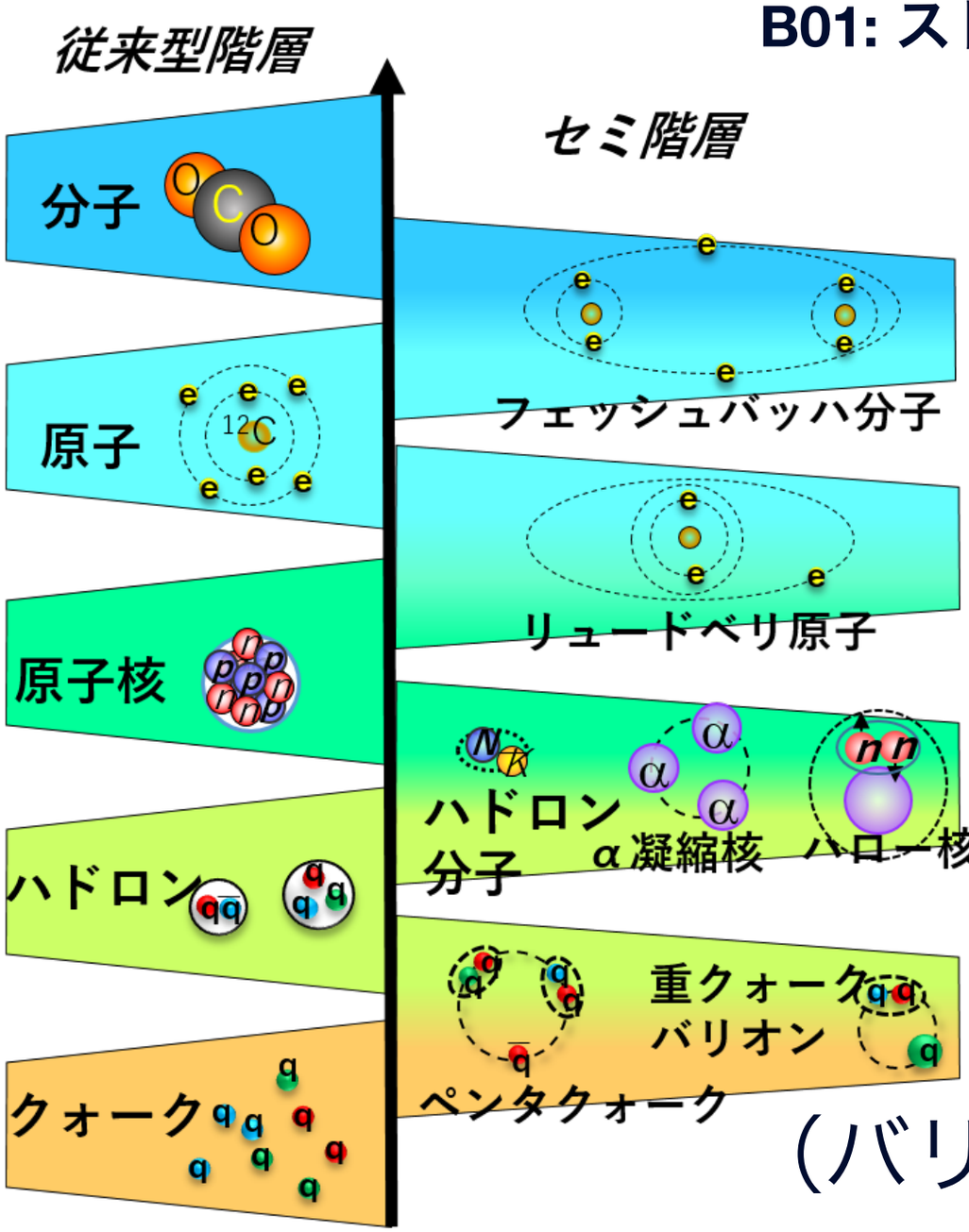
ダブルΛハイパー核の分光実験に用いるガス検出器の読み出しシステム構築と性能評価

藤岡　宏之　（東工大）

東京工業大学
Tokyo Institute of Technology

本研究の位置付け

B01: ストレンジ・ハドロンクラスターで探る物質の階層構造



ダブルΛハイパー核の分光実験

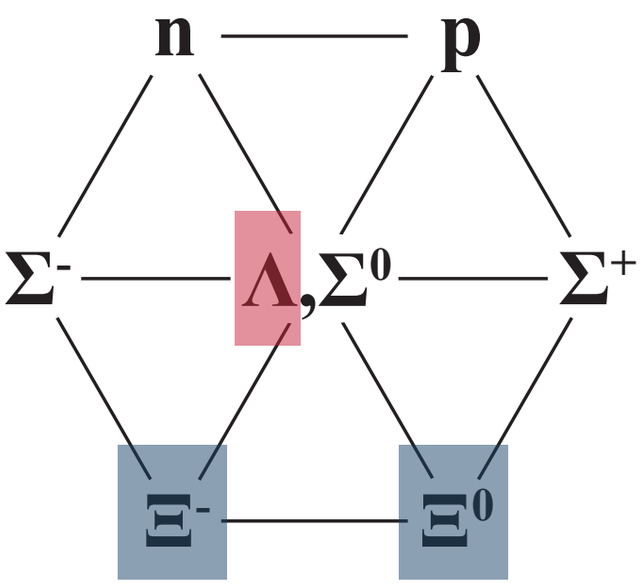
→ **ΛΛ-ΞN 結合**の研究

$$(uds)(uds) \leftrightarrow (dss)(uud)$$

「クラスター組み替え」

(バリオンクラスター内のクォークを交換)

