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Nuclear Science Symposium@Rome

Recent Progress of Hypernuclear Research

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Contents

1. Introduction:

Hypernuclei tell us about nuclear force and neutron stars

Origin of nuclear force studied with s quarks

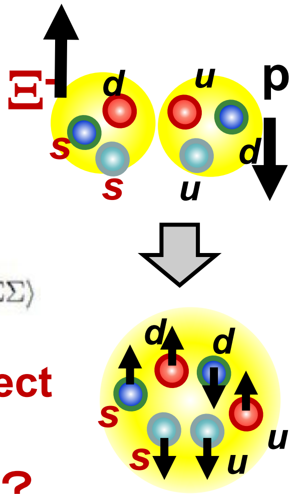
Quark Cluster Model (Oka-Yazaki)

- **Pauli effect btw quarks**
- **Color magnetic interaction**

Origin of repulsive core?

Pauli effect btw quarks

-> Strong repulsive core?



flavor singlet

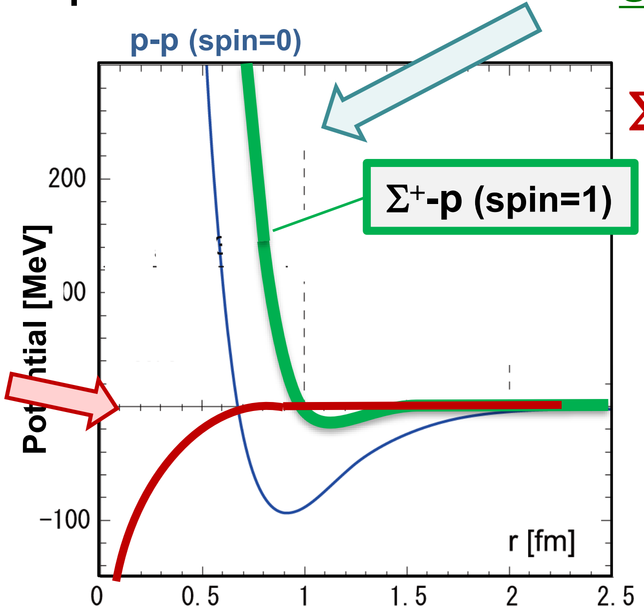
$$-\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle+\sqrt{\frac{4}{8}}|N\Xi\rangle+\sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

CMI + no Pauli effect btw quarks

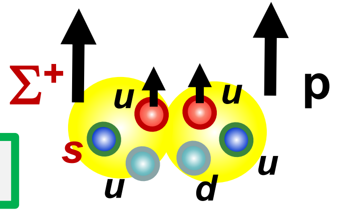
-> Attractive core？

H dibaryon

Under study by (K^-,$K^+\Lambda\Lambda$) exp.
(J-PARC E42)



Calc. by Lattice QCD (HAL QCD)

