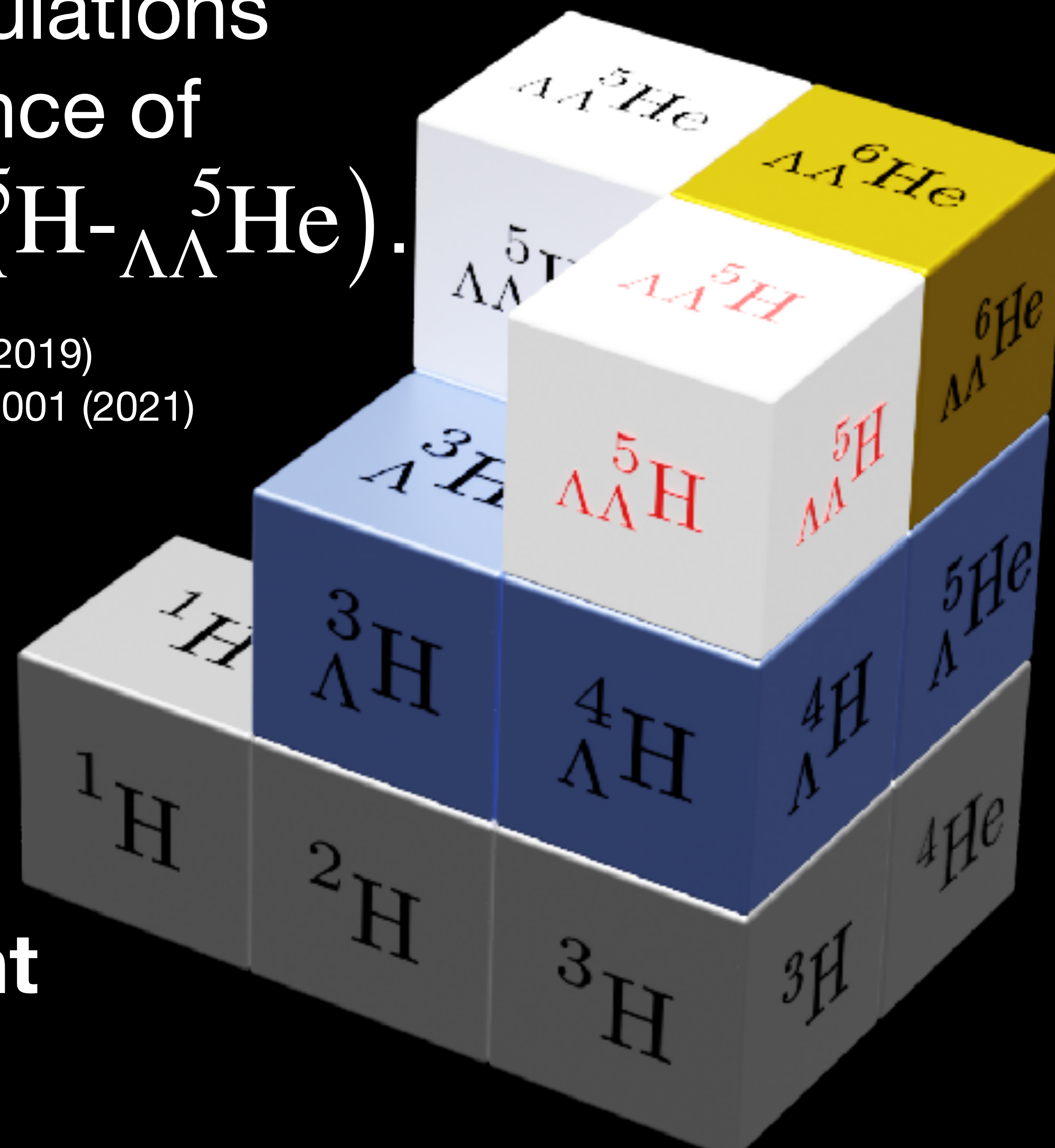


s-shell double-Λ hypernuclei

(expectation)

Many theoretical calculations supports the existence of the $A = 5$ isodoublet $\left({}^{5}_{\Lambda\Lambda}\mathrm{H}\text{-}{}^{5}_{\Lambda\Lambda}\mathrm{He}\right)$.

L. Contessi et al., Phys. Lett. B **797**, 134893 (2019)
G. Meher and U. Raha, Phys. Rev. C **103**, 014001 (2021)
and references therein



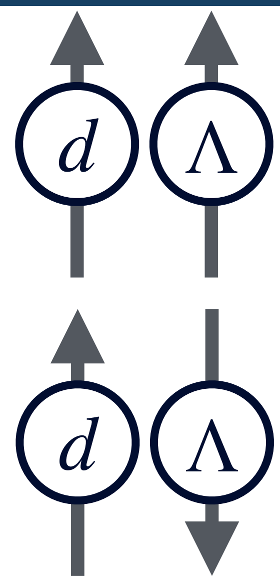
J-PARC E75 Experiment will investigate ${}^{5}_{\Lambda\Lambda}\mathrm{H}$.

https://j-parc.jp/researcher/Hadron/en/pac_1901/pdf/P75_2019-09.pdf

Why is $^{5}_{\Lambda\Lambda}\mathrm{H}$ special? (1)

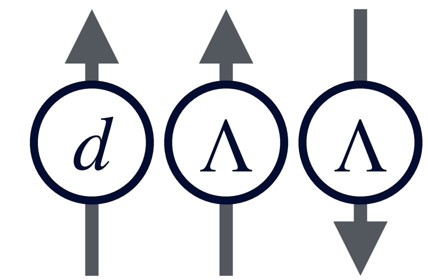
$A = 4$

$^{3}_{\Lambda}\mathrm{H} \Rightarrow {}^{4}_{\Lambda\Lambda}\mathrm{H}$



$3/2^{+}$: unbound

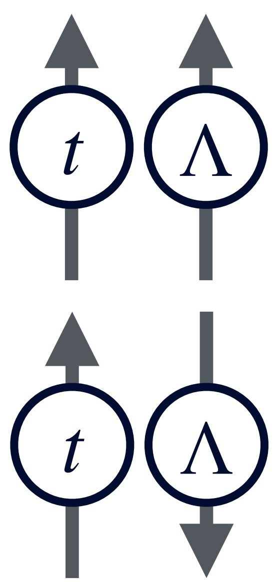
$1/2^{+}$: $B = 0.13\,\mathrm{MeV}$



most likely unbound

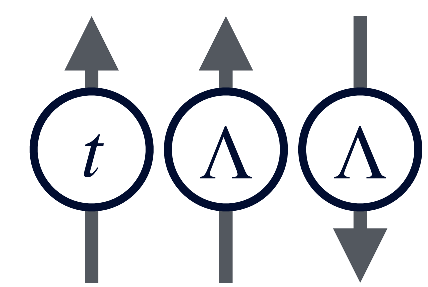
$A = 5$

$^{4}_{\Lambda}\mathrm{H} \Rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H}$



1^{+}: $B = 1.07\,\mathrm{MeV}$

0^{+}: $B = 2.16\,\mathrm{MeV}$



expected to be bound

The lightest Double Λ Hypernuclei will be $^{5}_{\Lambda\Lambda}\mathrm{H}/^{5}_{\Lambda\Lambda}\mathrm{He}$

Table 1

Λ separation energies $B_\Lambda({}^{A}_{\Lambda\Lambda}\mathrm{Z})$ for $A = 3$–6, calculated using $a_{\Lambda\Lambda} = -0.8$ fm, cutoff $\lambda = 4\ \mathrm{fm}^{-1}$ and the Alexander[B] ΛN interaction model [24]. In each row a $\Lambda\Lambda N$ LEC was fitted to the underlined binding energy constraint.

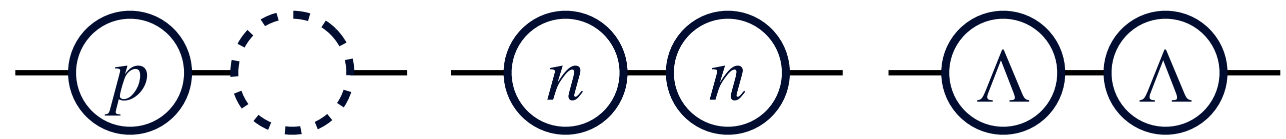
Constraint (MeV)	${}^{3}_{\Lambda\Lambda}\mathrm{n}$	${}^{4}_{\Lambda\Lambda}\mathrm{n}$	${}^{4}_{\Lambda\Lambda}\mathrm{H}$	${}^{5}_{\Lambda\Lambda}\mathrm{H}$	${}^{6}_{\Lambda\Lambda}\mathrm{He}$	
$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = \underline{0.67}$	–	–	–	1.21	3.28	NAGARA
$B_\Lambda({}^{4}_{\Lambda\Lambda}\mathrm{H}) = \underline{0.05}$	–	–	0.05	2.28	4.76	
$B({}^{4}_{\Lambda\Lambda}\mathrm{n}) = \underline{0.10}$	–	0.10	0.86	4.89	7.89	
$B({}^{3}_{\Lambda\Lambda}\mathrm{n}) = \underline{0.10}$	0.10	15.15	18.40	22.13	25.66	

L. Contessi et al., Phys. Lett. B **797**, 134893 (2019)

Why is ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ special? (2)

$A = 5$

${}^{5}_{\Lambda\Lambda}\mathrm{H}$

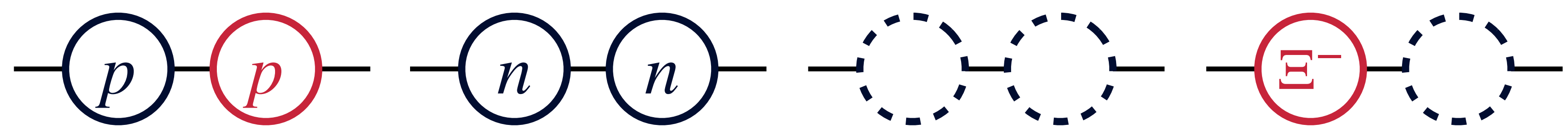


~11MeV mass difference

$\Lambda\Lambda \leftrightarrow \Xi^{-}p$ mixing

cf. B.F. Gibson et al.,
Prog. Theor. Phys. Suppl. 117, 339 (1994)