Hypernuclei with $S = -2$

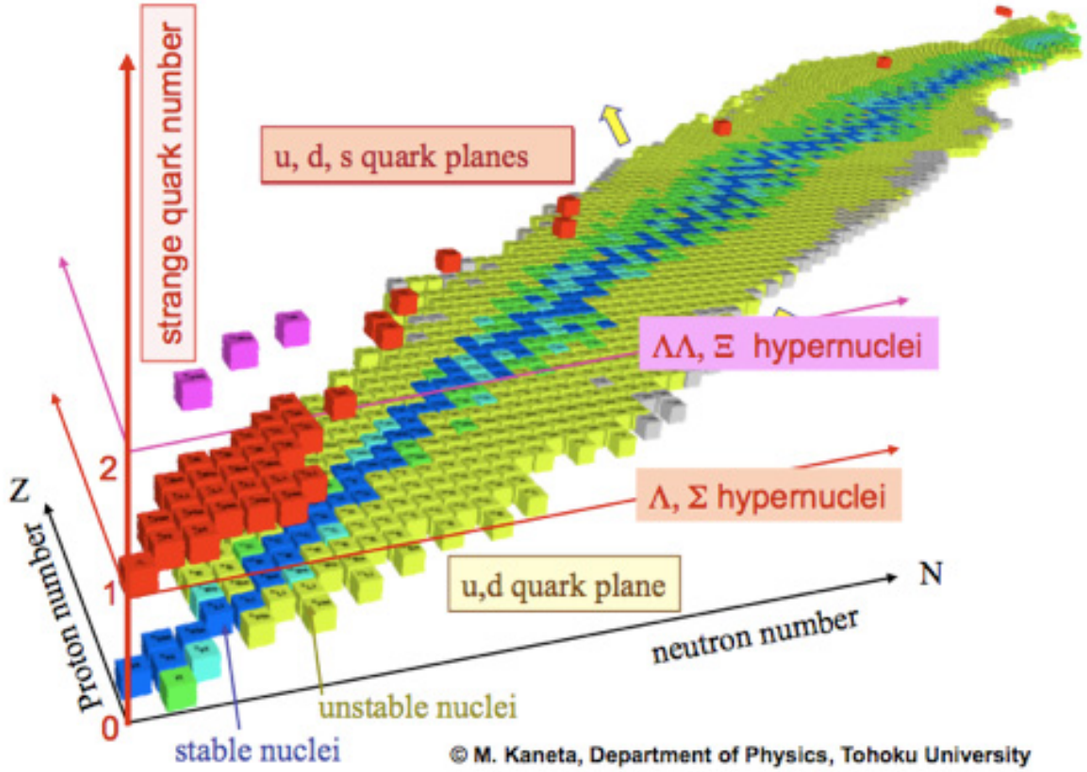


$S = 0$

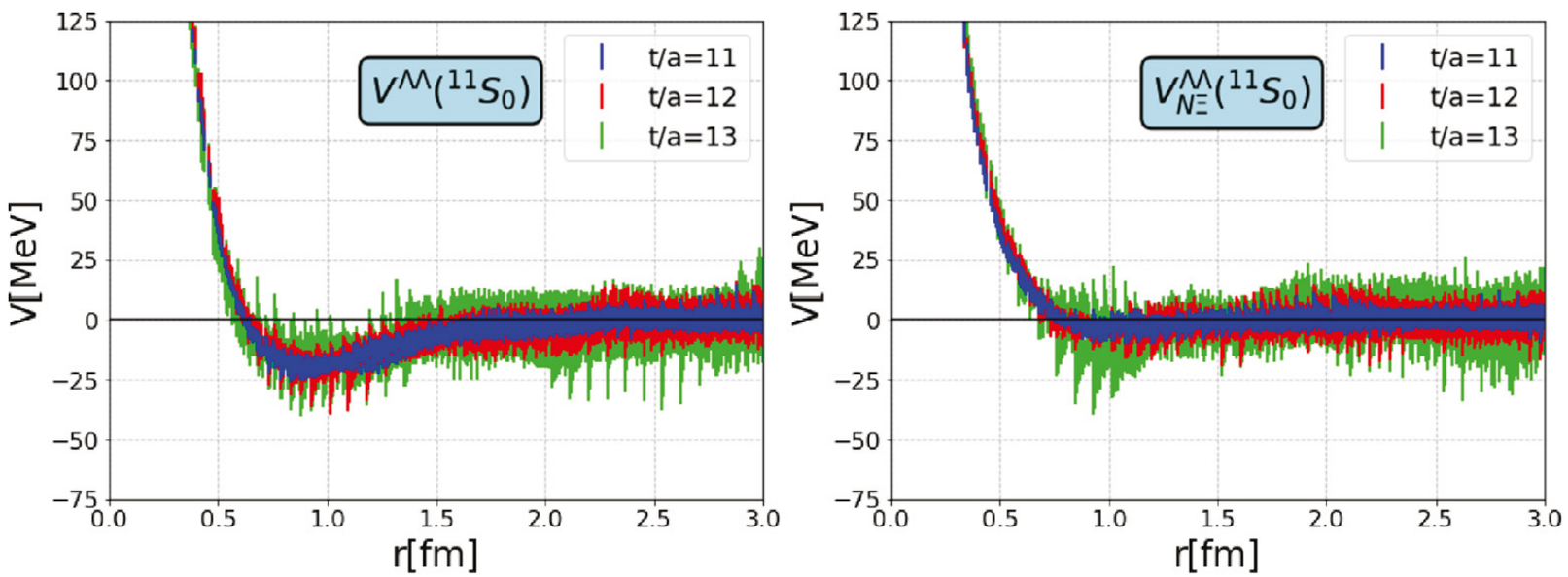
$S = -1$ ⟹ **Double Λ Hypernuclei**

$S = -2$ ⟶ **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



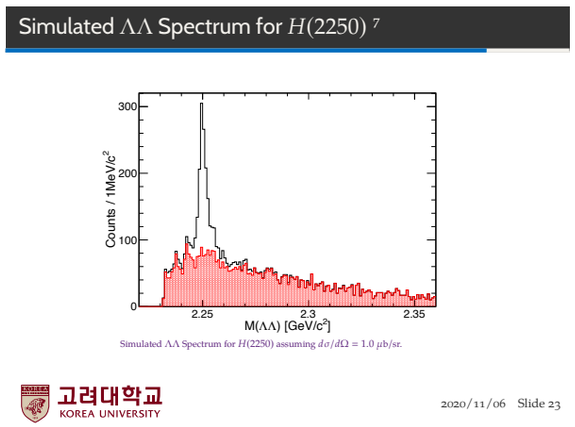
K. Sasaki et al. (HAL-QCD Collaboration) NPA 998 (2020) 121737

Study of ΞN, ΛΛ interaction

H-dibaryon

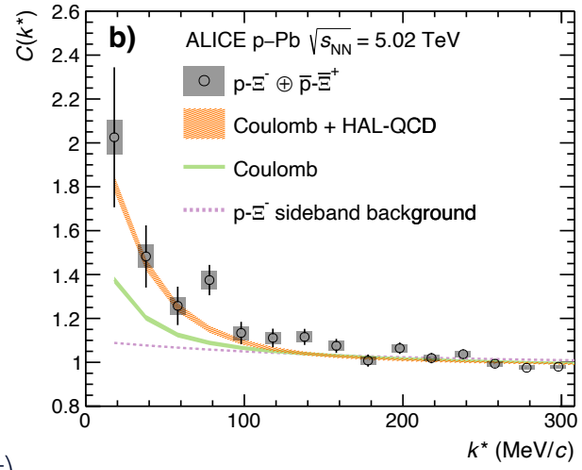
femtoscopy

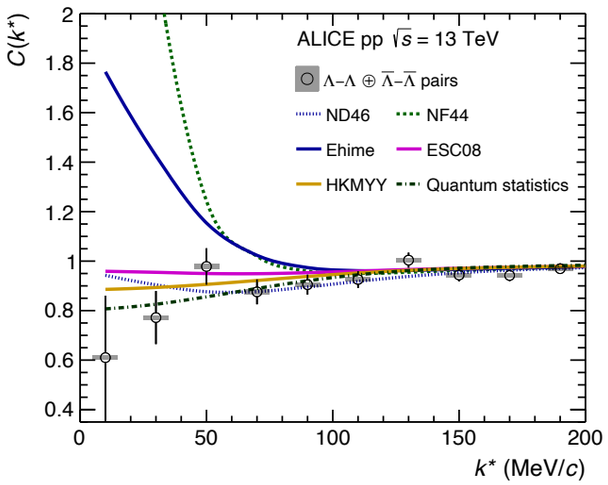
ΞN scattering

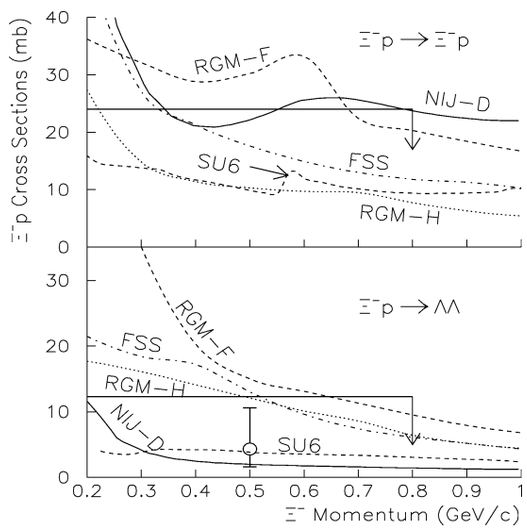


Ahn (J-PARC E42 Experiment)

http://apollo.lns.tohoku.ac.jp/workshop/c029/slides/ahn.pdf





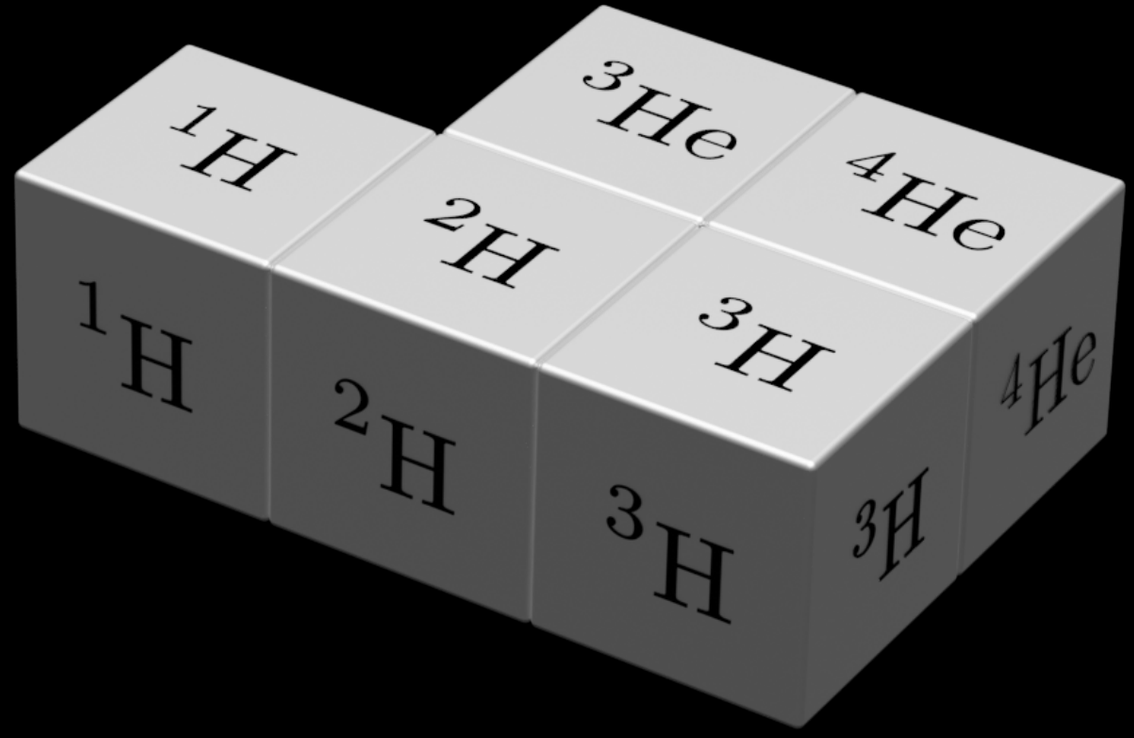


ALICE, PRL 123, 112002 (2019) ALICE, PLB 797, 134822 (2019) Ahn et al., PLB 633, 214 (2006)

