2023.2.14
EMMI workshop in Bologna

Recent results and prospects in hypernuclear physics (mainly at J-PARC)

Tohoku University
Japan Atomic Energy Agency
H. Tamura

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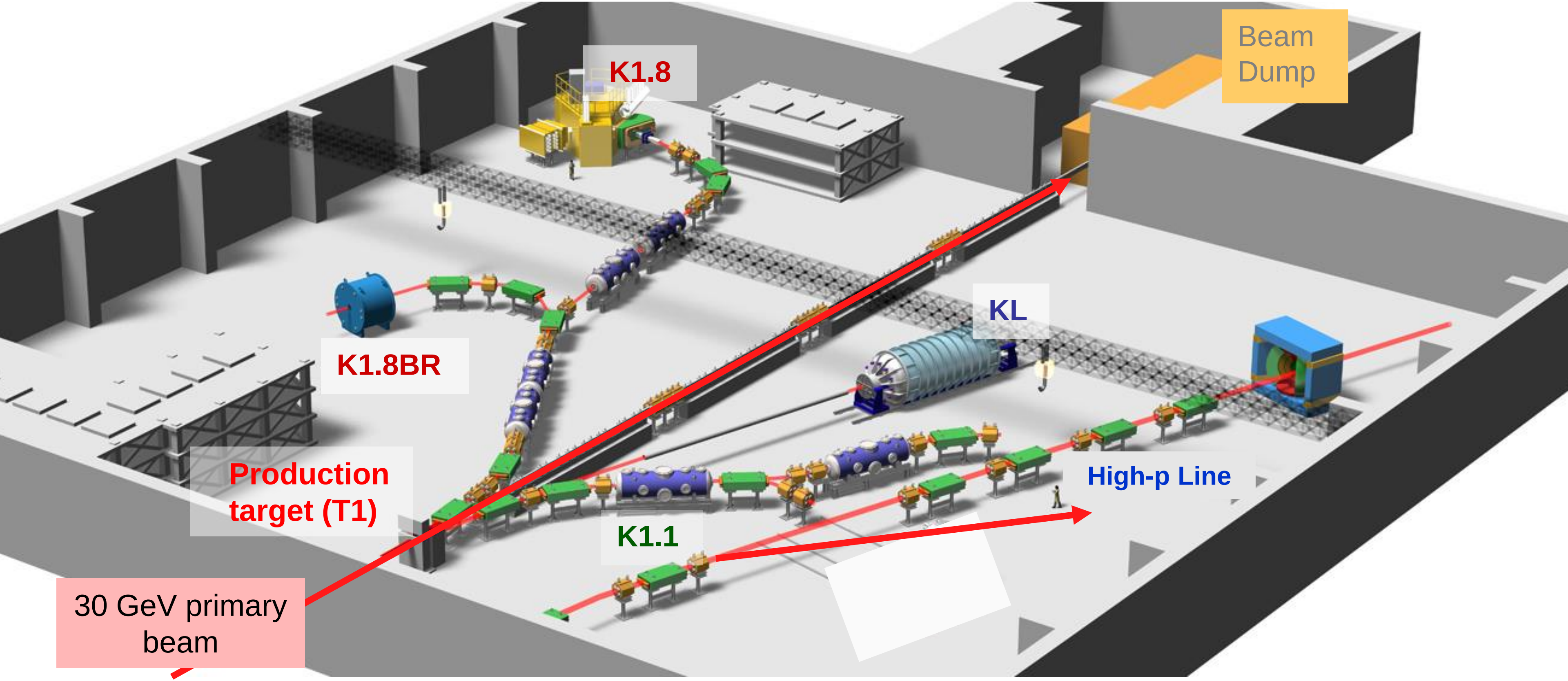
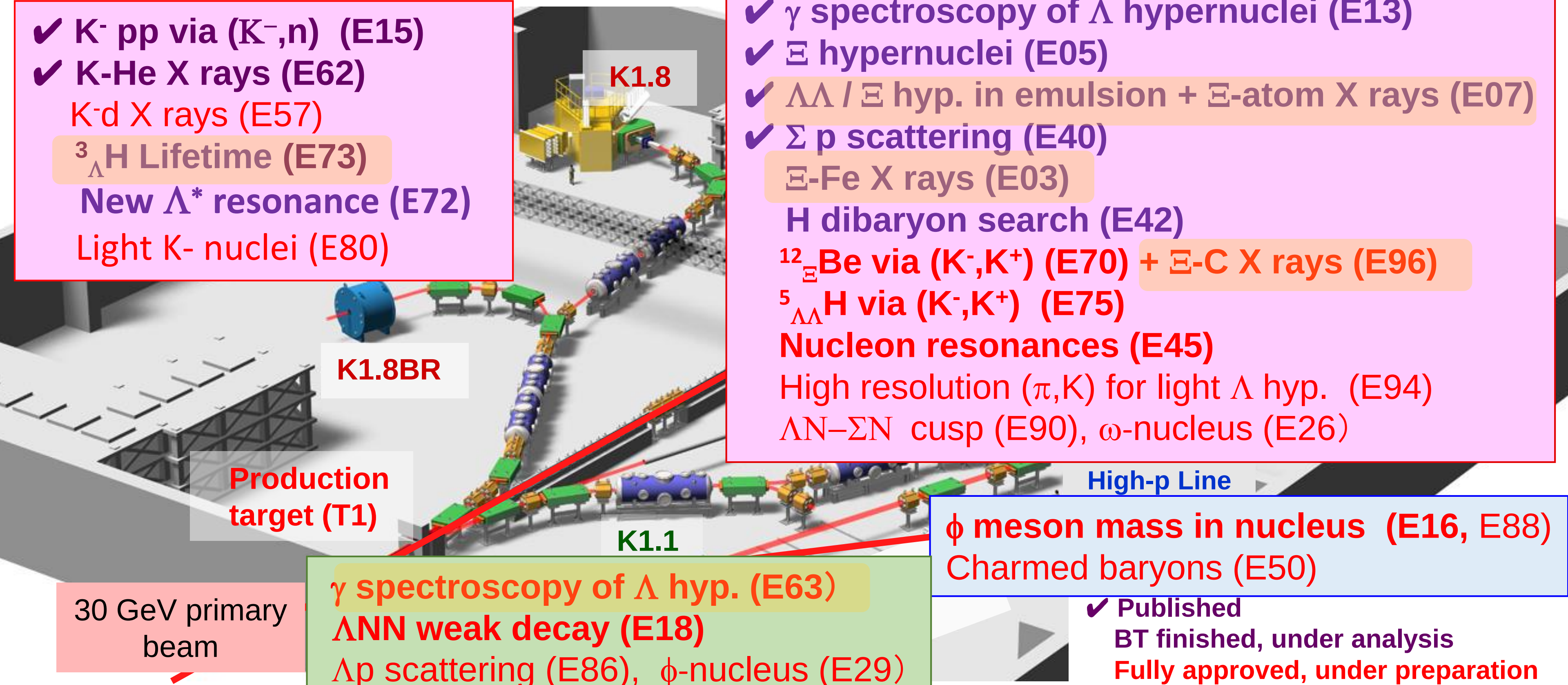
1. Introduction

Present status at J-PARC

J-PARC Hadron Hall
Present status of nuclear/hadron experiments



J-PARC
Present status of nuclea



- ✔ K$^-$ pp via (K$^-$,n) (E15)
- ✔ K-He X rays (E62)
- K$^-$d X rays (E57)
- $^{3}_{\Lambda}$H Lifetime (E73)
- New Λ^* resonance (E72)
- Light K- nuclei (E80)