${}^{5}_{\Xi^{-}}\mathrm{H}$

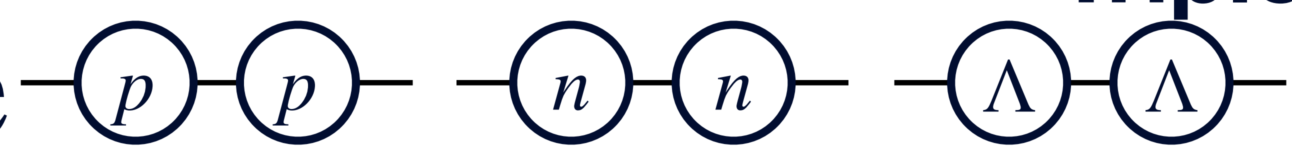


study of $\Lambda\Lambda$-ΞN interaction as well as $\Lambda\Lambda$ interaction

Triple-shell closure

$A = 6$

${}^{6}_{\Lambda\Lambda}\mathrm{He}$



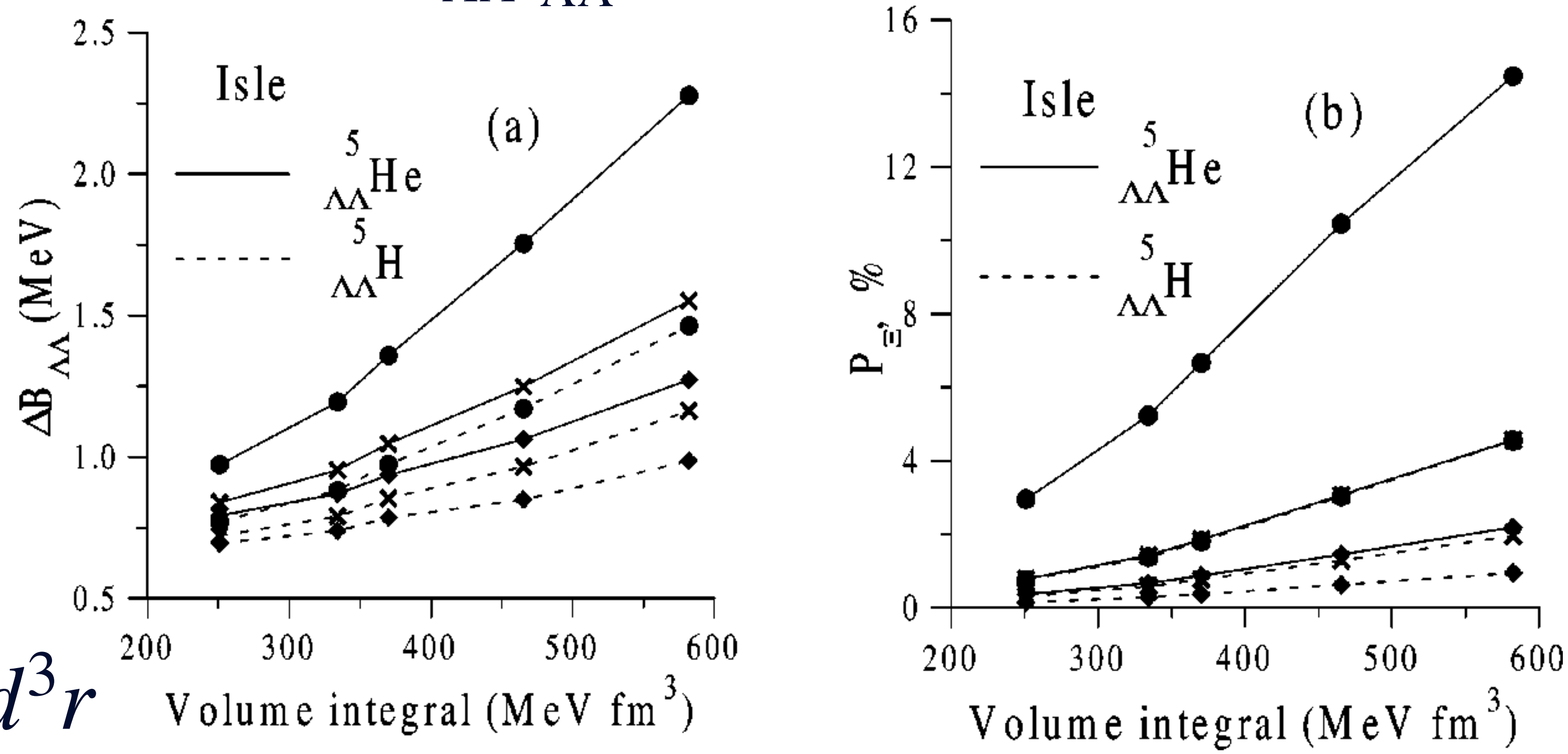
($A \geq 7$ as well)

study of $\Lambda\Lambda$ interaction

Suppression of $\Lambda\Lambda \leftrightarrow \Xi^{-}p$ mixing due to the Pauli principle

$\Lambda\Lambda$-ΞN int. and $\Delta B_{\Lambda\Lambda}$, Ξ mixing

$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 1.0\,\mathrm{MeV}$ (fixed)



$$\int V_{\Lambda\Lambda,\Xi N}(r)d^3r$$

D. E. Lanskoy and Y. Yamamoto, Phys. Rev. C **69**, 014303 (2004)

the $\Lambda\Lambda$ interaction as deduced from $B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$, we have argued that the $\Lambda\Lambda$-ΞN coupling effect should not exceed 0.2 MeV in ${}^{6}_{\Lambda\Lambda}$He, and a similar order of magnitude is expected for this and other medium effects in the $A=5$ $\Lambda\Lambda$ hypernuclei. For comparison with the better studied $S=-1$

I.N. Filikhin, A. Gal, and V.M. Suslov, Phys. Rev. C **68**, 024002 (2003)

Short summary for physics motivation

- In the s-shell region of double-Λ hypernuclei, only ${}_{\Lambda\Lambda}^{6}$He has been discovered in a nuclear-emulsion experiment.

  - The ΛΛ bond energy ($\Delta B_{\Lambda\Lambda}$) may be larger, if the assumption "*Ξ^- was captured at the atomic 3D level*" in the analysis of the NAGARA event is not valid. A cross-check with different experiments is necessary!

- The **lightest double-Λ hypernucleus**, probably ${}_{\Lambda\Lambda}^{5}$H-${}_{\Lambda\Lambda}^{5}$He, is yet to be discovered up to now.

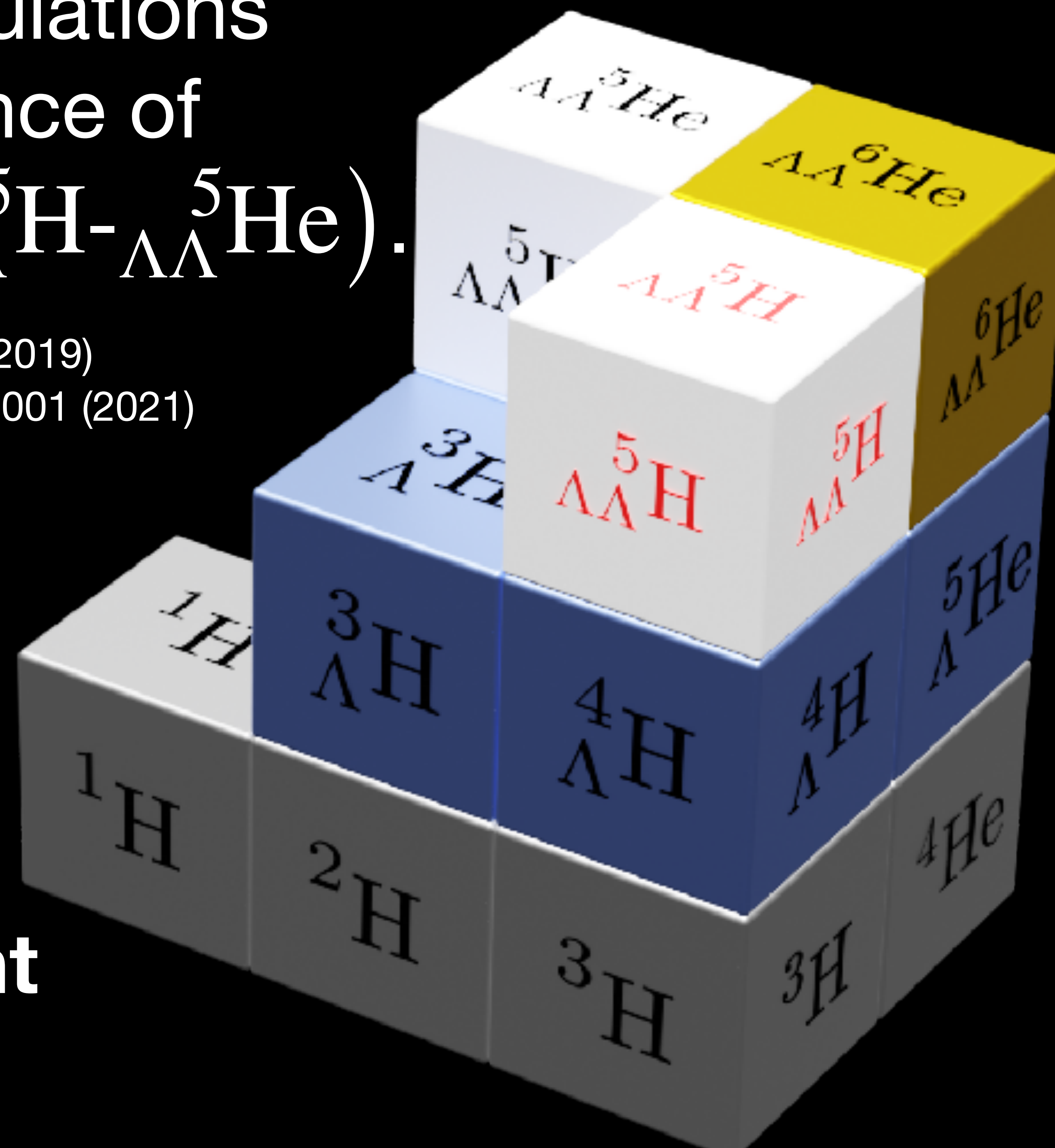
- The comparison between ${}_{\Lambda\Lambda}^{6}$He and ${}_{\Lambda\Lambda}^{5}$H-${}_{\Lambda\Lambda}^{5}$He will reveal the effect of **ΛΛ-ΞN mixing** in light double-Λ hypernuclear systems.

s-shell double-Λ hypernuclei

(expectation)

Many theoretical calculations supports the existence of the $A = 5$ isodoublet $\left({}^{5}_{\Lambda\Lambda}\mathrm{H}\text{-}{}^{5}_{\Lambda\Lambda}\mathrm{He}\right)$.