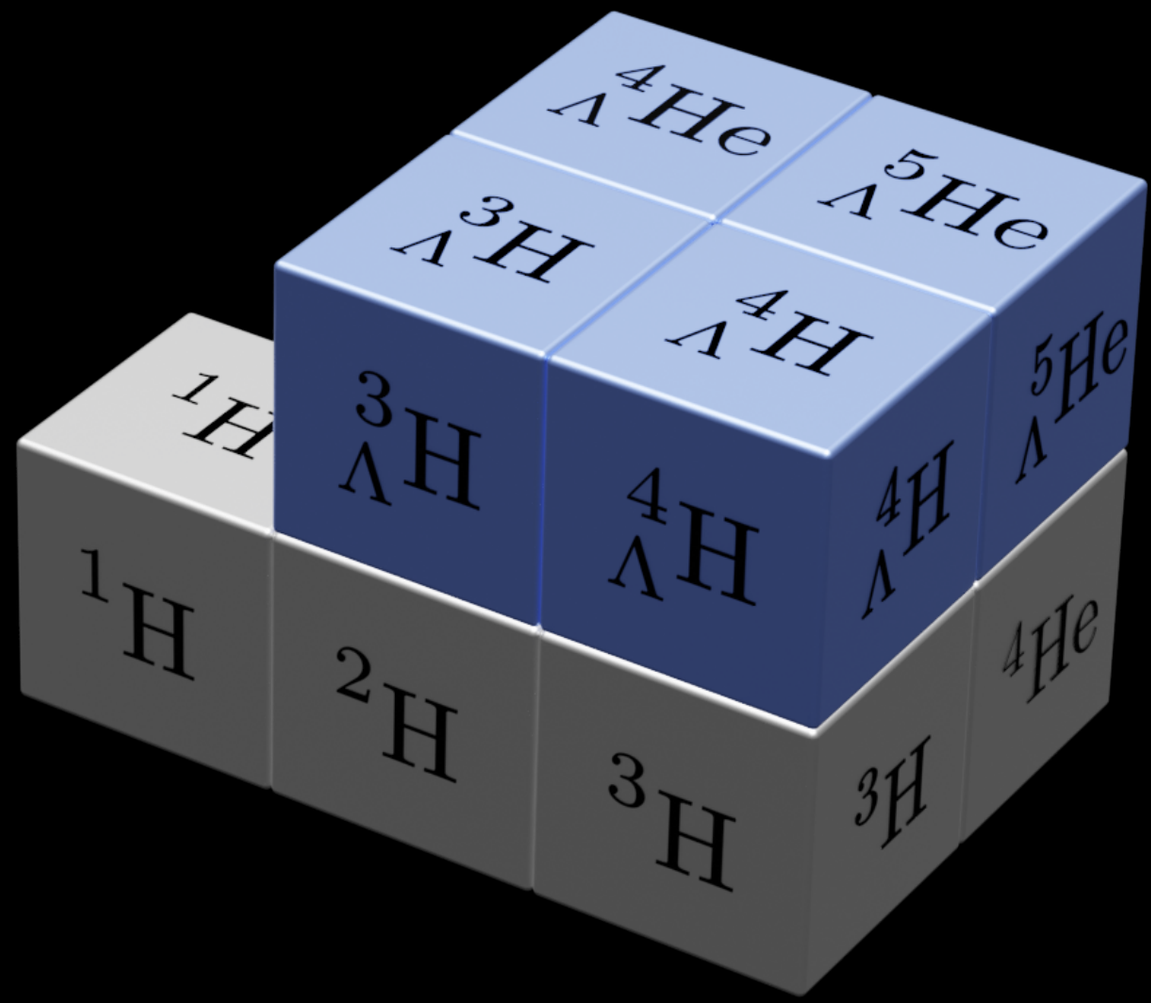
Ξ Hypernuclei

Double-Λ Hypernuclei

s-shell nuclei



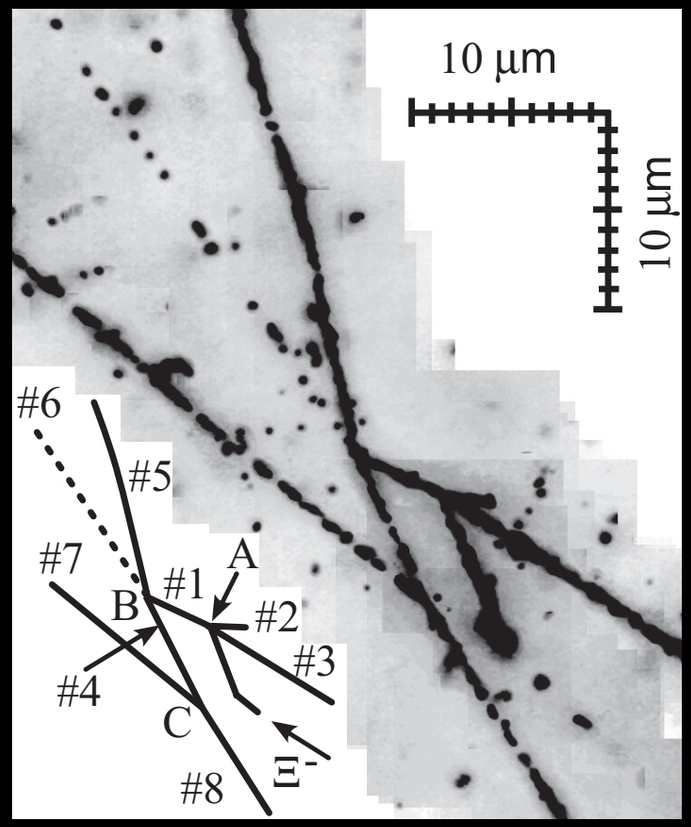
s-shell single-Λ hypernuclei



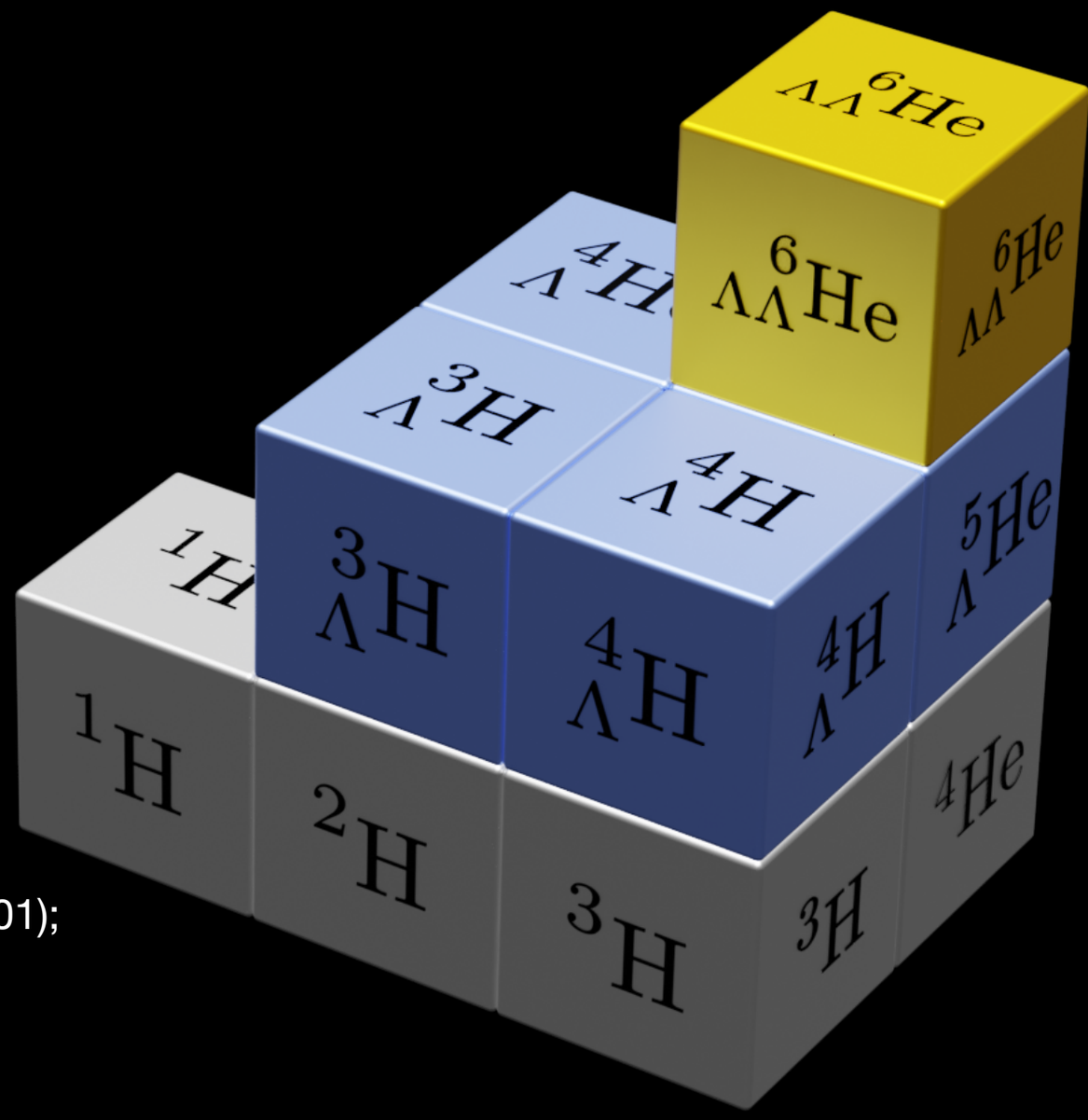
s-shell double-Λ hypernuclei

(as of June 2021)