- ✔ Θ^+ pentaquark search (E19)
- ✔ n-rich Λ hypernuclei (E10)
- ✔ K$^-$pp via (π^+,K$^+$) (E27)
- ✔ γ spectroscopy of Λ hypernuclei (E13)
- ✔ Ξ hypernuclei (E05)
- ✔ $\Lambda\Lambda$ / Ξ hyp. in emulsion + Ξ-atom X rays (E07)
- ✔ Σ p scattering (E40)
- Ξ-Fe X rays (E03)
- H dibaryon search (E42)
- $^{12}_{\Xi}$Be via (K$^-$,K$^+$) (E70) + Ξ-C X rays (E96)
- $^{5}_{\Lambda\Lambda}$H via (K$^-$,K$^+$) (E75)
- Nucleon resonances (E45)
- High resolution (π,K) for light Λ hyp. (E94)
- ΛN–ΣN cusp (E90), ω-nucleus (E26)

- ϕ meson mass in nucleus (E16, E88)
- Charmed baryons (E50)

30 GeV primary beam

- γ spectroscopy of Λ hyp. (E63)
- ΛNN weak decay (E18)
- Λp scattering (E86), ϕ-nucleus (E29)

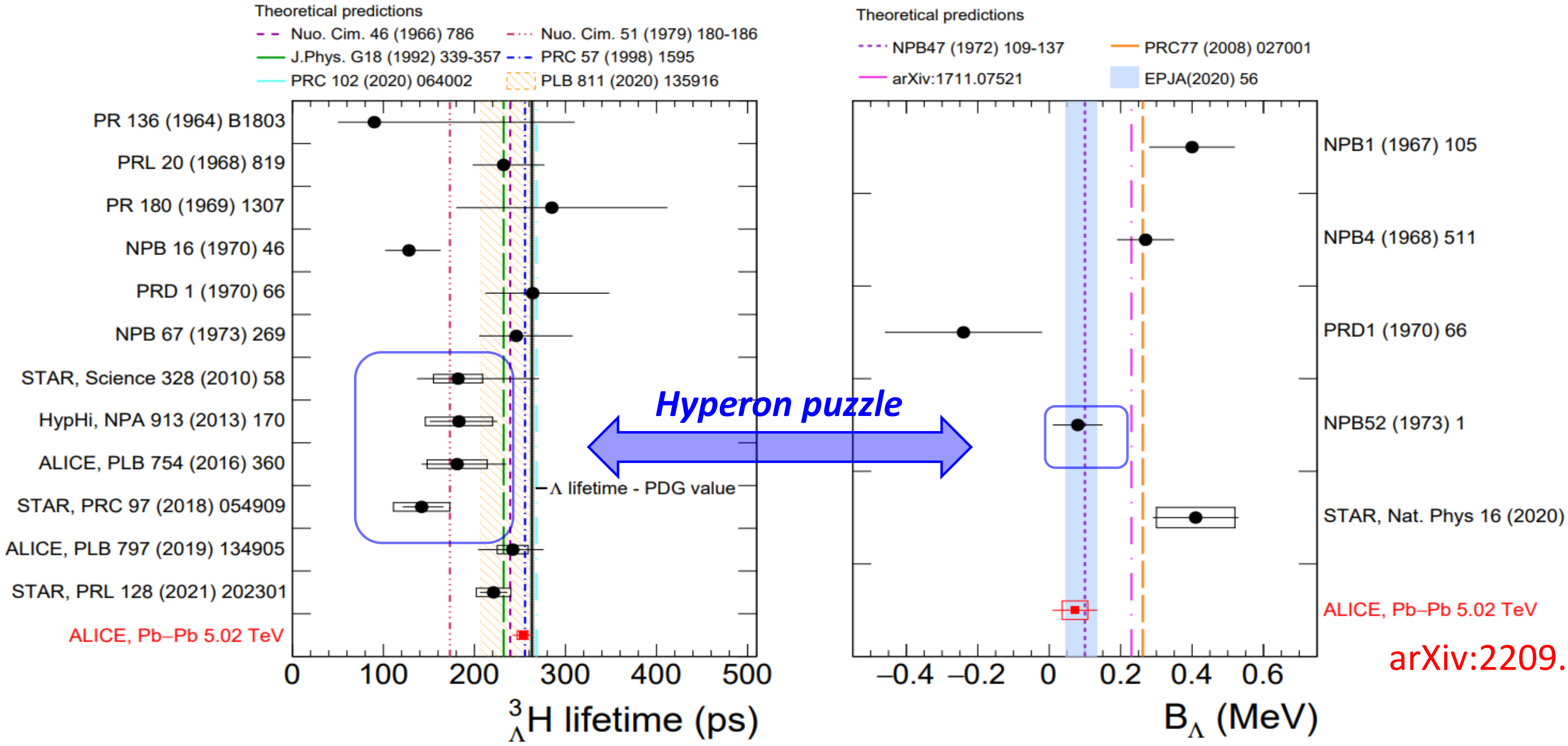
✔ Published
BT finished, under analysis
Fully approved, under preparation
Stage-1 approved

2. Few-body (A=3,4) Λ hypernuclei

Features of few-body hypernuclei

- Precise few-body calculations possible
- Experimentally clear due to simple level structure
- Quite sensitive to YN interaction
  - $^{3}_{\Lambda}$H puzzle : $\tau - B_{\Lambda}$ relationship
  - Charge Symmetry Breaking puzzle ($^{4}_{\Lambda}$H/ $^{4}_{\Lambda}$He)
  - Large effects of spin-isospin dependence of YN interaction
  - Large effects of ΛN–ΣN coupling

Compilation on hypertriton (ALICE arXiv:2209.07360)



arXiv:2209.07360

Precise data via <u>different methods</u> from HI are necessary.

Direct timing measurement at J-PARC

Decay pion at MAMI
Analysis of emulsion at J-PARC

Hypertriton: New data after 2018 and prospects

Experiment	Reaction	Method	τ ($^3_\Lambda$H)	τ ($^4_\Lambda$H)	B_Λ($^3_\Lambda$H)
STAR	HI (Au+Au) √s=3GeV	decay length inv. mass	142+24−21±29 221±15±19	 218±6±13	0.41±0.12±0.11 under analysis
ALICE	HI (Pb+Pb) √s=5TeV	decay length inv. mass	242+34−38±17 253±11±6	preliminary	0.072±0.063 ±0.036
HADES	HI (Ag+Ag) √s=2.55GeV	decay length	256±22±36 (preliminary)	222±8±13 (preliminary)	
WASA-FRS	HI (^{6}Li+^{12}C) 2GeVA	decay length	under analysis	under analysis	under analysis
J-PARC E73	^{3,4}He(K$^-$,π^0)	decay time	test data taken run in 2023	190±8±?? to be published	-
MAMI	^{7}Li(e,K$^+$)	decay pion momentum	-	-	under analysis ΔM~±0.02
J-PARC E07	K$^-$ on emulsion	decay time decay energy	under analysis	later	under analysis
JLab E12-19-002	^{3}He(e,e'K$^+$)	missing mass	-	-	approved
ELPH	^{3,4}He(γ, K$^+$)	decay time	proposed	partly approved	