L. Contessi et al., Phys. Lett. B **797**, 134893 (2019)
G. Meher and U. Raha, Phys. Rev. C **103**, 014001 (2021)
and references therein



J-PARC E75 Experiment

will investigate $^{5}_{\Lambda\Lambda}\mathrm{H}$.

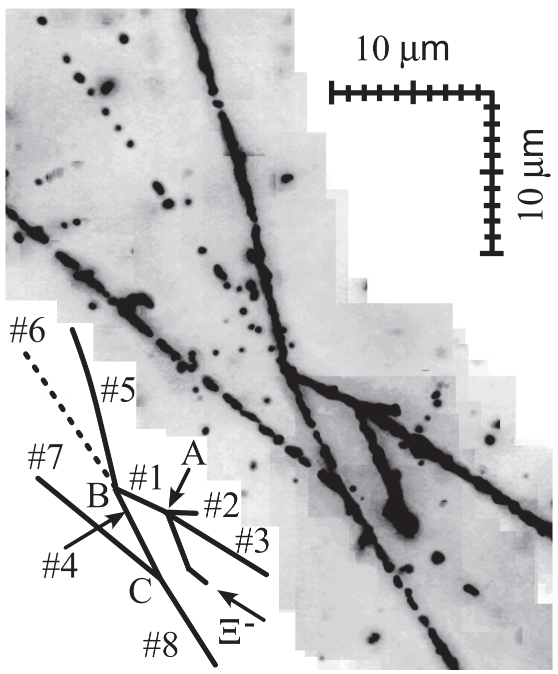
https://j-parc.jp/researcher/Hadron/en/pac_1901/pdf/P75_2019-09.pdf

Novelty in the E75 experiment

- The (hybrid-)emulsion method has been adopted since the discovery of double-Λ hypernuclei in 1960's.
  - Many kinds of double-Λ hypernuclei, including ${}^{6}_{\Lambda\Lambda}\mathrm{He}$, have been reported.
- The J-PARC E75 experiment will NOT use a nuclear emulsion, hence a so-called counter experiment.
  - Nuclear target: ${}^{7}\mathrm{Li}$
  - ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ will be exclusively produced

Comparison

Emulsion method



captured from an atomic orbital of ^{12}C

$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$$^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

$$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-} \pm 0.16\,\mathrm{MeV}$$
$$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-} \pm 0.17\,\mathrm{MeV}$$

$\rightarrow$

$$B_{\Lambda\Lambda} = 6.91 \pm 0.16\,\mathrm{MeV}$$
$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17\,\mathrm{MeV}$$

$B_{\Xi^-}(3D) = 0.13\,\mathrm{MeV}$
(assumption)

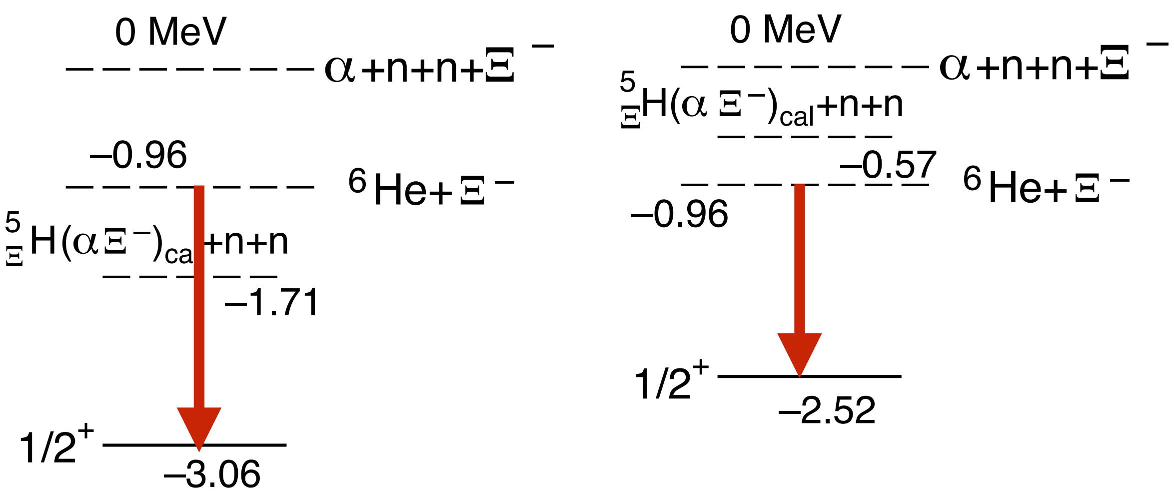
H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)

J-PARC E75 experiment

1) Production of Ξ hypernuclei: $^{7}\mathrm{Li}(K^-, K^+)^{7}_{\Xi^-}\mathrm{H}$
2) Strong decay of Ξ hypernuclei: $^{7}_{\Xi^-}\mathrm{H} \rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$
3) Weak decay of double-Λ hypernuclei: $^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-$

Production of $^{7}_{\Xi}\mathrm{H}$

E75 Phase-1 Proposal
https://j-parc.jp/researcher/Hadron/en/pac_2001/pdf/P75_2020-02.pdf

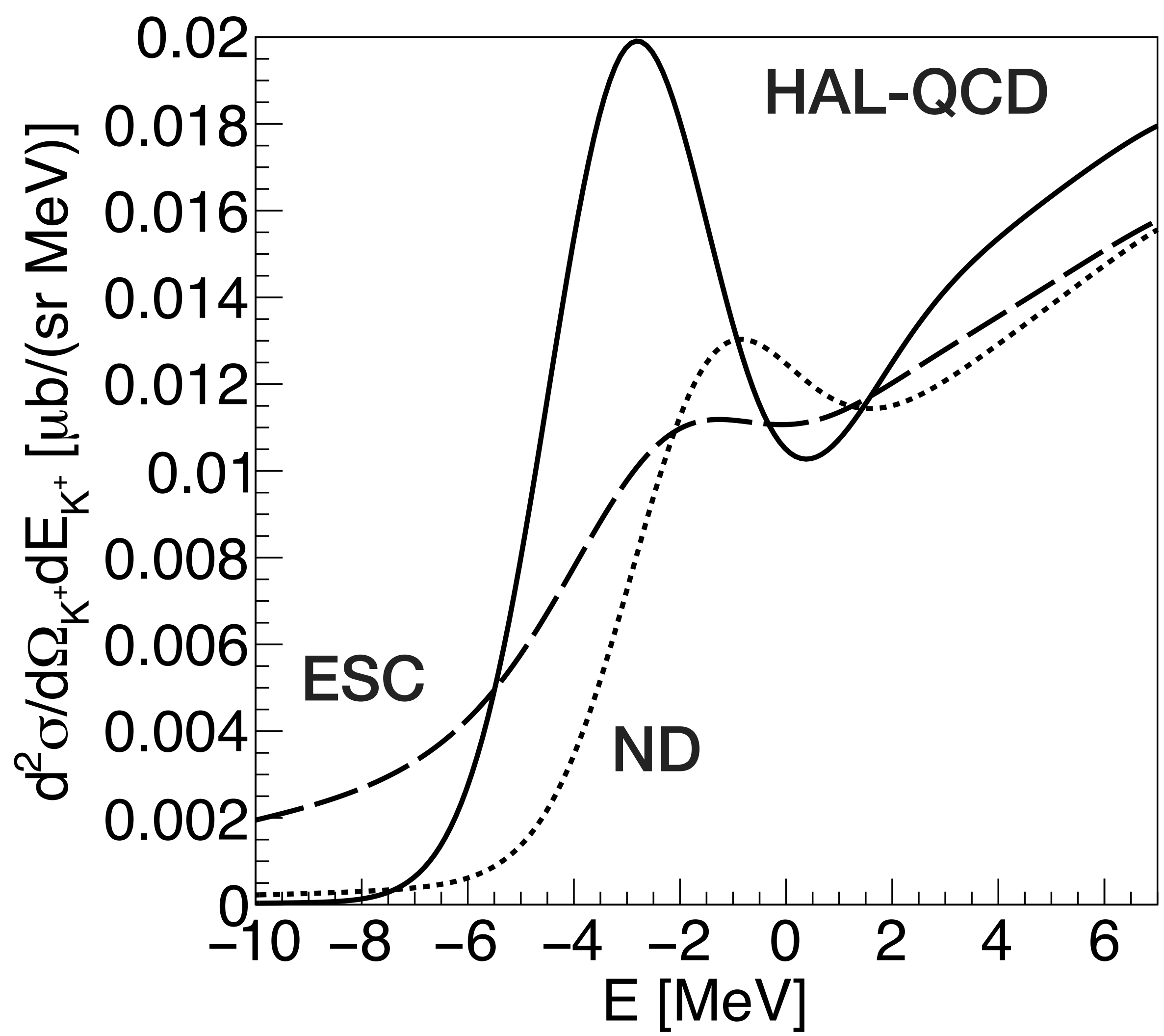


E. Hiyama et al., PRC **78**, 054316 (2008)

$^{7}_{\Xi}\mathrm{H}$ will be bound relative to $^{6}\mathrm{He}+\Xi^{-}$

interaction model	B [MeV]	Γ [MeV]
ESC04d	1.80	2.64
ND	1.55	0.27
HAL ($t/a = 11$)	3.15	0.02