NAGARA Event



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

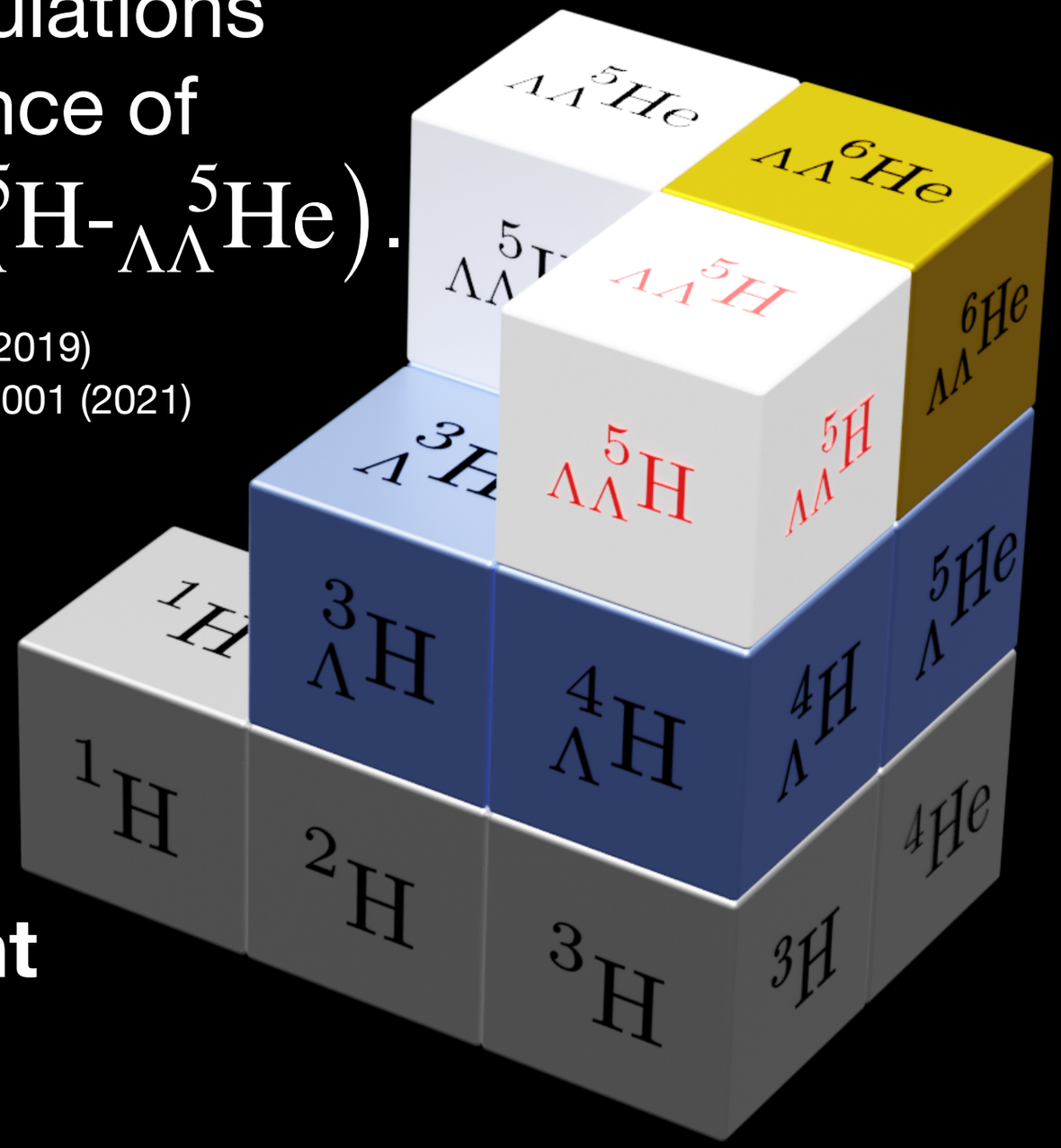


s-shell double-Λ hypernuclei

(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

Proposal for J-PARC 50 GeV Synchrotron

Decay Pion Spectroscopy of ${}^{5}_{\Lambda\Lambda}$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*

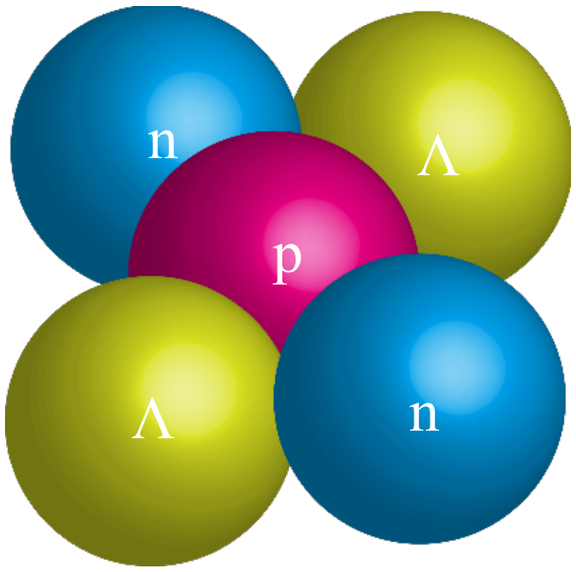
[5] *Department of Physics, Kyushu University*

[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*



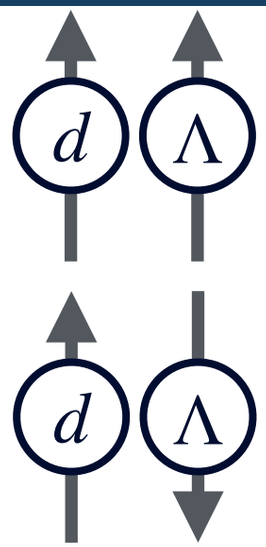
December 14, 2018

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

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

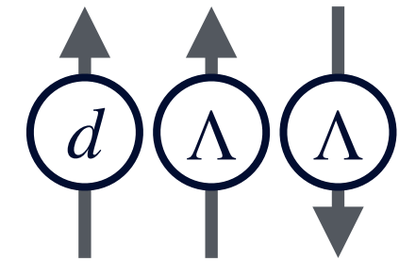
$A = 4$

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



$3/2^{+}$: unbound

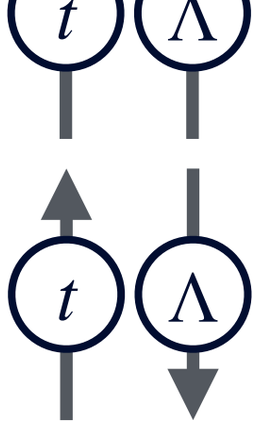
$1/2^{+}$: $B = 0.13\,\mathrm{MeV}$



most likely unbound

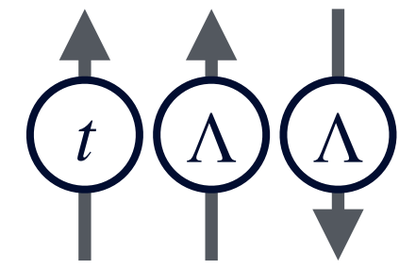
$A = 5$

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



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

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



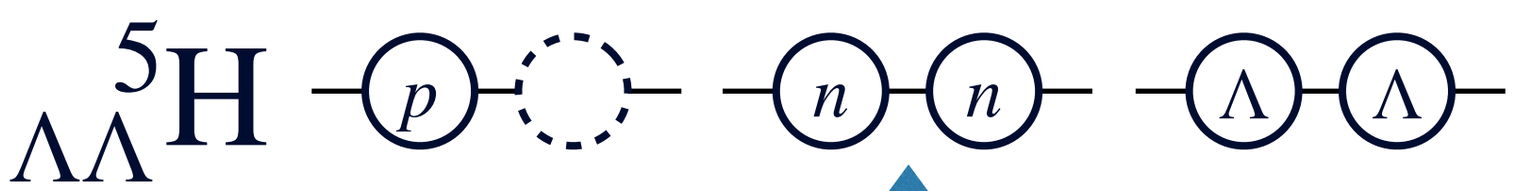
expected to be bound

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

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

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

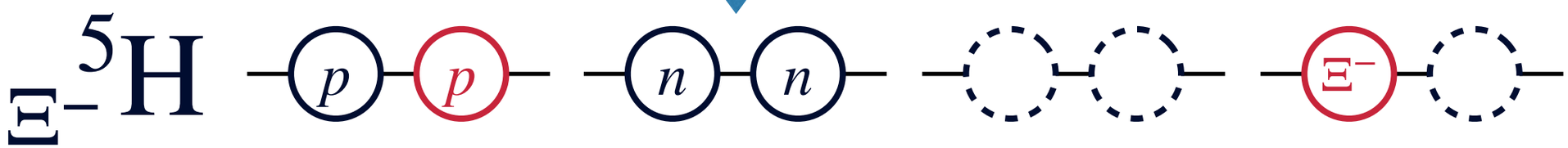
$A = 5$



~11MeV mass difference

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

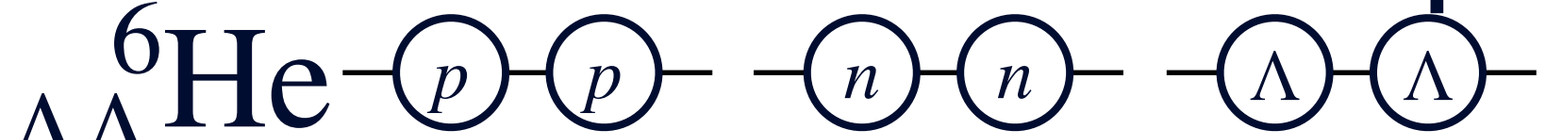
cf. B.F. Gibson et al.,
Prog. Theor. Phys. Suppl. 117, 339 (1994)