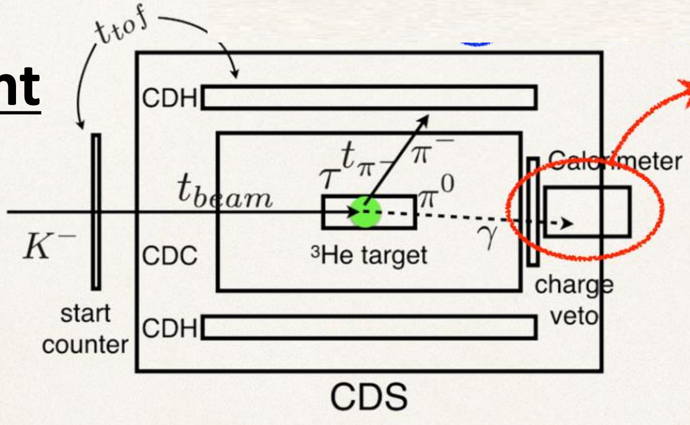
Direct timing measurement

J-PARC E73

$K^- \ {}^{3,4}He \rightarrow {}^{3,4}_{\Lambda}H + \pi^0$

${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$

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



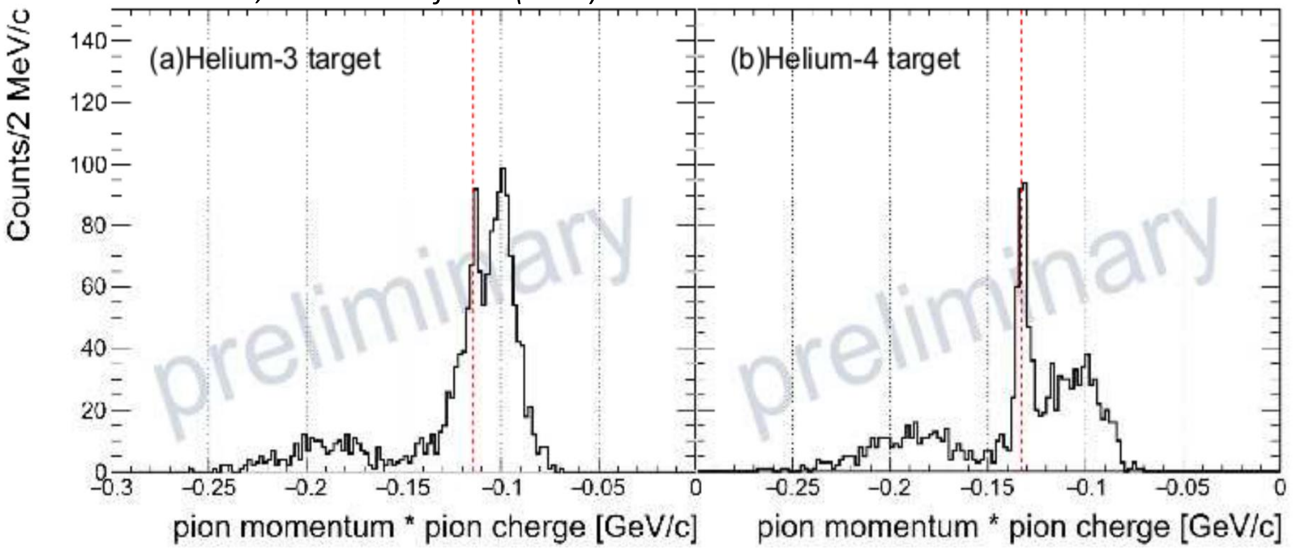
5x8 PbF2 Cherenkov Calo

R&D has been completed

${}^{3}_{\Lambda}H$ decay time can be derived by TOF and CDS tracking

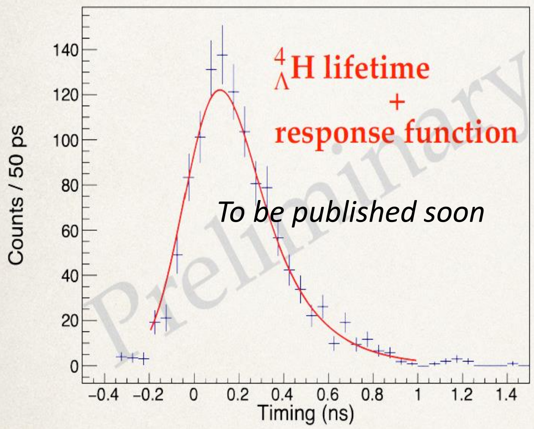
The idea of ***direct measurement***: $T_{CDH} - T_0 = t_{beam} + t_{\pi^-} + \tau$;

T. Akaishi et al., EPJ Web Conf. 271 (2022) 01003



Y. Ma, HYP2022

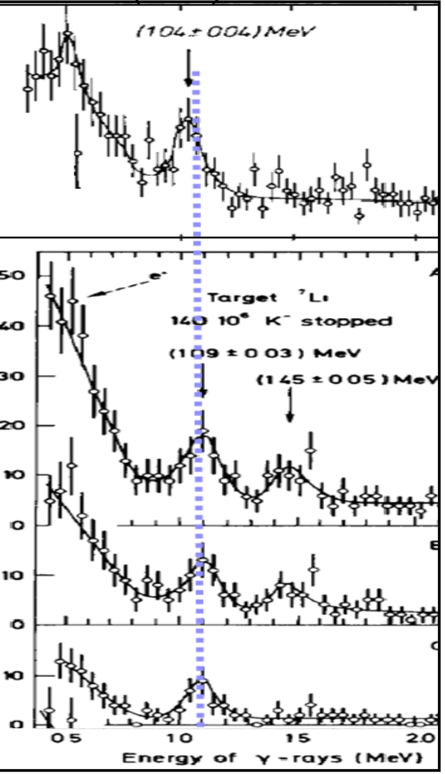
$190 \pm 8(\text{stat.}) \pm ??(\text{sys.})$ ps



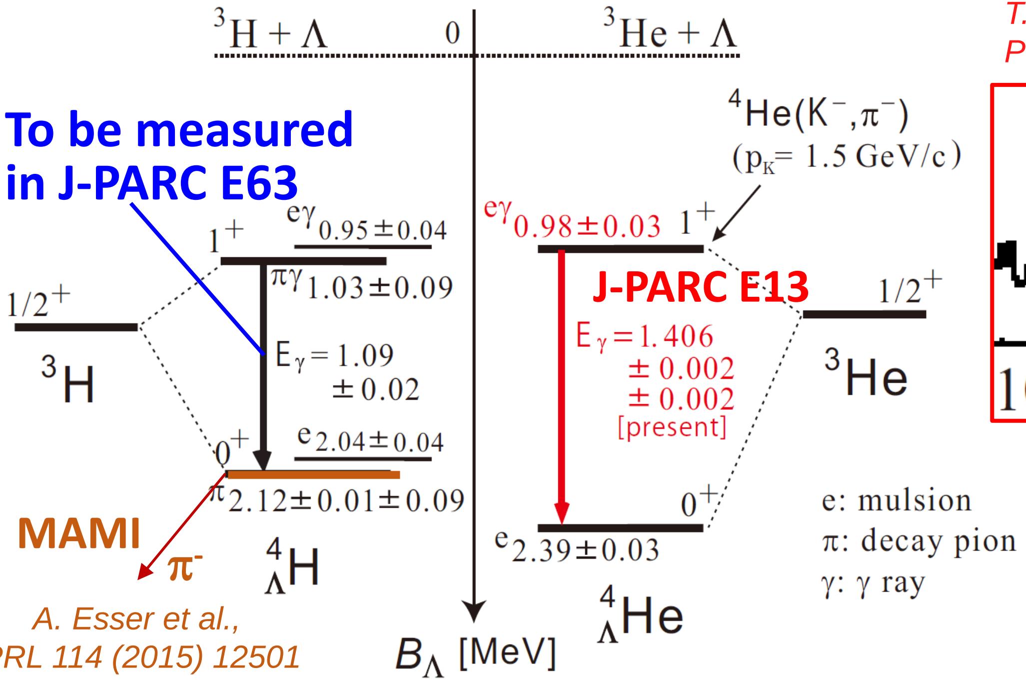
Charge Symmetry Breaking in A=4 Λ hypernuclei