(K^{-}, K^{+}) spectrum [3.5MeV$_{\mathrm{FHWM}}$]



E. Hiyama and T. Koike, private communication

Formation Probability of $^{5}_{\Lambda\Lambda}\mathrm{H}$

PHYSICAL REVIEW C VOLUME 54, NUMBER 1 JULY 1996

Double-Λ hypernuclear formation via a neutron-rich Ξ state

Izumi Kumagai-Fuse and Yoshinori Akaishi
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

(Received 21 March 1996)

Conversion processes for $^{7}_{\Xi}\mathrm{H}$ are discussed as a typical example of the double-Λ hypernuclear formation via a neutron-rich Ξ state. $^{5}_{\Lambda\Lambda}\mathrm{H}$ is formed with a surprisingly large branching ratio of about 90% from $^{7}_{\Xi}\mathrm{H}$ that is produced by the (K^-,K^+) reaction on the $^{7}\mathrm{Li}$ target. The $^{7}_{\Xi}\mathrm{H}$ state has a narrow width, 0.75 MeV, and its population can be confirmed by tagging K^+ momentum. [S0556-2813(96)50507-8]

PACS number(s): 21.80.+a. 21.45.+v. 25.80.Nv, 25.80.Pw

I. Kumagai-Fuse, Y. Akaishi, Phys. Rev. C **54**, R24 (1996)

PTEP Prog. Theor. Exp. Phys. **2020**, 063D01 (17 pages)
DOI: 10.1093/ptep/ptaa047

Statistical double Λ hypernuclear formation from Ξ^- absorption at rest in light nuclei

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Received November 28, 2019; Revised March 16, 2020; Accepted March 17, 2020; Published June 18, 2020

A. Ohnishi et al., Prog. Theor. Exp. Phys. **2020**, 063D01 (2020)

$$^{7}_{\Xi}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + n + n \quad \sim 11 \ \ \mathrm{MeV},$$

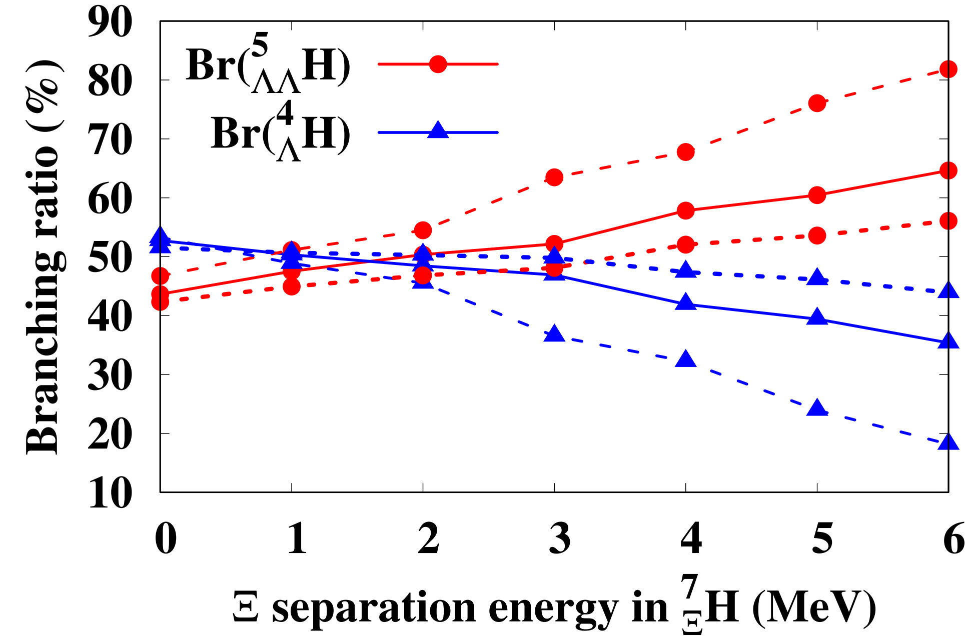
$$\to {}^{4}_{\Lambda}\mathrm{H} + \Lambda + n + n \quad \sim 7 \ \ \mathrm{MeV},$$

$$\to {}^{4}_{\Lambda}\mathrm{H}^{*} + \Lambda + n + n \quad \sim 6 \ \ \mathrm{MeV},$$

$$\to {}^{3}\mathrm{H} + \Lambda + \Lambda + n + n \quad \sim 5 \ \ \mathrm{MeV}.$$

B.R. ~90%

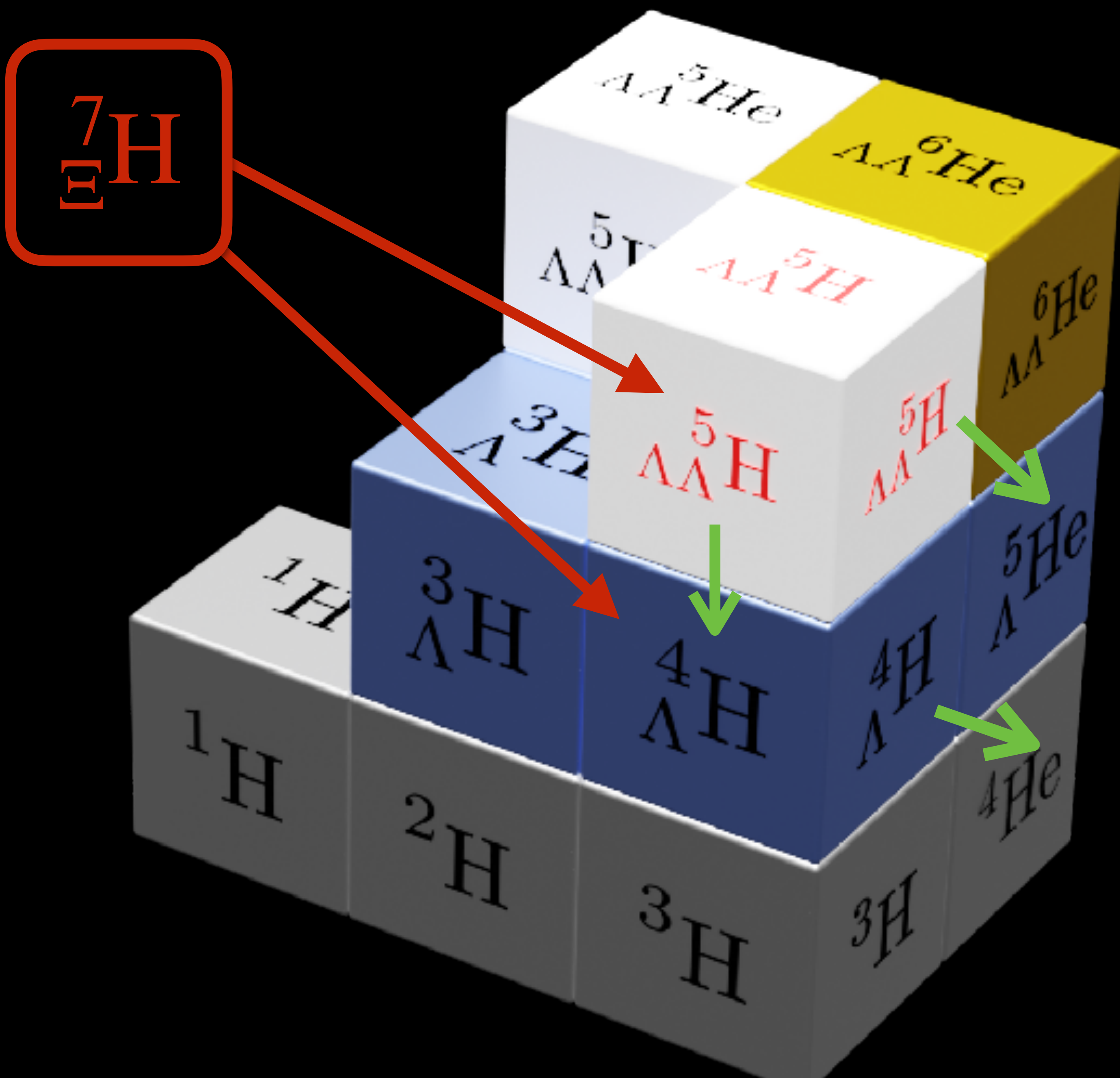
$^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ $^{4}_{\Lambda}\mathrm{H}(0^+,1^+) + \Lambda + 2n$



B.R. ~50%

Production and Decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$

Mass of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will be determined
(decay pion spectroscopy)