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

Triple-shell closure

$A = 6$



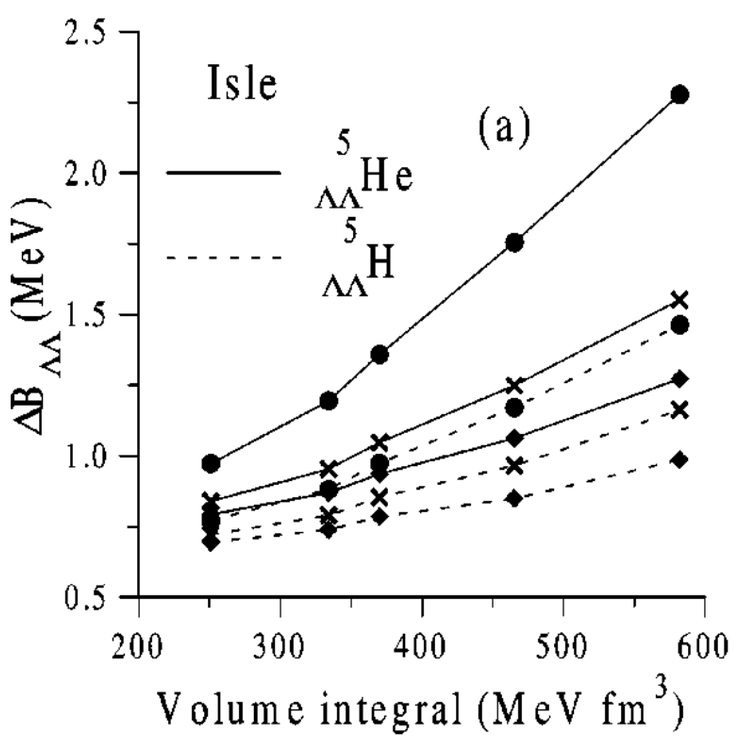
$(A \geq 7$ as well$)$

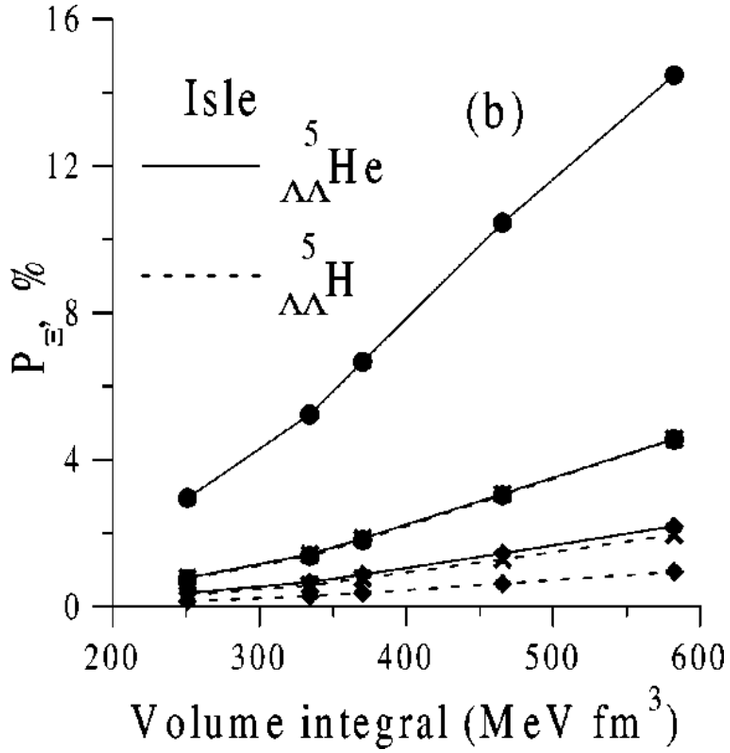
study of $\Lambda\Lambda$ interaction

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

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

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





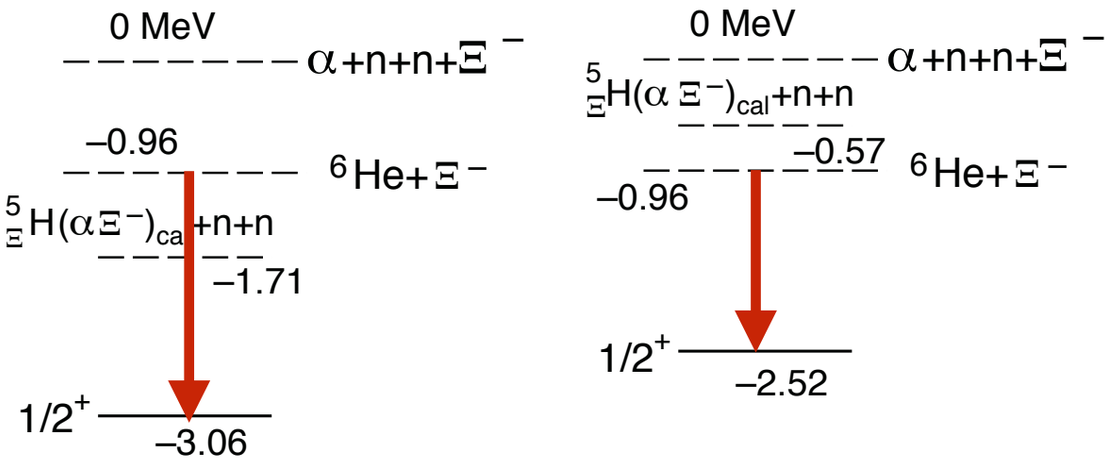
$$\int V_{\Lambda\Lambda,\Xi N}(r)d^3r$$

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

$\Delta B_{\Lambda\Lambda}$の値から、ΛΛ-ΞN結合ポテンシャルを評価する

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

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

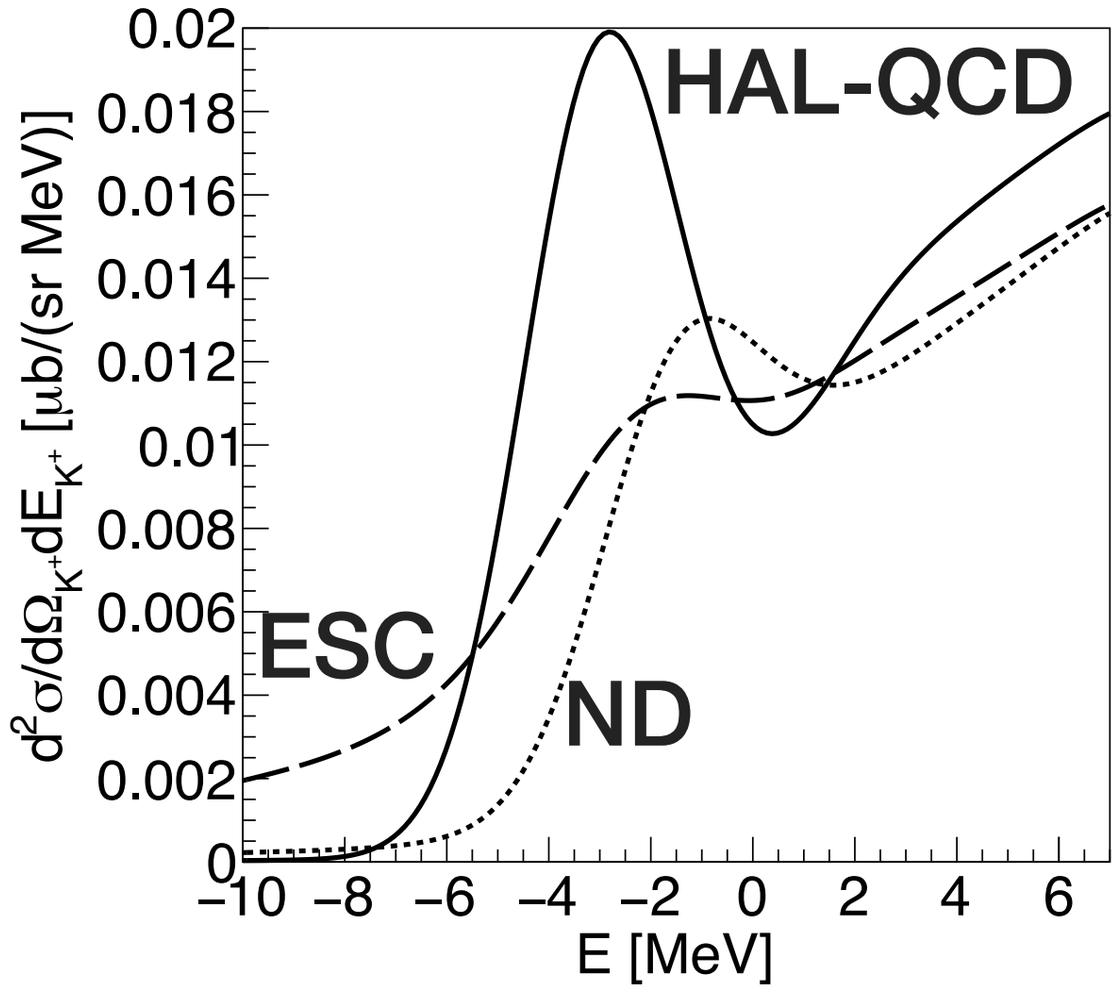


E. Hiyama et al., PRC **78**, 054316 (2008)

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

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*

[3] *Osaka Electro-Communication University*

[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

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)

$$
\begin{aligned}
{}^{7}_{\Xi}\mathrm{H} &\rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H} + n + n \quad \sim 11 \ \mathrm{MeV}, \\
&\rightarrow {}^{4}_{\Lambda}\mathrm{H} + \Lambda + n + n \quad \sim 7 \ \mathrm{MeV}, \\
&\rightarrow {}^{4}_{\Lambda}\mathrm{H}^{*} + \Lambda + n + n \quad \sim 6 \ \mathrm{MeV}, \\
&\rightarrow {}^{3}\mathrm{H} + \Lambda + \Lambda + n + n \quad \sim 5 \ \mathrm{MeV}.
\end{aligned}
$$