Precise data are necessary to be compared with few-body calculations

Bedjidian et al.
PLB 62 (1976) 467
PLB 83 (1979) 252

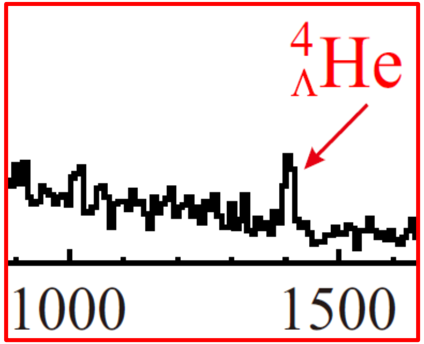


$^4_\Lambda$H γ-ray will be precisely measured with Ge detector array
via ^{7}Li(K$^-$,π^-) $^7_\Lambda$Li* , $^7_\Lambda$Li* → $^4_\Lambda$H* + X



A. Esser et al.,
PRL 114 (2015) 12501

T.O. Yamamoto et al.,
PRL 115 (2015) 222501



Level scheme of A=3 Λ hypernuclei

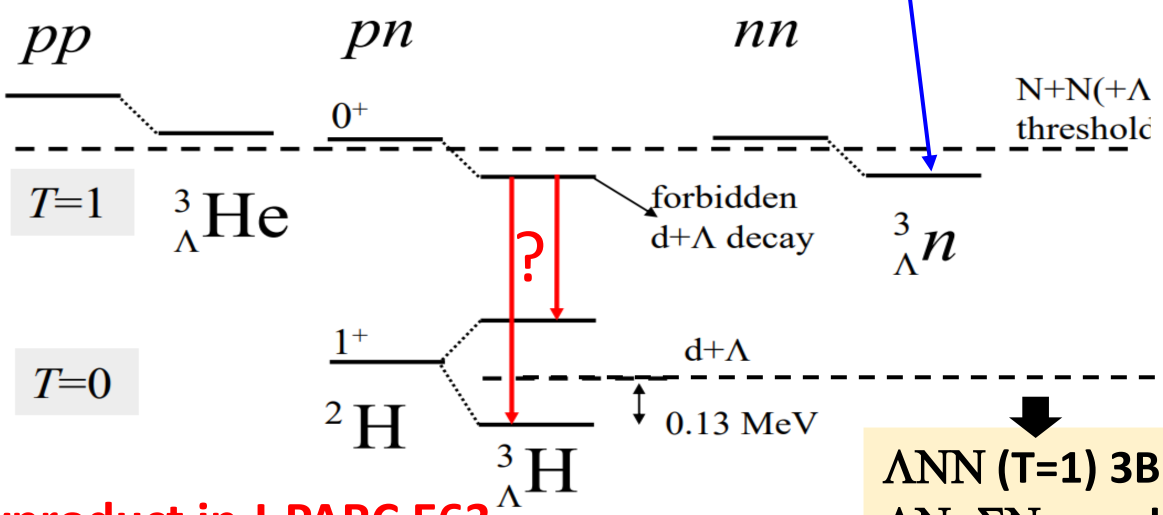
HypHI (^{6}Li + ^{12}C) reported a bound state.

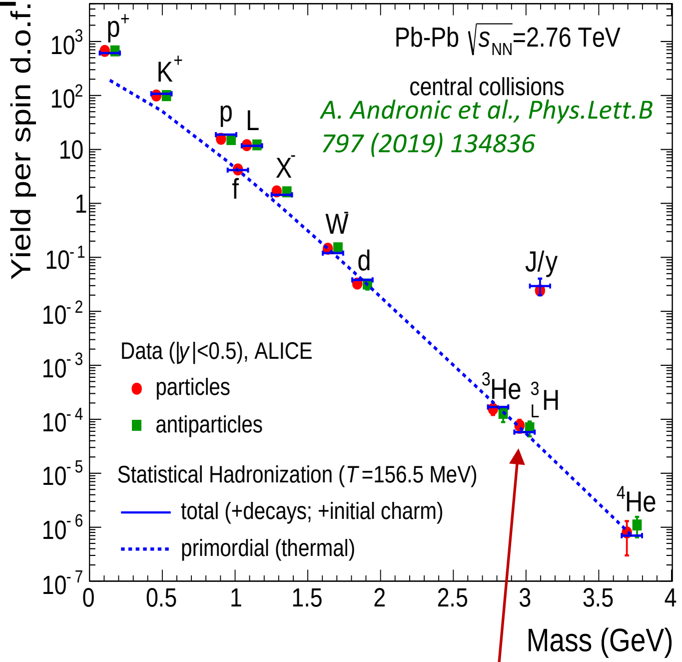
C. Rappold et al., Phys. Rev. C 88, 041001(R) (2013)

JLab Hall A (E12-17-003) ^{3}H(e,e'K^{+}) found no bound state but suggests a resonance.

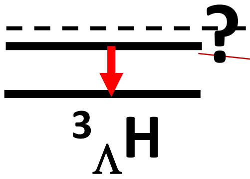
K. N. Suzuki et al., Prog. Theor. Exp. Phys. 2022, 013D01 (2022)