$p_{\pi^-} \approx 132\text{—}135\ \mathrm{MeV}/c$

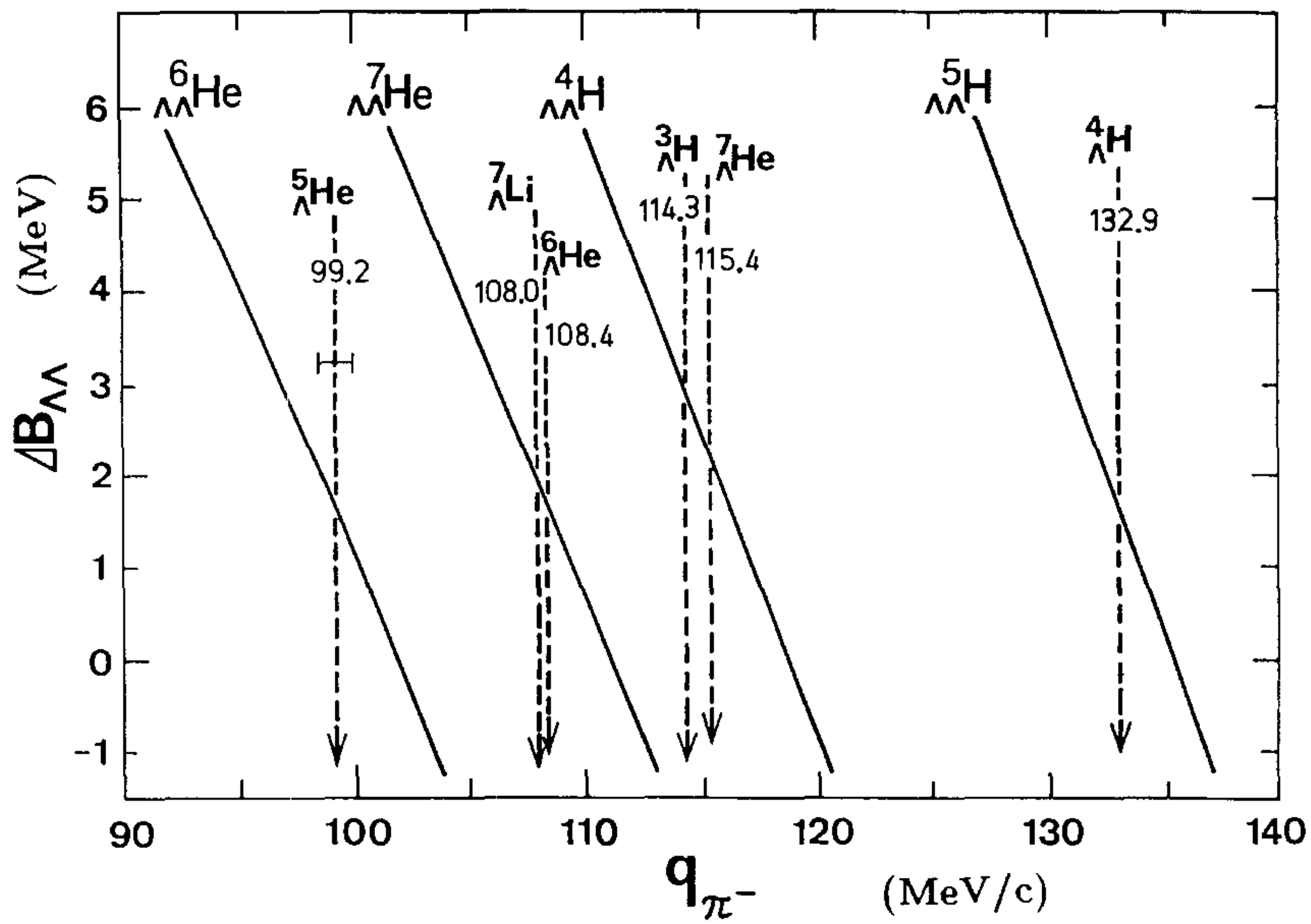
$${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$$

$${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$$

$p_{\pi^-} \approx 132.9\ \mathrm{MeV}/c$

Tag of a fast proton from NMWD of ${}^{5}_{\Lambda}\mathrm{He}$ ⇒ distinction between ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$

Momentum of decay pions



$$p_{\pi^-} \approx 132\text{—}135\,\mathrm{MeV}/c$$

$$^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-$$

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^-$$

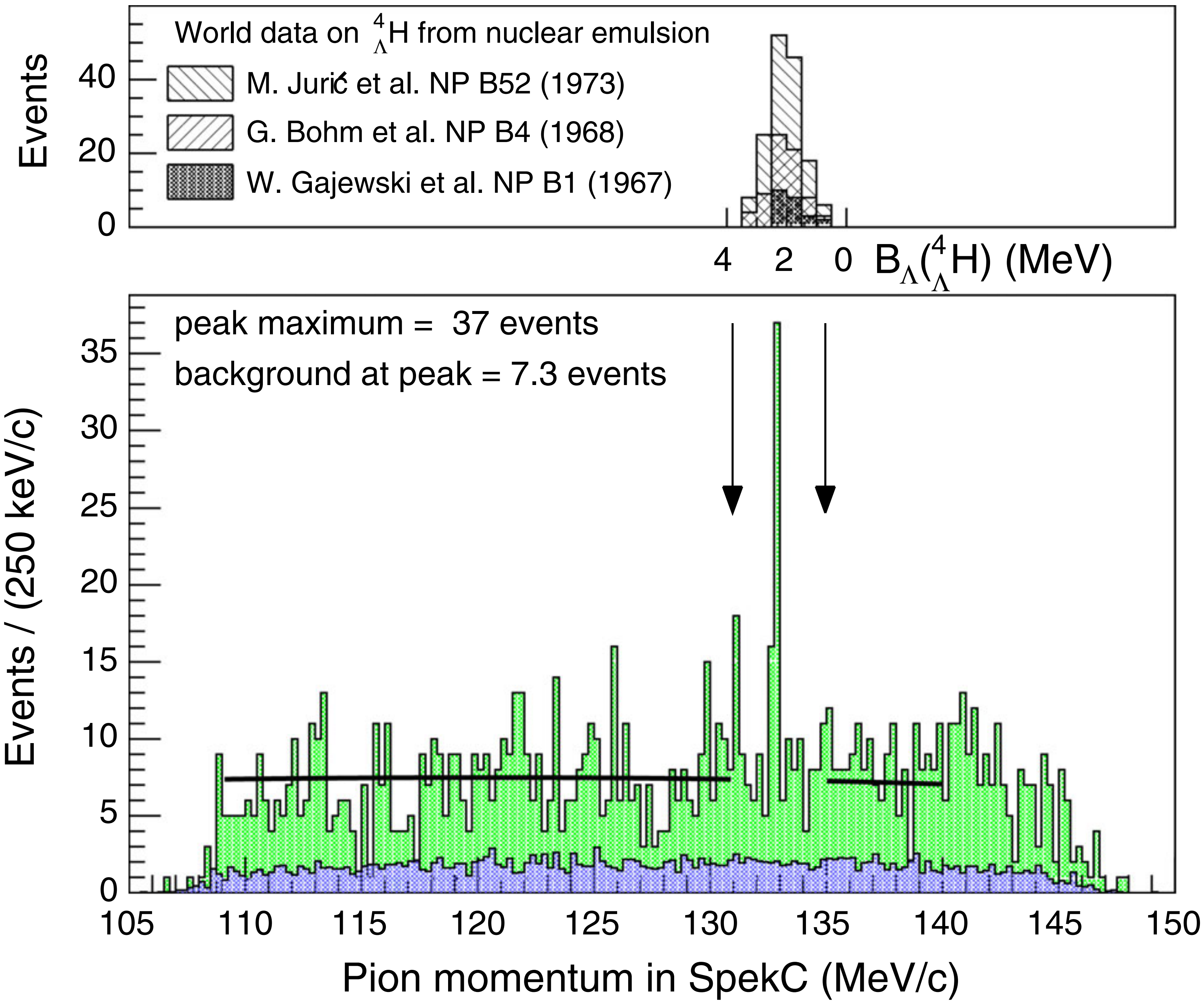
$$p_{\pi^-} \approx 132.9\,\mathrm{MeV}/c$$

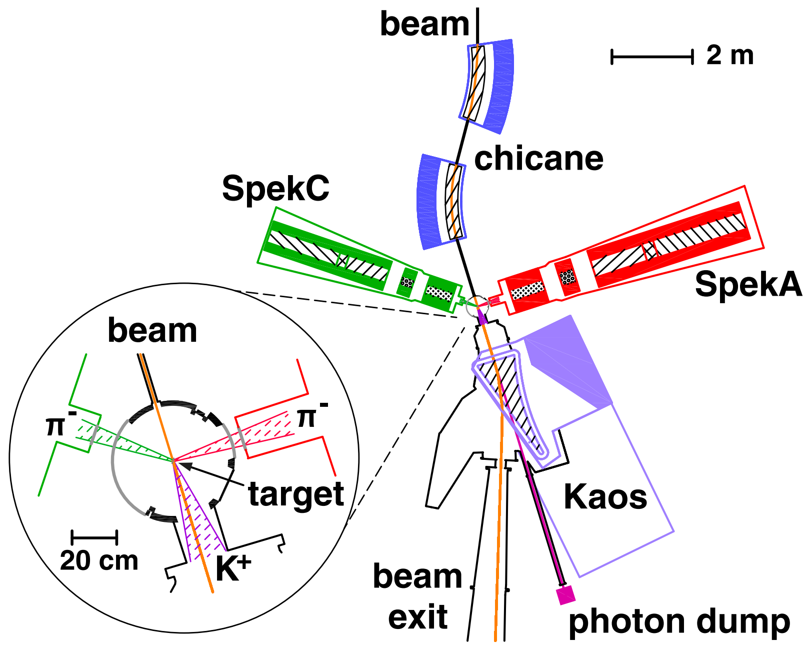
Y. Yamamoto, M. Wakai, T. Motoba and T. Fukuda, Nucl. Phys. A **625**, 107 (1997)