B.R. ~90%

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

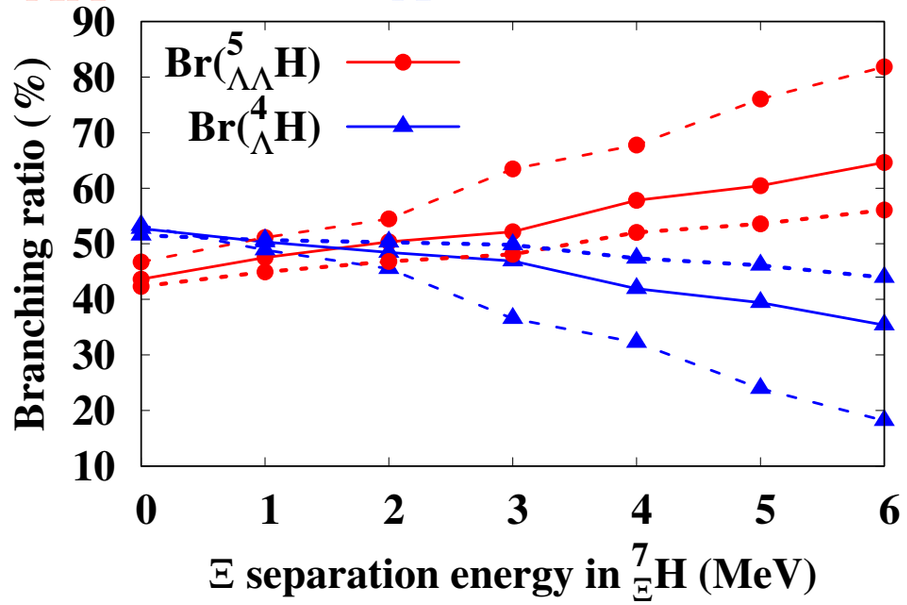
Akira Ohnishi[1,*], Chikako Ishizuka[2], Kohsuke Tsubakihara[2,3], and Yuichi Hirata[4]

[1]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Laboratory for Advanced Nuclear Energy, Institute of Innovative Research, Tokyo Institute of Technology, Tokyo 152-8550, Japan*
[3]*National Institute of Technology, Asahikawa College, Asahikawa 071-8142, Japan*
[4]*Central Institute of Isotope Science, Hokkaido University, Sapporo 060-0815, Japan*
[*]E-mail: ohnishi@yukawa.kyoto-u.ac.jp

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

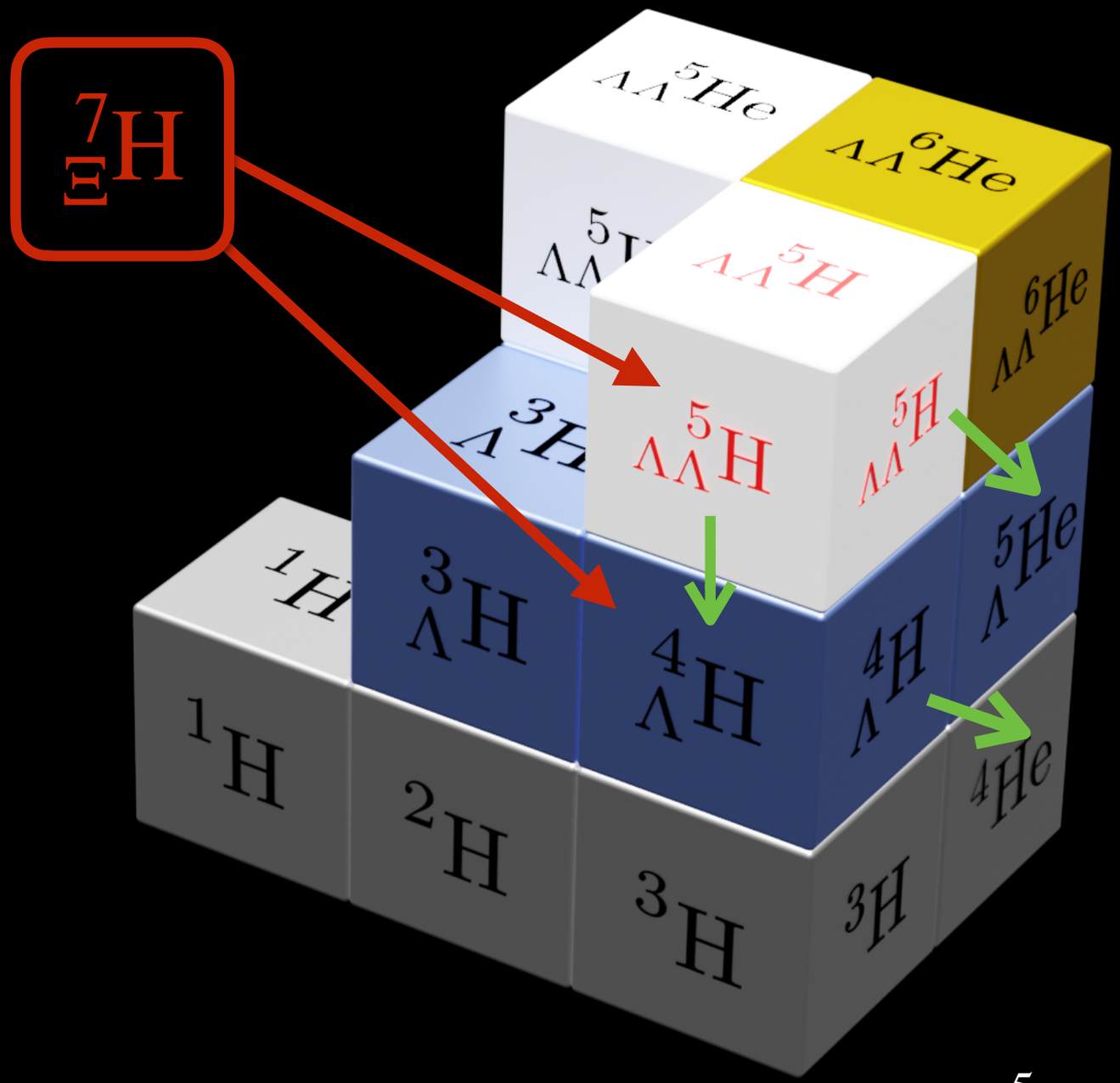
A. Ohnishi et al., Prog. Theor. Exp. Phys. **2020**, 29 (2020)

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



B.R. ~50%

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



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

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

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

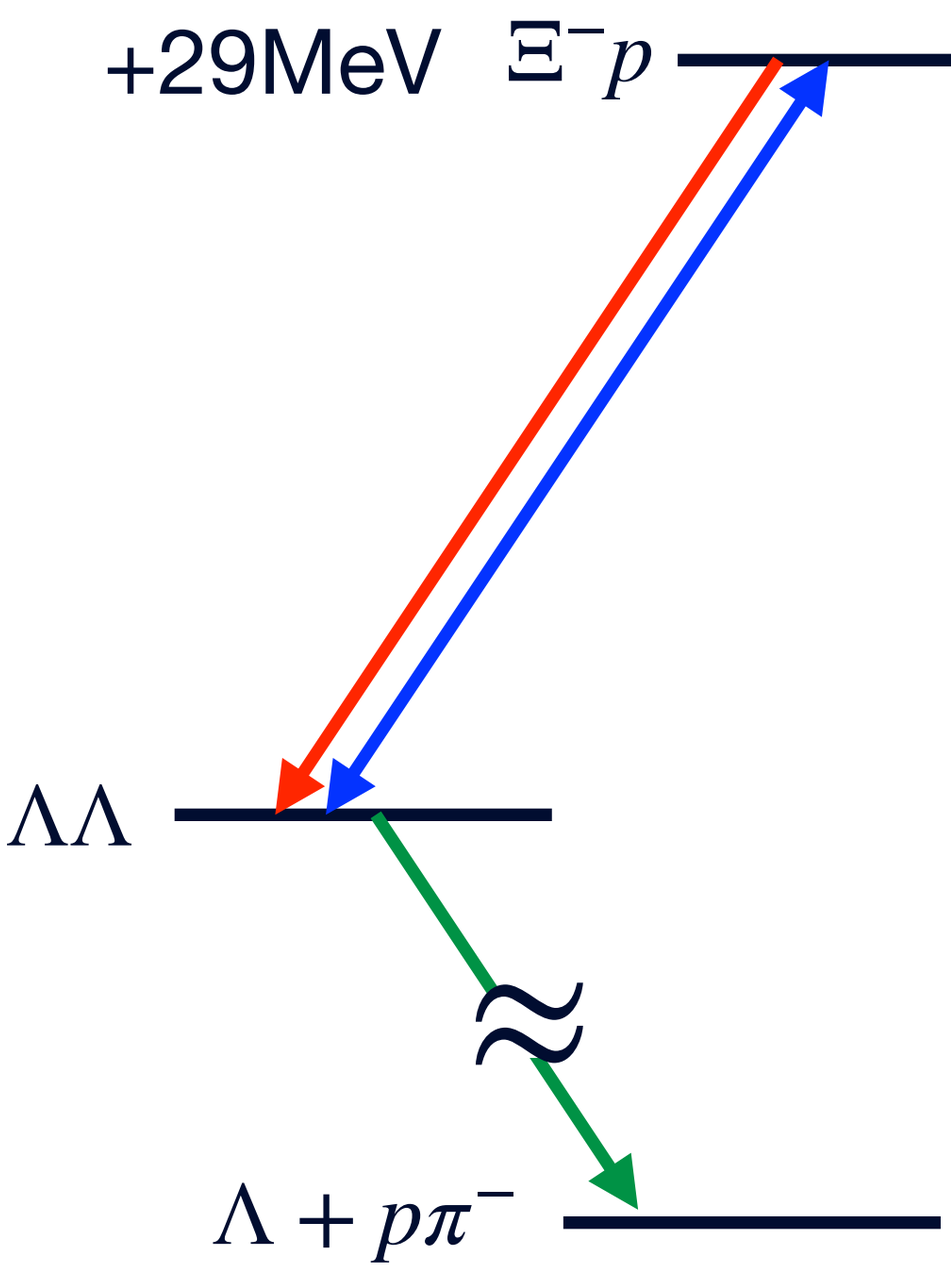
$$_{\Lambda}{}^{4}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^-$$