B.Pandey et al., Phys.Rev.C 105 (2022) 5, L051001





ΛNN (T=1) 3BF
ΛN–ΣN coupling



May not be bound

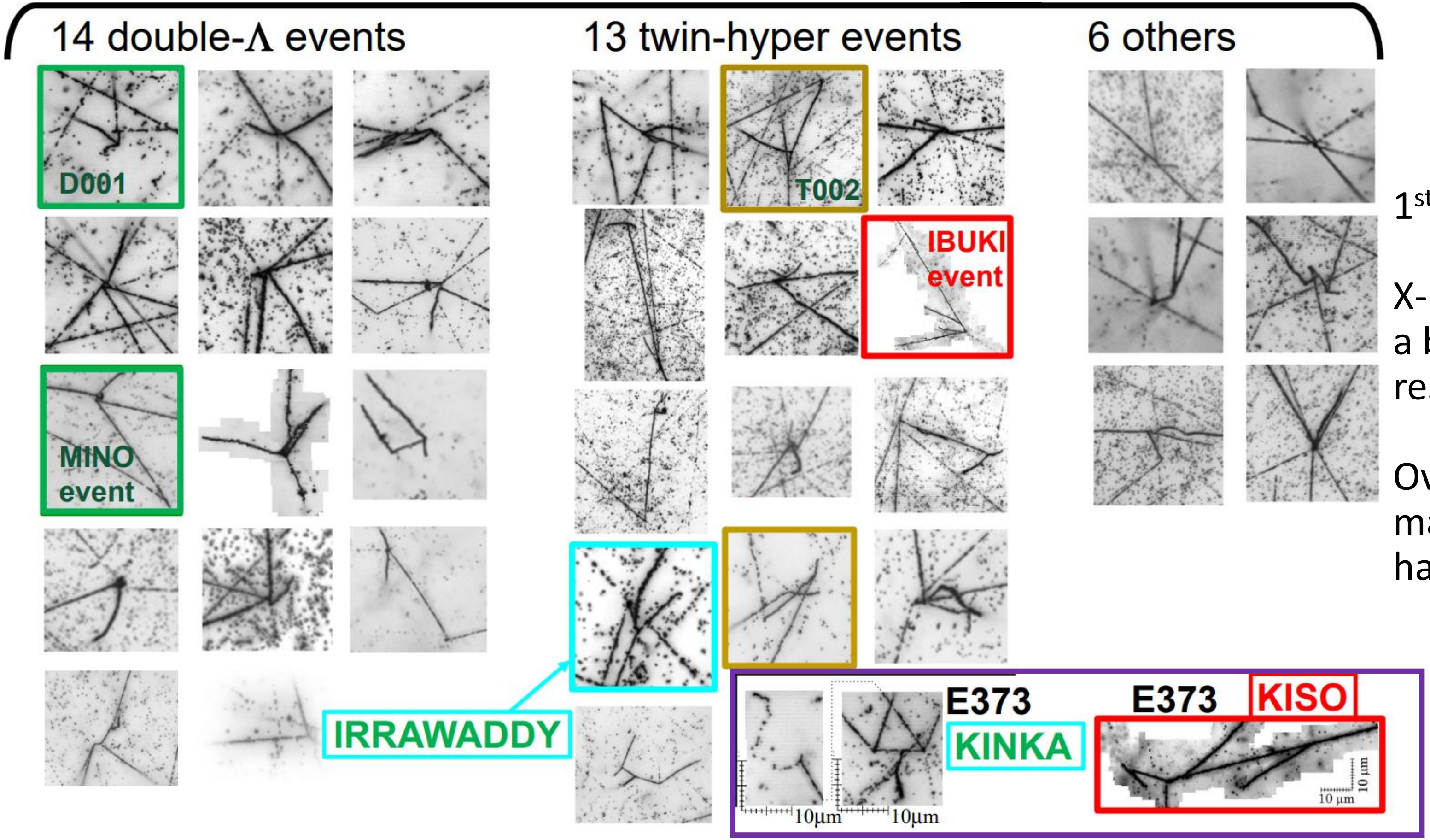
Byproduct in J-PARC E63

M. Ukai, EPJ Web of Conf. 271, 01008 (2022)

3. Double strange (Ξ /ΛΛ) hypernuclei

List of detected events in E07 (Jun., 2022)

Nakazawa, HYP2022



1[st] scanning finished.

X-ray microscope for a better track resolution.

Overall scan with machine learning has been developed.
=> T. Saito

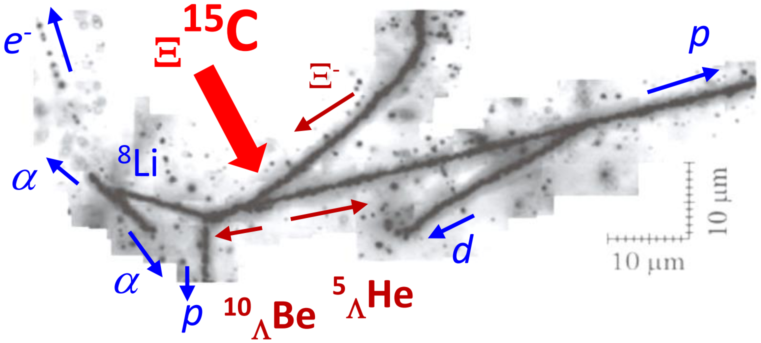
Unambiguous determination of B_{Ξ} of Ξ hypernucleus

$\Xi^{-} + {}^{14}N \rightarrow {}^{15}_{\Xi}C \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$

K. Nakazawa et al. PTEP 2015, 033D02 (2015)

S. H. Hayakawa, PRL 126, 062501 (2021)

Kiso event (KEK E373)

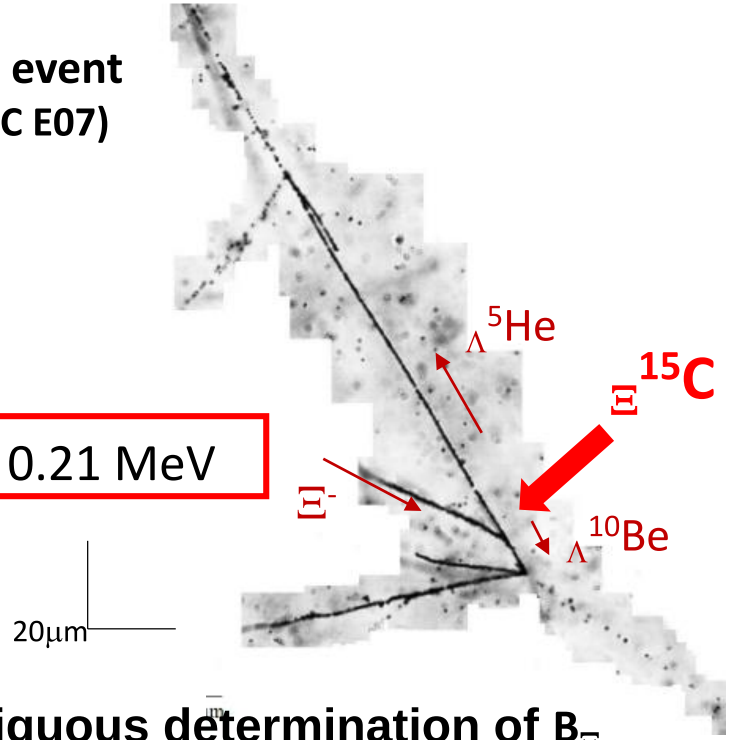


The first clear Ξ hypernucleus

$$B_{\Xi^-} = 4.38 \pm 0.25\ \text{MeV},\quad \text{or}\ 1.11 \pm 0.25\ \text{MeV}$$

Much deeper than the Coulomb binding energy

IBUKI event
(J-PARC E07)



$B_{\Xi^-} = 1.27 \pm 0.21$ MeV

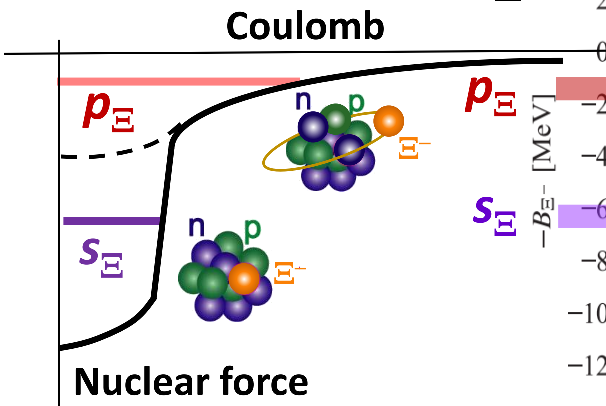
Unambiguous determination of B_{Ξ}

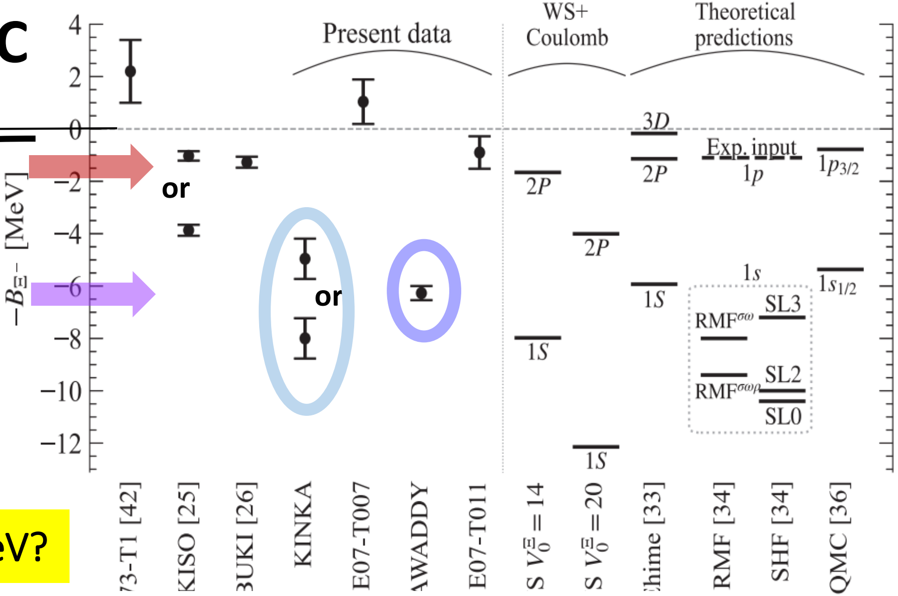
Observation of *s*-state Ξ hypernucleus ?