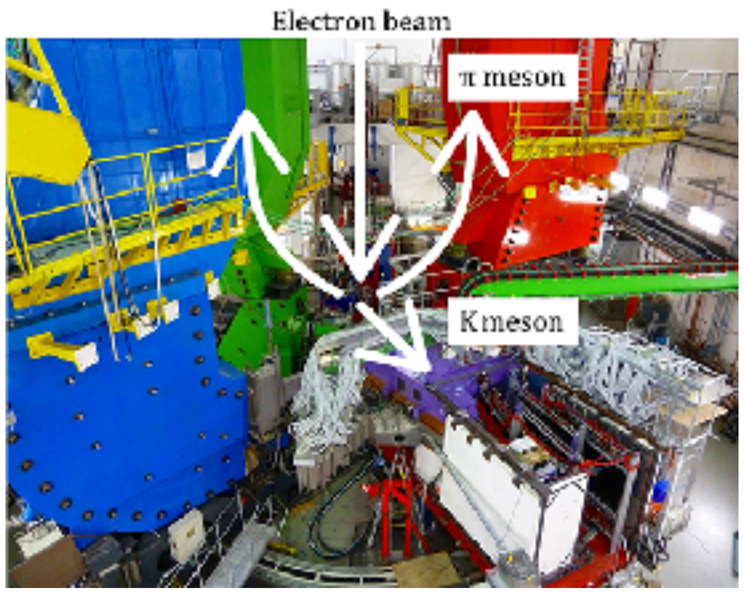
Hiroyuki Fujioka (fujioka@phys.titech.ac.jp)

Decay Pion Spectroscopy

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$$

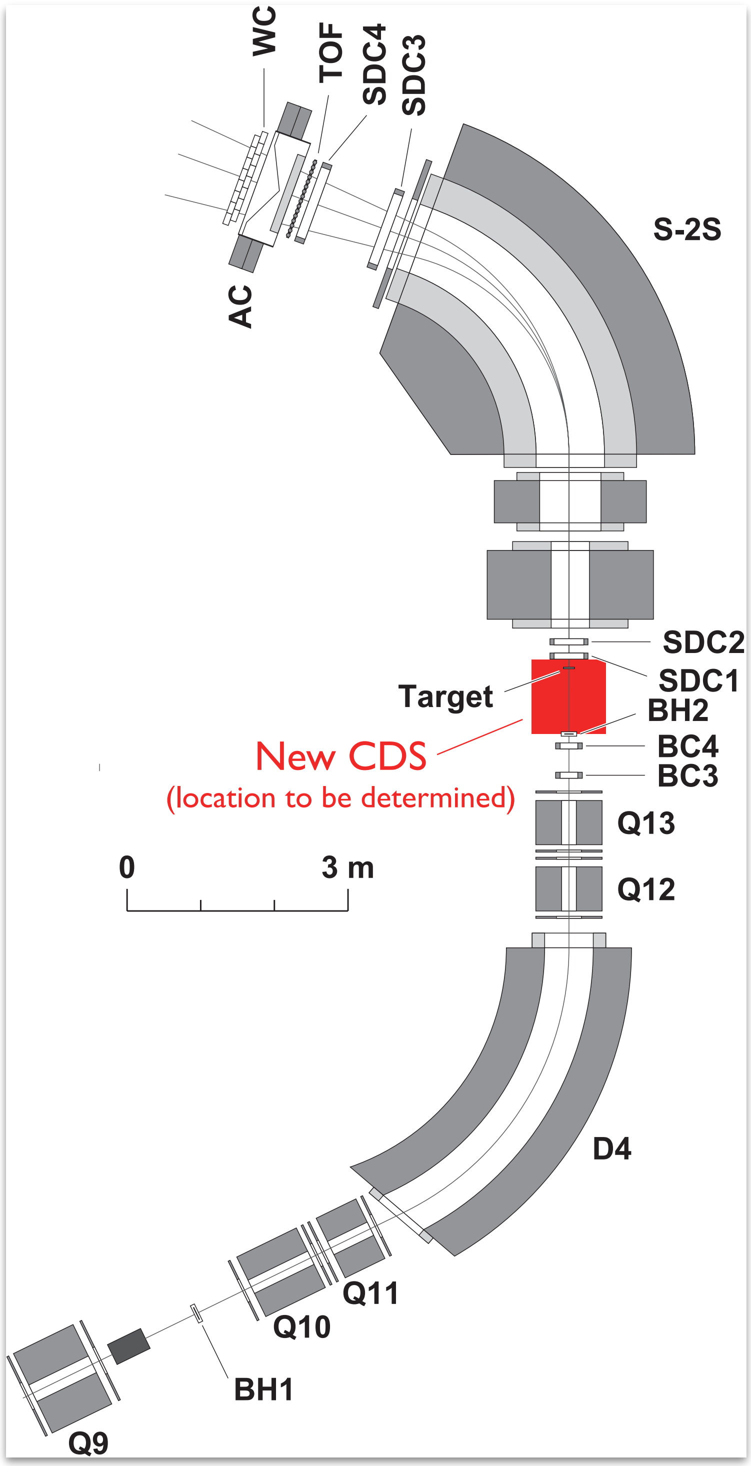






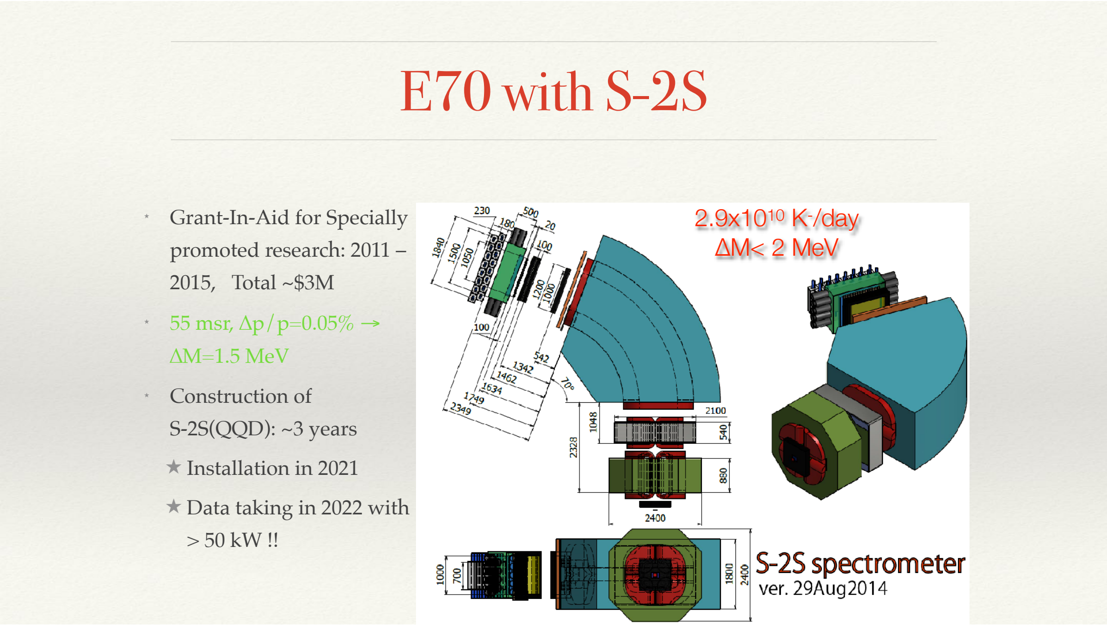
A. Esser et al.,
PRL **114**, 232501 (2015)
A1 Collaboration,
NPA **954**, 149 (2016)

Experimental Setup



$^{7}\mathrm{Li}(K^{-}, K^{+})_{\Xi^{-}}{}^{7}\mathrm{H}$ (missing-mass spectroscopy)

K1.8 + “S-2S” (common to E70 Exp.)

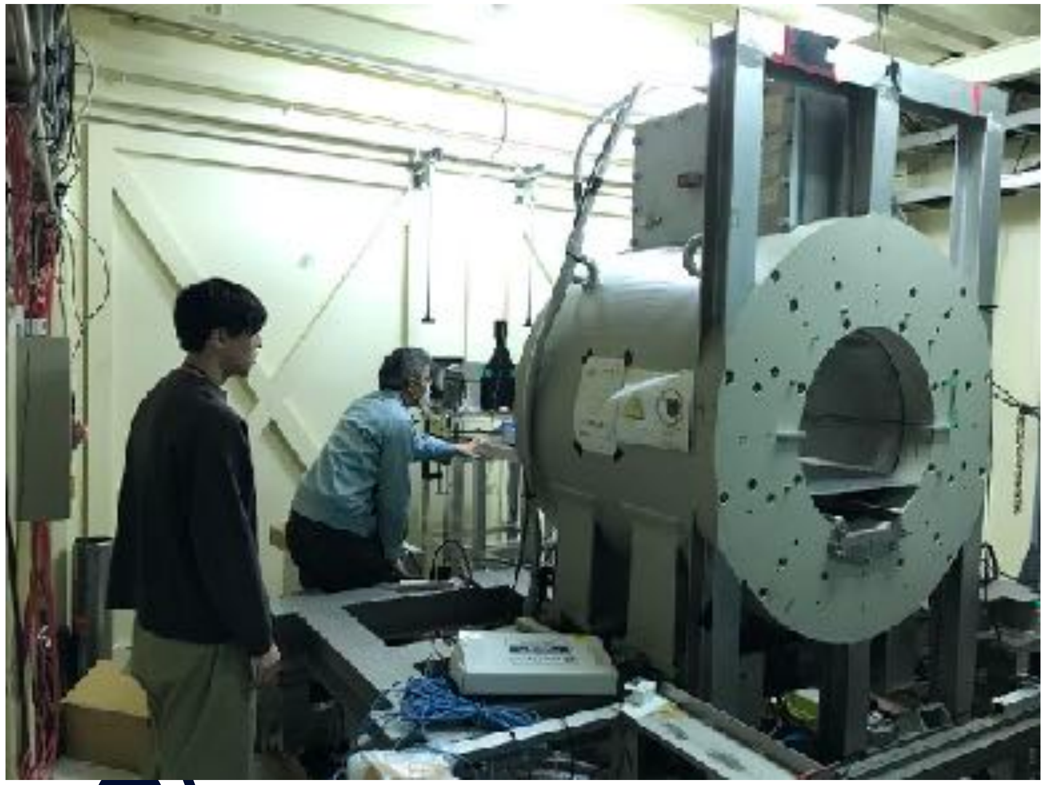


T. Nagae
THEIA-REIMEI seminar
(18/Nov/2020)

$_{\Lambda\Lambda}^{5}\mathrm{H} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + \pi^{-}$ (decay pion spectroscopy)