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

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

クォーク・ハドロン　セミ階層

$$(uds)(uds) \leftrightarrow (dss)(uud)$$

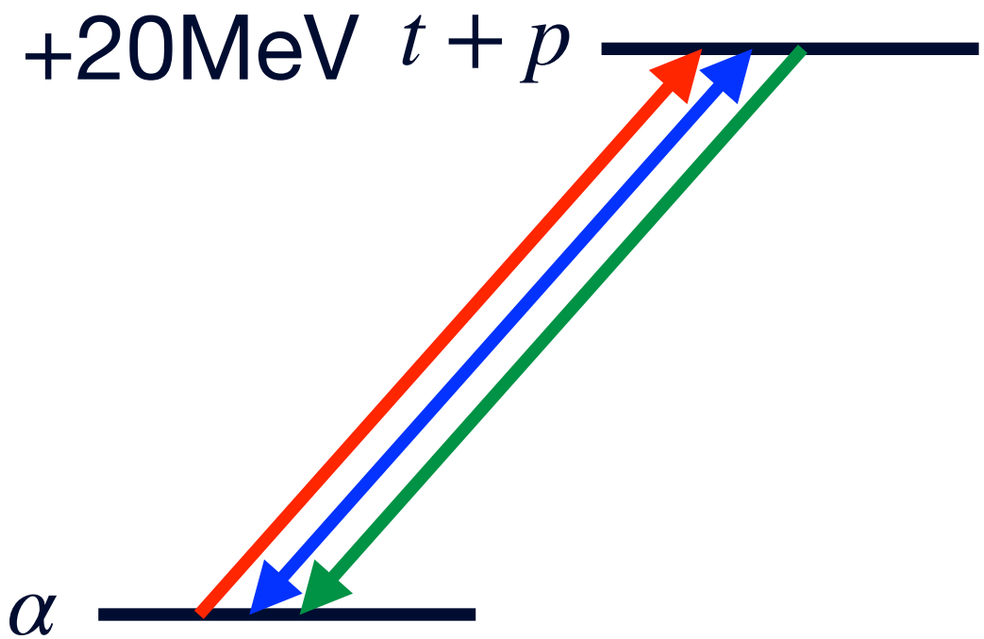


ハドロン・原子核　セミ階層

(1) ${}^{7}_{\Xi}\mathrm{H} \rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$

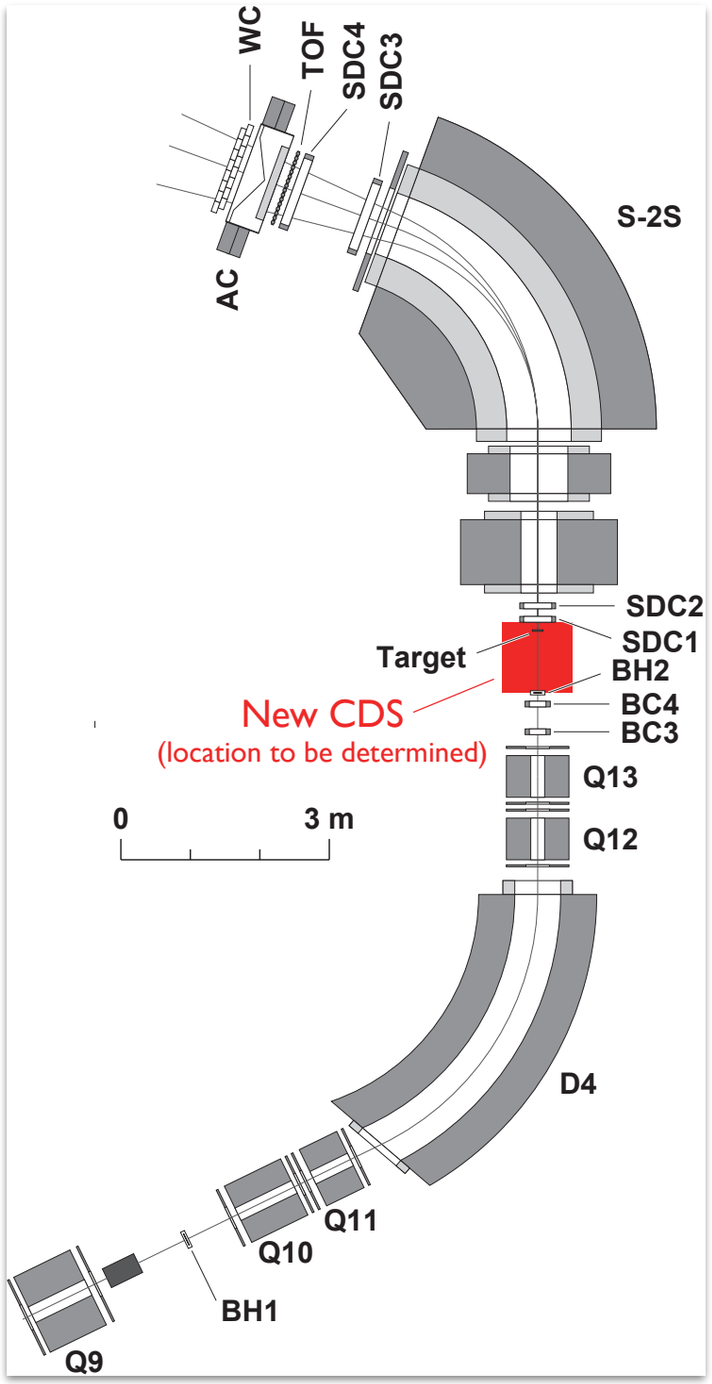
(2) ${}^{5}_{\Lambda\Lambda}\mathrm{H} \leftrightarrow {}^{5}_{\Xi}\mathrm{H}$

(3) ${}^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-$



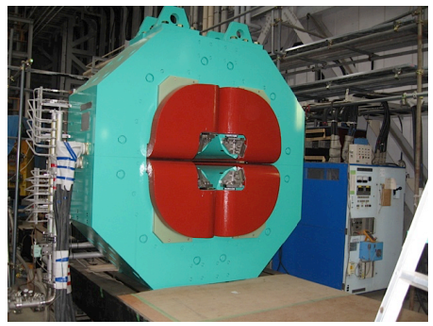
クラスターの組み替え

Experimental Setup



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

K1.8 + “S-2S” (common to E70 Exp.)

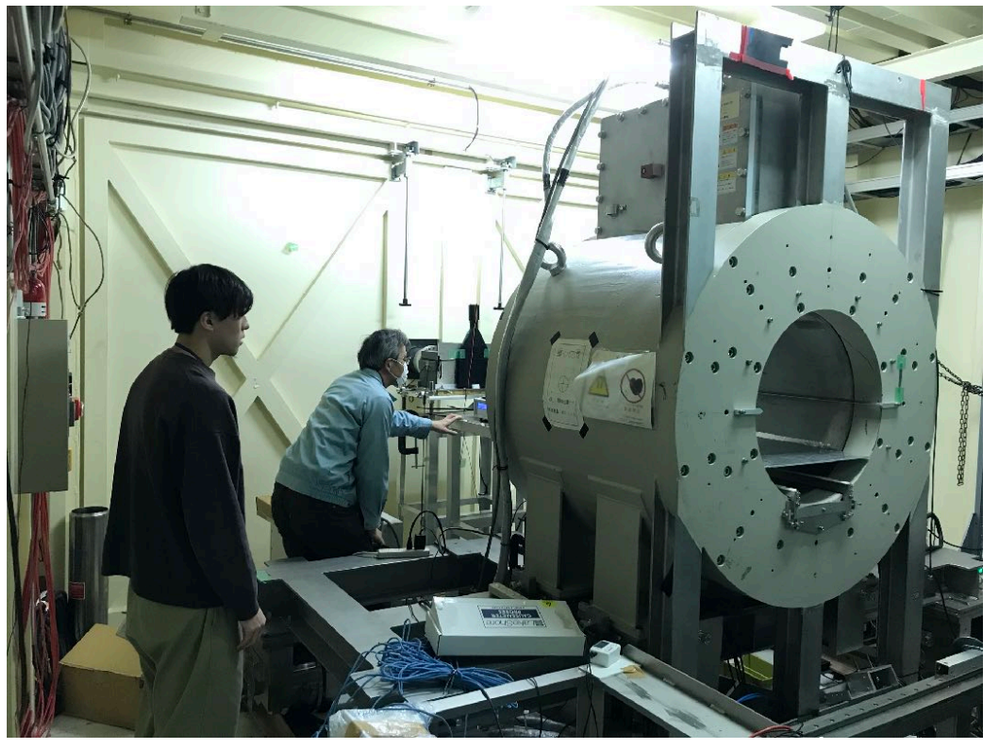


${}^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^{-}$ (decay pion spectroscopy)