$\Xi^- + {}^{14}N \rightarrow {}^{15}_{\Xi}C$

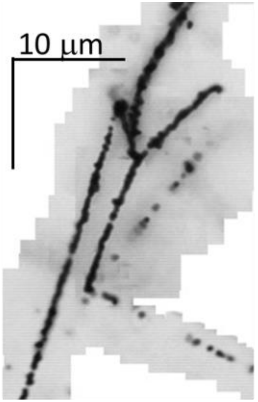
M. Yoshimoto et al., Prog. Theor. Exp. Phys. 2021, 073D02

IRRAWADDY (E07)	${}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + {}^{4}He + n$: 6.27±0.27 MeV
KINKA (KEK E373)	${}^{9}_{\Lambda}Be + {}^{5}_{\Lambda}He + n$: 8.00±0.77 or 4.96±0.77 MeV





Potential depth of ~12 MeV?



IRRAWADDY (E07)

Caution:
Theories seem to agree with the data, but they used the BNL suggestion of U_Ξ ~ -15MeV.

Why Ξ survives until it cascades down to the 0s orbit ??

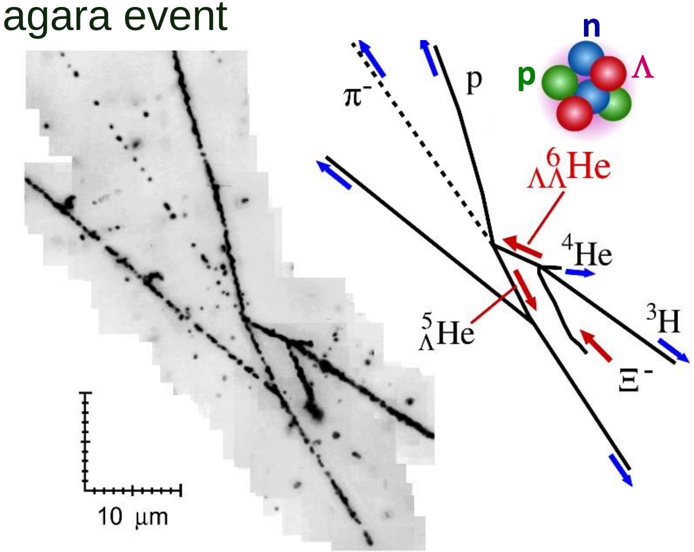
=> Gal's talk

ΞN→ΛΛ in Nijmegen/ HAL QCD => Ξ absorption mainly at 3D / 2P orbits

Observation of s states => **extremely weak ΞN→ΛΛ interaction?**

ΛΛ hypernuclei (J-PARC E07)

Nagara event



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

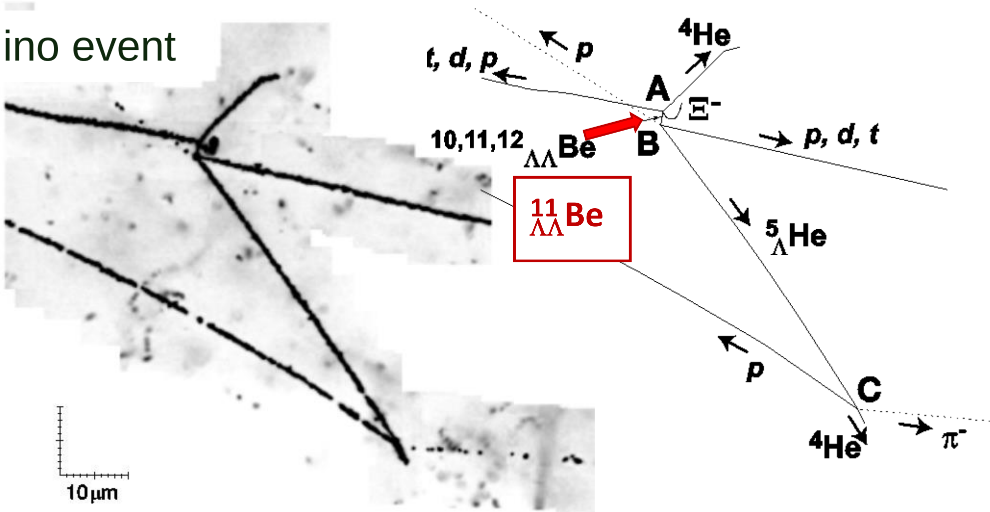
${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$

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

H. Takahashi et al., PRL 87 (2001) 212502

=> Λ-Λ is weakly attractive

Mino event



$\Xi^- + {}^{16}O + \rightarrow {}^{11}_{\Lambda\Lambda}Be + {}^{4}He + d,\quad {}^{11}_{\Lambda\Lambda}Be \rightarrow {}^{5}_{\Lambda}He + d + p + 3n$

$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV

H. Ekawa et al., PTEP 2019 (2019) 021D02

Weakly attractive Λ-Λ force is confirmed.

But consistency with Nagara should be studied.

Different effect of ΛΛ–ΞN coupling

A-dependence of $0s_\Lambda$ wave function

4. Ξ-atomic X-rays

Ξ^- atomic X-rays at J-PARC

Atomic X rays (shifts and widths) give clear quantitative info. on the Ξ-nuclear potential

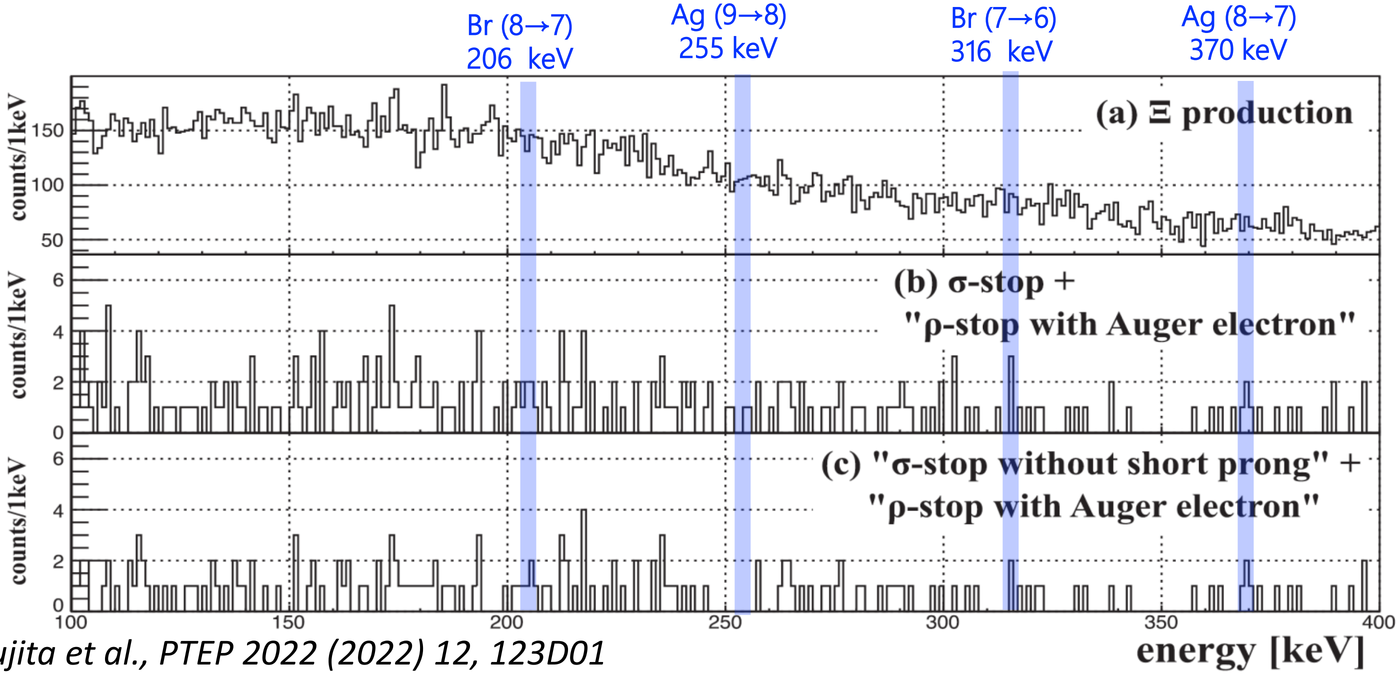
Ξ-Ag/Br atomic X rays in emulsion (J-PARC E07)