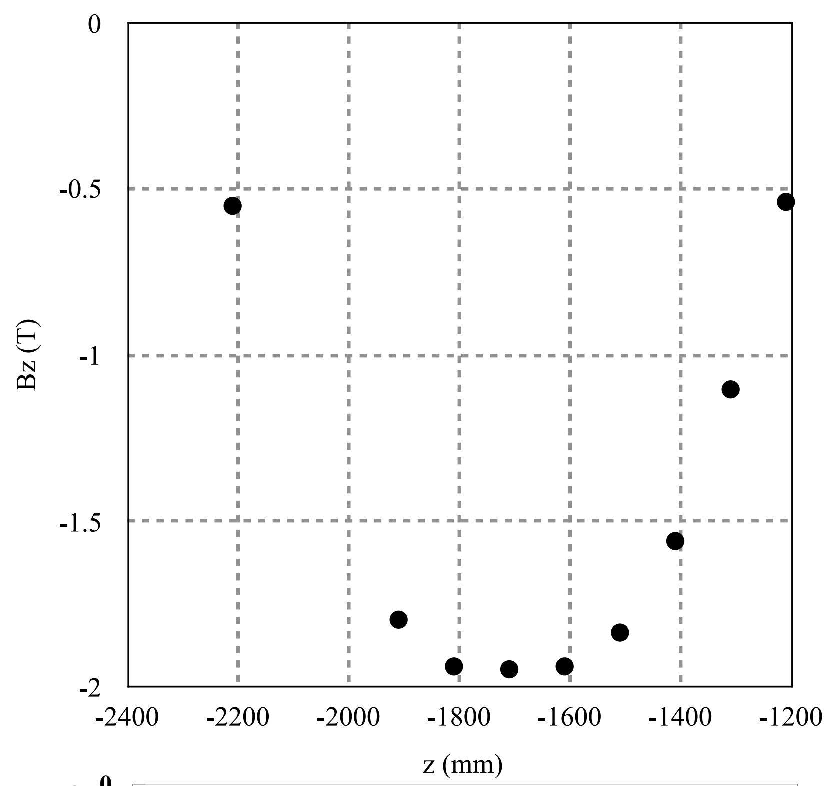
Cylindrical Detector System
solenoid magnet + TPC + …

Superconducting solenoid



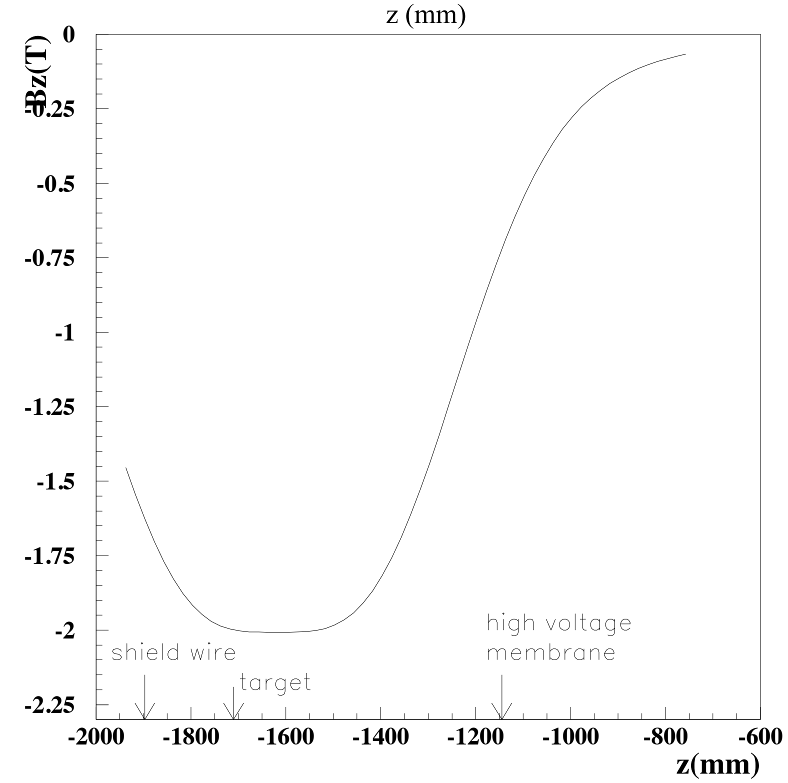
- Excitation Test in Nov.-Dec. 2019

Measurement (2019/12/16)



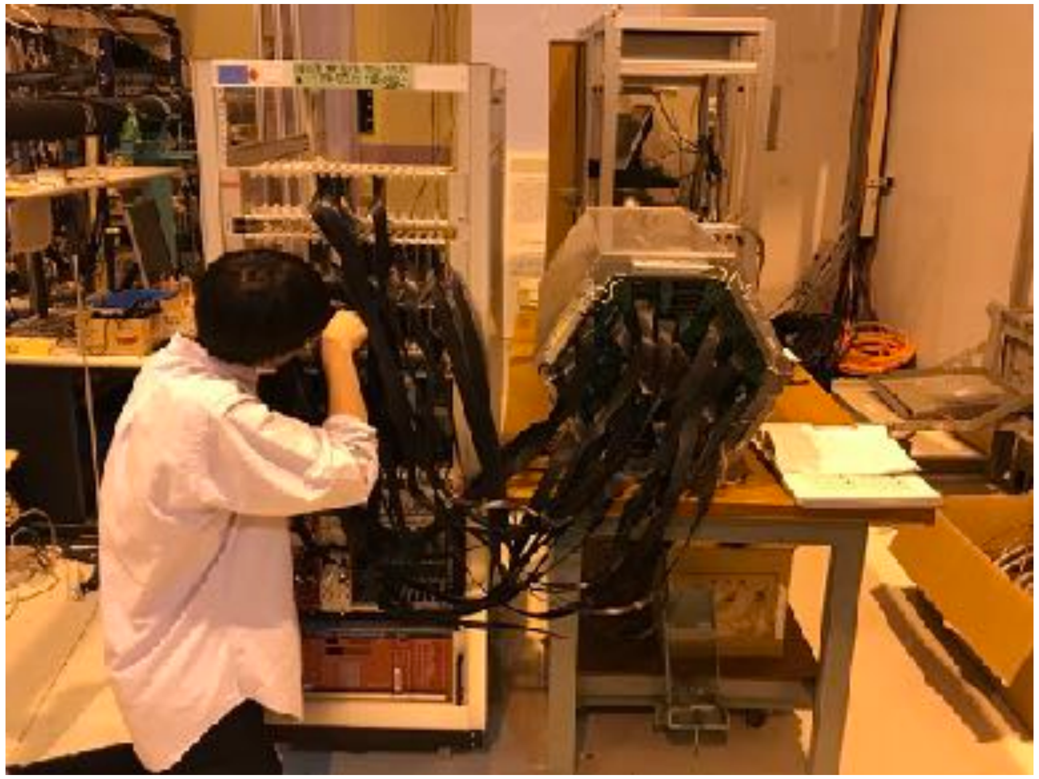
calculation by OPERA-3D (TOSCA)

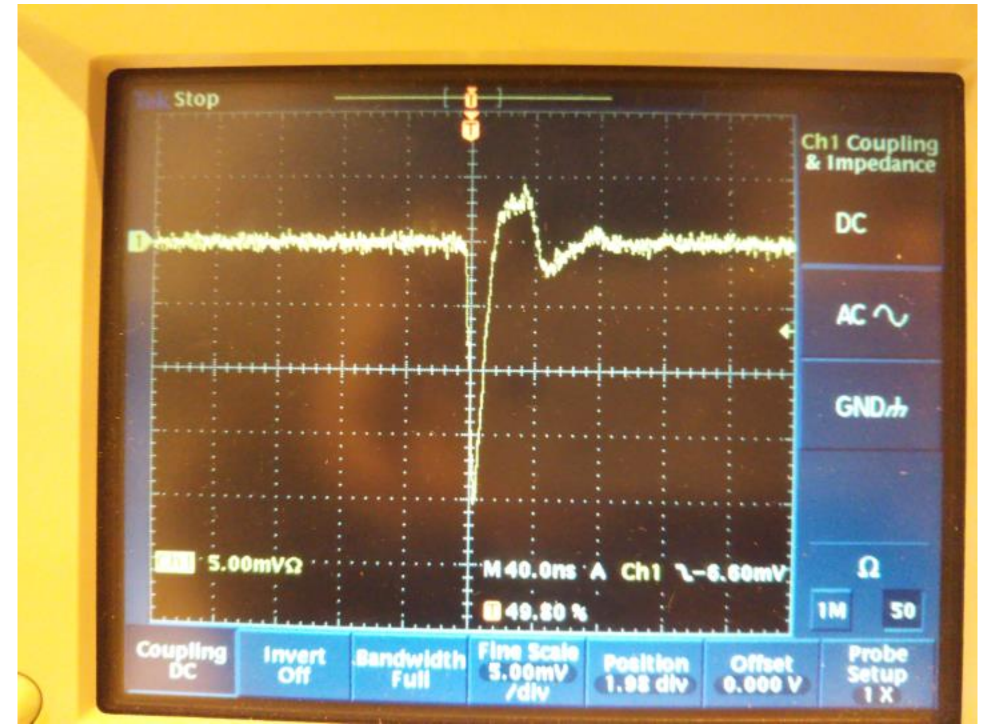
Y. Nakatsugawa et al., Ph. D thesis, Osaka Univ. (2013)