Cylindrical Detector System

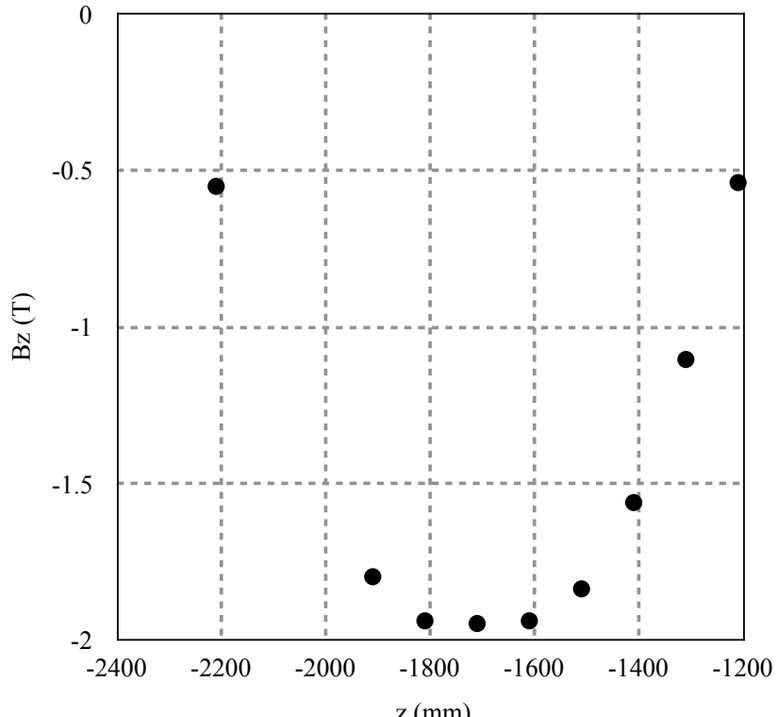
solenoid magnet + TPC + …

Superconducting solenoid

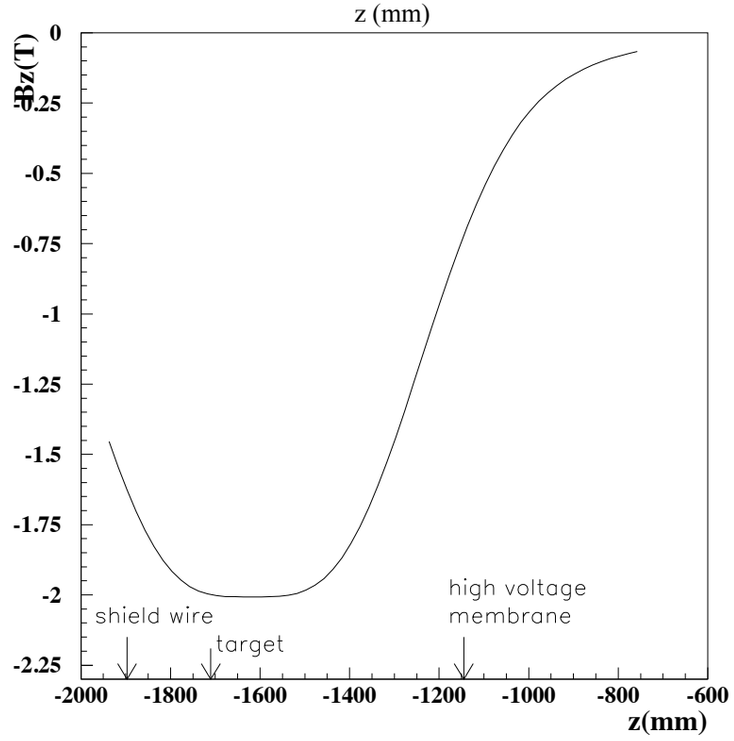


Excitation Test
in Nov.-Dec. 2019

Measurement
(2019/12/16)



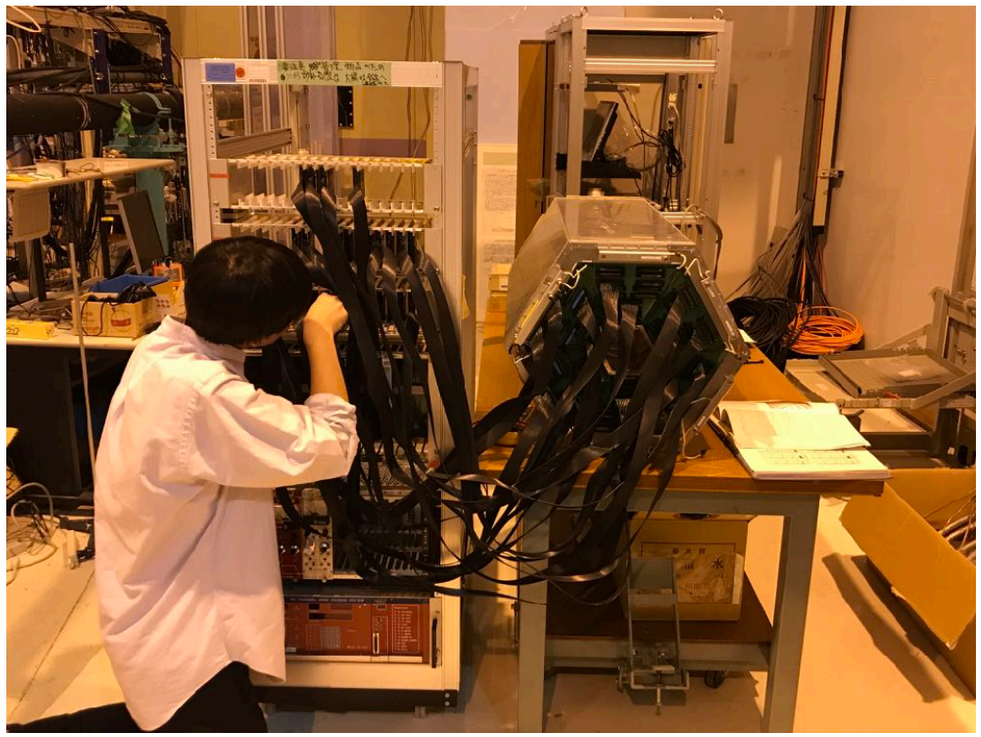
calculation by
OPERA-3D (TOSCA)

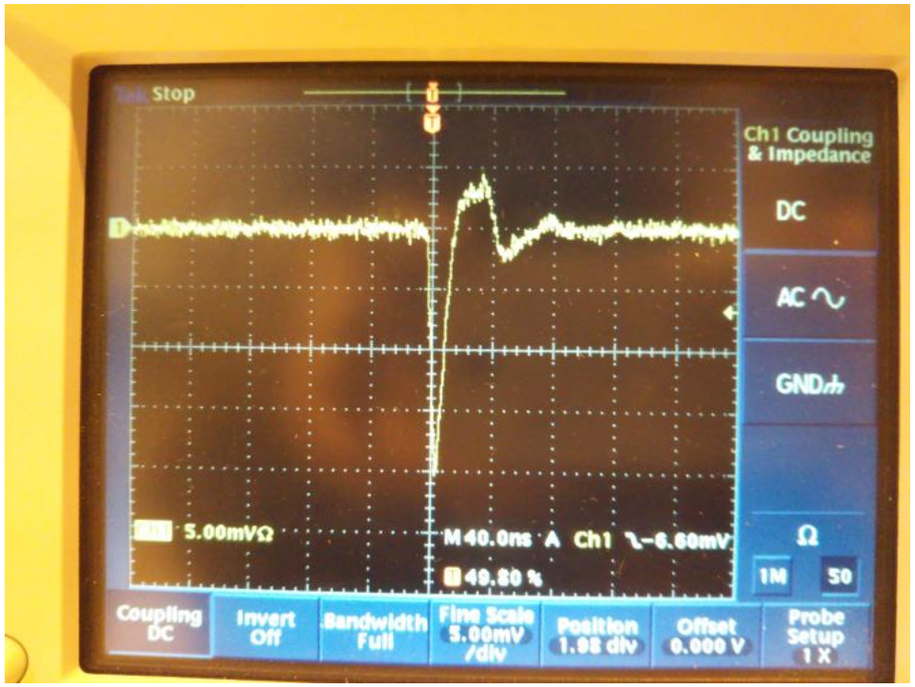


Y. Nakatsugawa et al.,
Ph. D thesis, Osaka Univ. (2013)

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.

supported by Joint Usage/Research Programs of RCNP

- The TPC was moved to TokyoTech in Nov. 2020.

- 本研究では TPC の読み出しシステム整備、性能評価

新学術領域「クラスター階層」「量子ビーム応用」合同検出器ワークショップ (2019年度)
味村周平氏（大阪大RCNP）のスライドより引用

まとめ

- J-PARC において ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ の分光実験を提案している。
  - ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ と異なり、$\Lambda\Lambda$-ΞN 結合が寄与する可能性。
  - Ξハイパー核 ${}^{7}_{\Xi^-}\mathrm{H}$ の崩壊により生成する。
  - ${}^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-$ という崩壊により生じたπ^-中間子の運動量を測定することで${}^{5}_{\Lambda\Lambda}\mathrm{H}$ の質量を決定する。

- 本研究ではπ^-中間子と陽子の運動量解析に用いるTPCの読み出しシステムの整備、TPCの性能評価を実施する。