"Reaction-Xray-Emulsion" triple-coincidence hybrid method

Ξ absorption events selected via emulsion image analysis

- BG level reduced to 1/170
- Calibration method of <0.1 keV developed

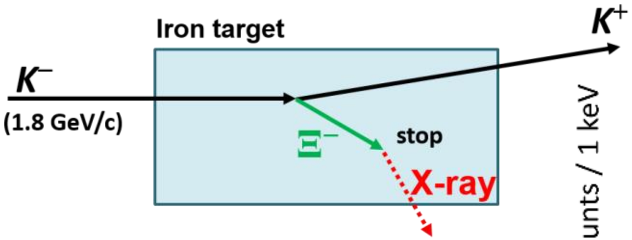
X-ray peaks not observed due to lower emulsion and Ge detector efficiencies than expected

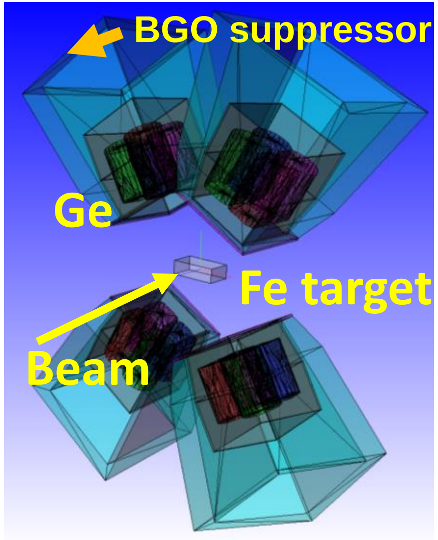


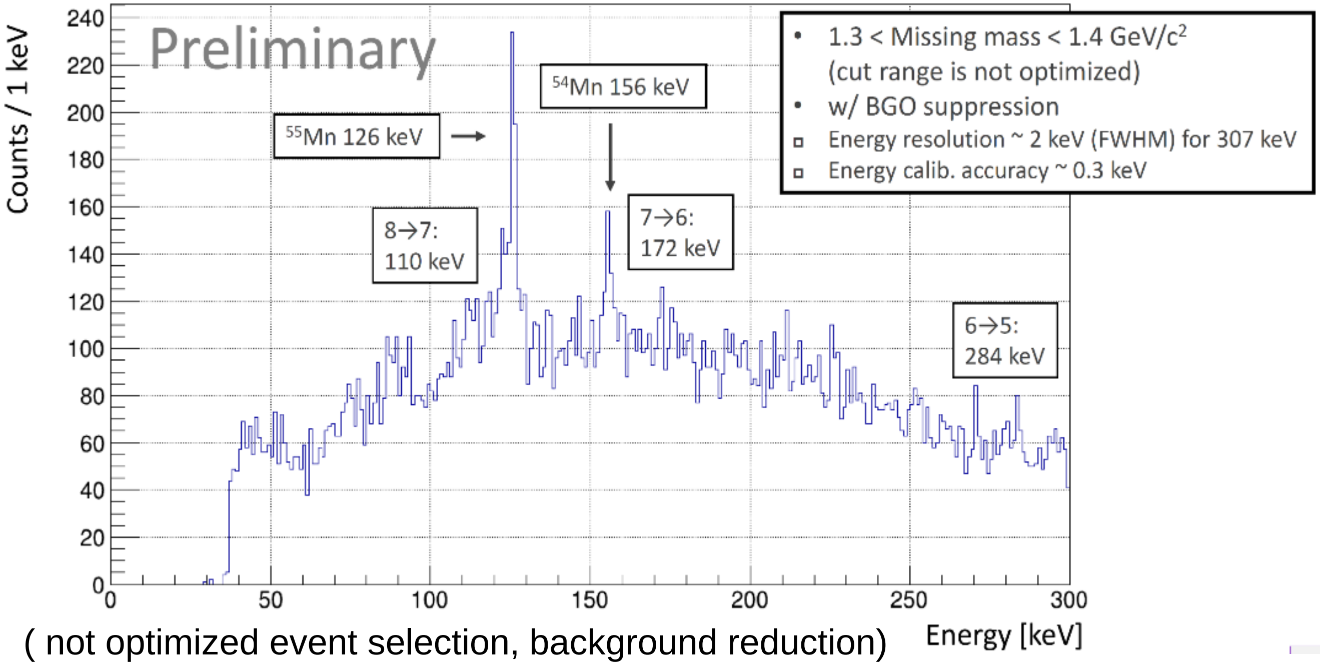
M. Fujita et al., PTEP 2022 (2022) 12, 123D01

Ξ^- Fe atomic X-ray (J-PARC E03-1st)

Y. Ishikawa,
HYP2022, 2022.6







(not optimized event selection, background reduction)

No clear peak structures are found at present.

BG level is consistent with our expectation

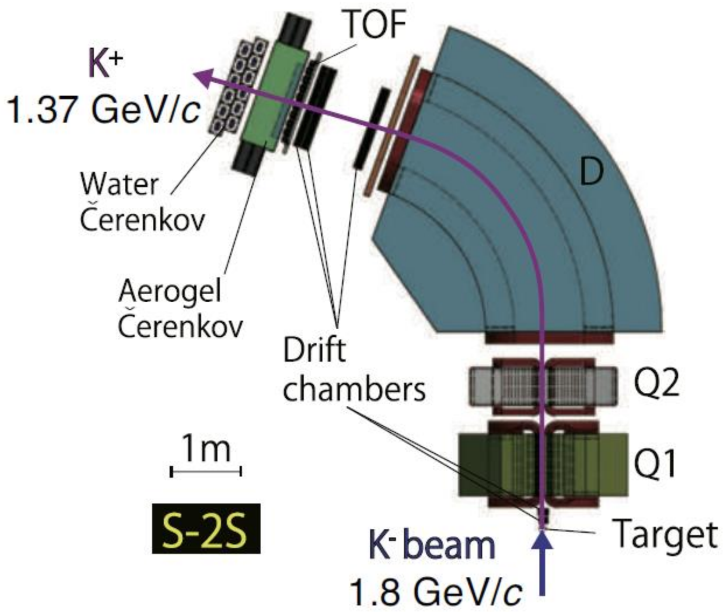
X ray yields are found to be smaller than expected.