supported by Joint Usage/Research Programs of RCNP

Time Projection Chamber



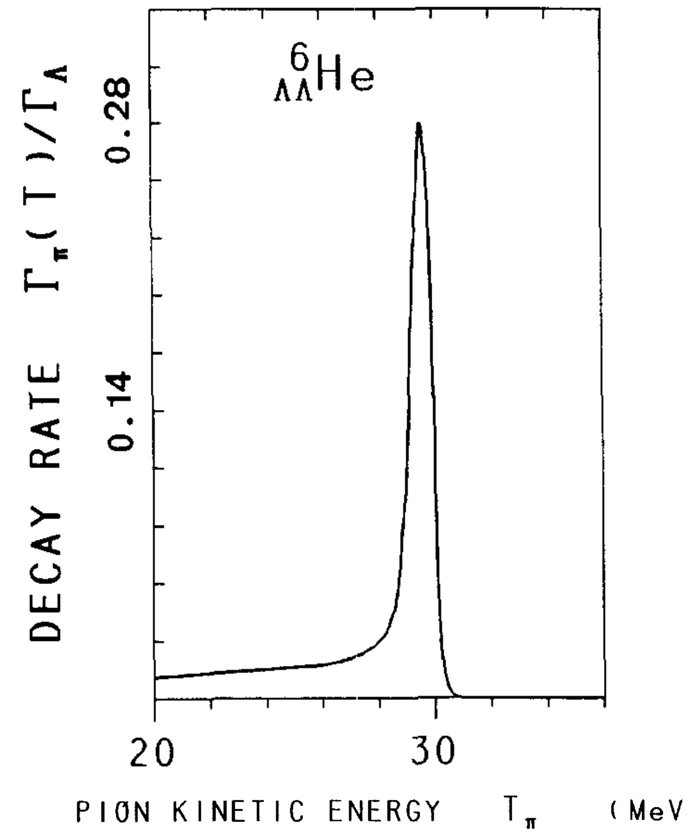


- Integrity assessment in Oct.-Nov. 2019
  We observed analog signals from every sense wire.
- The TPC was moved to TokyoTech in Nov. 2020.
- To-do: R&D of the readout system for the TPC

supported by Joint Usage/Research Programs of RCNP

Future plans

- Decay Pion Spectroscopy for ${}^{6}_{\Lambda\Lambda}\mathrm{He}$
  - ${}^{6}_{\Lambda\Lambda}\mathrm{He} \to {}^{6}_{\Lambda}\mathrm{Li}^{*} + \pi^{-} \to {}^{5}_{\Lambda}\mathrm{He} + p + \pi^{-}$
  - Cross-check with Nagara event



- Weak-decay
  - At least tens of events are necessary
  - Theory: $\Gamma\left({}^{5}_{\Lambda\Lambda}\mathrm{H}\right) = 1.30\Gamma_\Lambda, \Gamma\left({}^{6}_{\Lambda\Lambda}\mathrm{He}\right) = 0.96\Gamma_\Lambda$

Y. Yamamoto, M. Wakai, T. Motoba and T. Fukuda, Nucl. Phys. A 625, 107 (1997)

Weak decay of double-Λ hypernuclei

Table 7
Calculated pionic decay rates of light double-Λ hypernuclei to be produced in the (K^-, K^+) reaction on ^{9}Be. The calculations are made for the two-body and three-body final states. DW denotes the use of pion distorted waves described in the text. All decay rates are given in units of the free-Λ decay rate Γ_Λ

		π^- DW		π^0 DW
${}_{\Lambda\Lambda}^{4}$H	$\Longrightarrow {}^4_\Lambda$He$+\pi^-$	0.25	$\Longrightarrow {}^4_\Lambda$H $+\pi^0$	0.13
	$\Longrightarrow {}^3_\Lambda$H $+p+\pi^-$	0.52	$\Longrightarrow {}^3_\Lambda$H $+n+\pi^0$	0.28
${}_{\Lambda\Lambda}^{5}$H	$\Longrightarrow {}^5_\Lambda$He$+\pi^-$	0.38	$\Longrightarrow$ (No 2-body)	-
	$\Longrightarrow {}^4_\Lambda$H $+p+\pi^-$	0.61	$\Longrightarrow {}^4_\Lambda$H $+n+\pi^0$	0.31
${}_{\Lambda\Lambda}^{5}$He	$\Longrightarrow$ (No 2-body)	-	$\Longrightarrow {}^5_\Lambda$He$+\pi^0$	0.18
	$\Longrightarrow {}^4_\Lambda$He$+p+\pi^-$	0.48	$\Longrightarrow {}^4_\Lambda$He$+n+\pi^0$	0.22
${}_{\Lambda\Lambda}^{6}$He	$\Longrightarrow$ (No 2-body)	-	$\Longrightarrow {}^6_\Lambda$He$+\pi^0$	0.23
	$\Longrightarrow {}^5_\Lambda$He$+p+\pi^-$	0.60	$\Longrightarrow {}^5_\Lambda$He$+n+\pi^0$	0.13
${}_{\Lambda\Lambda}^{7}$He	$\Longrightarrow {}^7_\Lambda$Li$+\pi^-$	0.26	$\Longrightarrow {}^7_\Lambda$He$+\pi^0$	0.22
	$\Longrightarrow {}^5_\Lambda$He$+d+\pi^-$	0.06	$\Longrightarrow {}^6_\Lambda$He$+n+\pi^0$	0.03
	$\Longrightarrow {}^6_\Lambda$He$+p+\pi^-$	0.21		

No experimental information so far…

We may be able to investigate
the weak decay of ${}_{\Lambda\Lambda}^{5}$H in future …?

The first step: lifetime measurement

Y. Yamamoto, M. Wakai, T. Motoba and T. Fukuda,
Nucl. Phys. A 625, 107 (1997)

cf. single-Λ hypernuclei

A. Gal E.V. Hungerford, D.J. Millener,
Rev. Mod. Phys. 83, 035004 (2016).

TABLE X. Measured total pionic decay widths of selected hypernuclei in units of $\Gamma_\Lambda^{\rm free}$.

${}^A_\Lambda$Z	Γ_{π^-}	Γ_{π^0}	Reference
${}^4_\Lambda$He	0.289 ± 0.039	0.604 ± 0.073	Parker *et al.* (2007)
${}^5_\Lambda$He	0.340 ± 0.016	0.201 ± 0.011	Kameoka *et al.* (2005), Okada *et al.* (2005)
${}^{12}_\Lambda$C	0.123 ± 0.015	0.165 ± 0.008	Kameoka *et al.* (2005), Okada *et al.* (2005)
${}^{28}_\Lambda$Si	0.046 ± 0.011	…	Sato *et al.* (2005)
${}_\Lambda$Fe	≤ 0.015 (90% CL)	…	Sato *et al.* (2005)

TABLE XIII. Measured and calculated NMWD widths and related entities for selected hypernuclei in units of $\Gamma_\Lambda^{\rm free}$.

Entity	Method	${}^5_\Lambda$He	${}^{12}_\Lambda$C
Γ_n/Γ_p	Emulsion (${}_\Lambda$B, ${}_\Lambda$C, ${}_\Lambda$N) (Montwill *et al.*, 1974)		0.59 ± 0.15
	KEK-E462/E508 (Kang *et al.*, 2006; Kim *et al.*, 2006)	$0.45 \pm 0.11 \pm 0.03$	$0.51 \pm 0.13 \pm 0.05$
	OME $+ 2\pi + 2\pi/\sigma$ (Chumillas *et al.*, 2007)	0.415	0.366
	OME $+ 2\pi/\sigma + a_1$ (Itonaga *et al.*, 2008; Itonaga and Motoba, 2010)	0.508	0.418
Γ_{nm}	KEK-E462/E508 (Okada *et al.*, 2004)	0.406 ± 0.020	0.953 ± 0.032
	OME $+ 2\pi + 2\pi/\sigma$ (Chumillas *et al.*, 2007)	0.388	0.722
	OME $+ 2\pi/\sigma + a_1$ (Itonaga *et al.*, 2008; Itonaga and Motoba, 2010)	0.358	0.758
Γ_Λ	KEK-E462/E508 (Kameoka *et al.*, 2005)	0.947 ± 0.038	1.242 ± 0.042
a_Λ	KEK-E462/E508 (Maruta *et al.*, 2007)	$0.07 \pm 0.08 + 0.08$	$-0.16 \pm 0.28 + 0.18$
	OME (Chumillas *et al.*, 2007, 2008)	-0.590	-0.698
	With final-state interactions	-0.401	-0.340
	OME $+ 2\pi + 2\pi/\sigma$ (Chumillas *et al.*, 2007, 2008)	$+0.041$	-0.207
	With final-state interactions	$+0.028$	-0.126
	OME $+ 2\pi/\sigma + a_1$ (Itonaga *et al.*, 2008; Itonaga and Motoba, 2010)	$+0.083$	$+0.044$

Summary

- We propose the J-PARC E75 experiment to investigate ${}^{5}_{\Lambda\Lambda}\mathrm{H}$.
  - A light Ξ hypernucleus, ${}^{7}_{\Xi^-}\mathrm{H}$, will be produced by the ${}^{7}\mathrm{Li}(K^-, K^+)$ reaction in the phase-1 experiment.
  - ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will be produced by decay of ${}^{7}_{\Xi^-}\mathrm{H}$ with a large probability.
  - Decay pion spectroscopy for ${}^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-$.
- Beyond E75, different double-Λ hypernuclei (${}^{6}_{\Lambda\Lambda}\mathrm{He}$ etc.) and/or weak decay may be explored. (Any suggestion is welcome!)
- If you're interested in the J-PARC E75 experiment, please feel free to contact us!

Thank you for your attention!