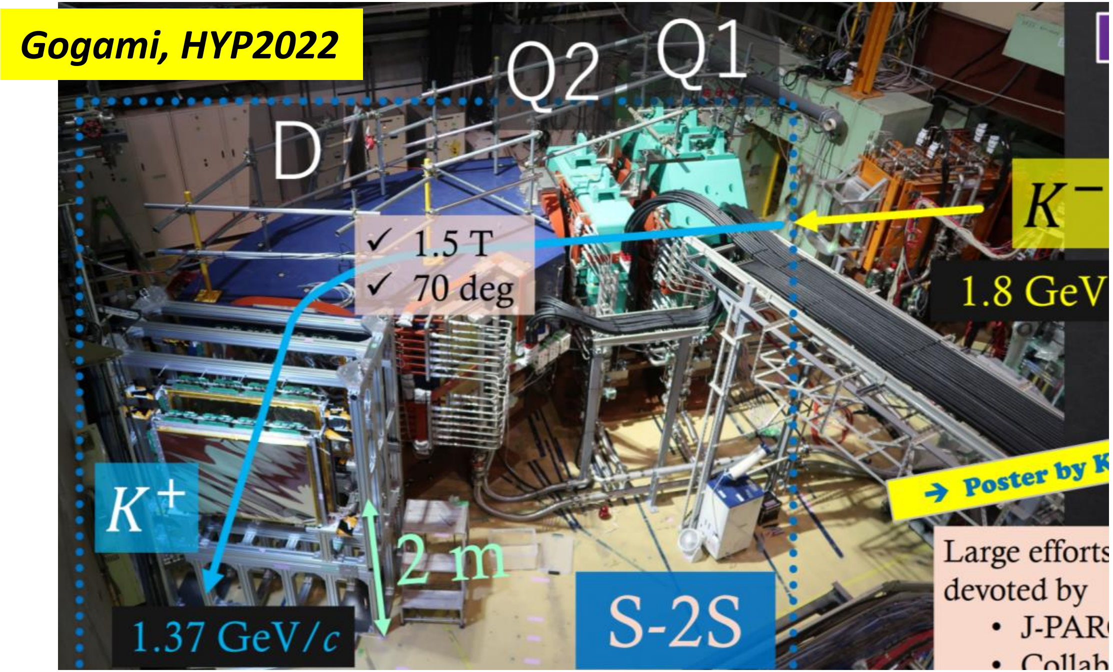
Spectroscopy of Ξ hypernuclei via (K^-,K^+) reaction

E70 (Nagae) : $^{12}C(K^-,K^+)^{12}{}_{\Xi}Be$

E75 (Fujioka) : $^{7}Li(K^-,K^+)^{7}{}_{\Xi}H$, $^{7}{}_{\Xi}H \rightarrow {}^{5}{}_{\Lambda\Lambda}H$

A new dedicated spectrometer, S-2S has been installed. Run from 2023.



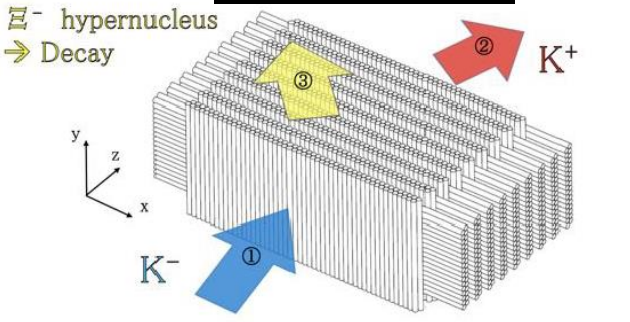


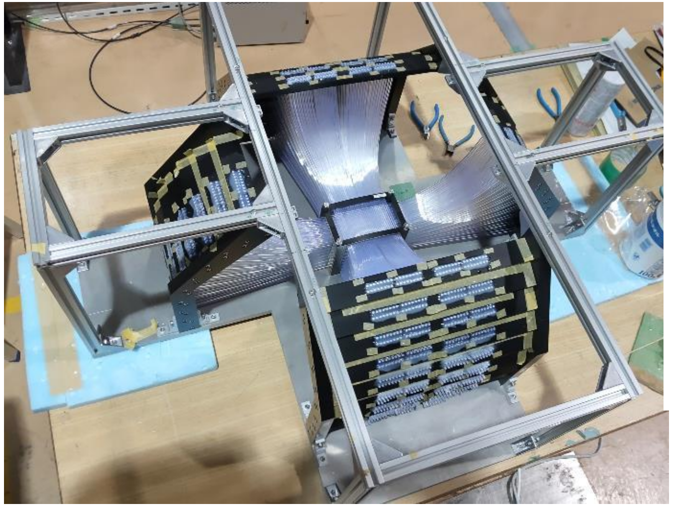
Ξ stop tagging with AFT for Ξ atomic X-rays (E96)

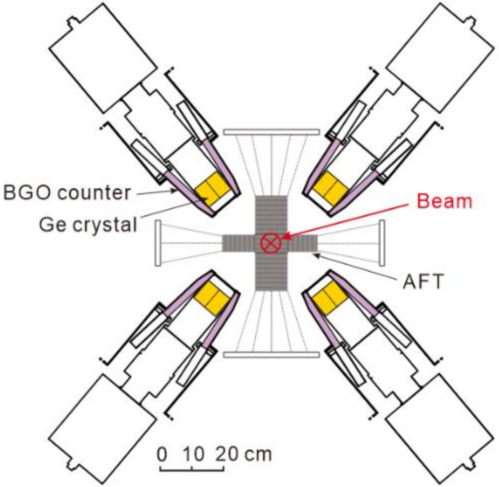
Active Fiber Target (AFT) gives

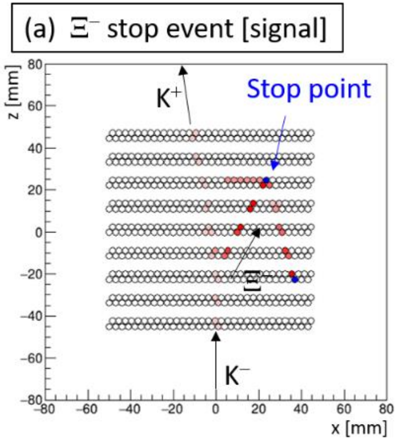
Ξ track information → Ξ stop tag

Active Fiber Target (for J-PARC E70)









Energy loss correction for missing mass spectroscopy of Ξ hypernuclei (E70)

ΔM = a few MeV => ~1 MeV (FWHM)

Identify Ξ stop events with AFT => ~95% B.G. reduction with 70% survival ratio for stop event

Run in 2023.

T.O. Yamamoto et al., EPJ Web Conf. 271, 03001 (2022)

Summary

- ${}^{3}_{\Lambda}H$ puzzle: new ALICE results appeared. Measurements with other methods still necessary.
- J-PARC E73: ${}^{4}_{\Lambda}H$ lifetime measured, run for ${}^{3}_{\Lambda}H$ this year.
- ${}^{4}_{\Lambda}H$/ ${}^{3}_{\Lambda}H$ γ-ray measurement is planned.
- New ${}^{15}_{\Xi}C$ hypernuclear events observed. Some have a large B_{Ξ} value, suggesting an s_{Ξ} state?
- Ξ atomic X-ray measurement tried twice, but not observed yet.
- ${}^{12}C(K^{-},K^{+})\,{}^{12}_{\Xi}Be$ spectroscopy will start soon, together with a Ξ-C atomic X-ray measurement.