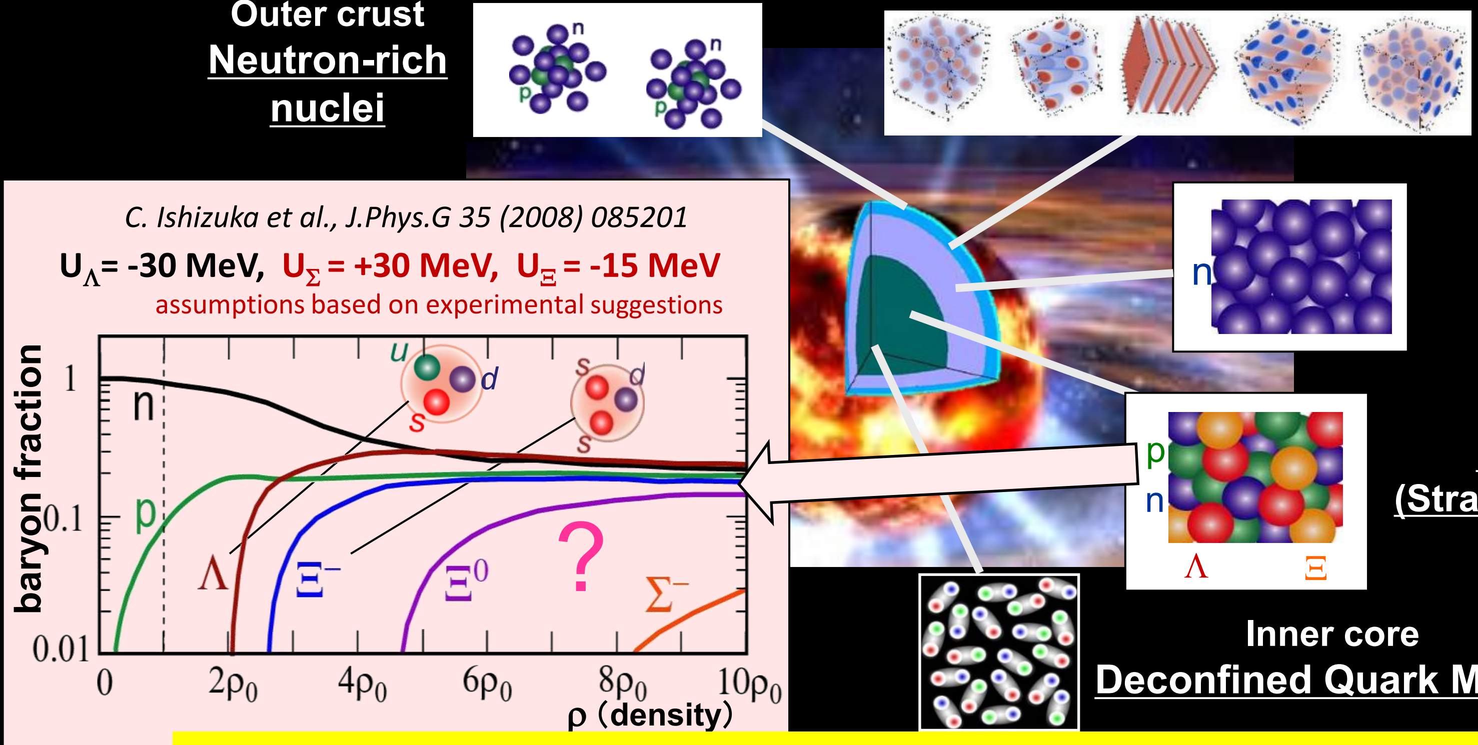


Confirmed by
Σ p scattering exp.
(J-PARC E40)

T. Nanamura et al., PTEP 2022 093D01

s quark is a key to elucidate the origin of nuclear force

Hyperons exist in neutron stars?



Outer crust
Neutron-rich nuclei

Inner crust
Pasta nuclei

Outer core
(Almost pure) Neutron Matter

Inner core
Hyperon Matter (Strange Hadronic Matter) ?

Inner core
Deconfined Quark Matter ??

C. Ishizuka et al., J.Phys.G 35 (2008) 085201

U_Λ= -30 MeV, U_Σ = +30 MeV, U_Ξ = -15 MeV

assumptions based on experimental suggestions

Hyperons (Λ, Ξ^-) <u>should appear</u> at ρ ~ 2-3 ρ_0 => max. mass of NS ~ 1.5 Msun

⇔ Three NS's with ~2.0 Msun were observed : "Hyperon puzzle"

=> Density dependence of YN int. (= YNN 3BF) should be clarified.

2. Hyperon-nucleon scattering

YN interaction

Λp, $\Sigma^{\pm}$p scattering with bubble chambers in (1960s)

<~ 0.30 GeV/c, poor quality, σ, no dσ/dΩ for Λp

Λ hypernuclei (+ Σ hypernuclei): B_Y + level scheme (1960-)

YN interaction Models (Nijmegen NSC, ESC)

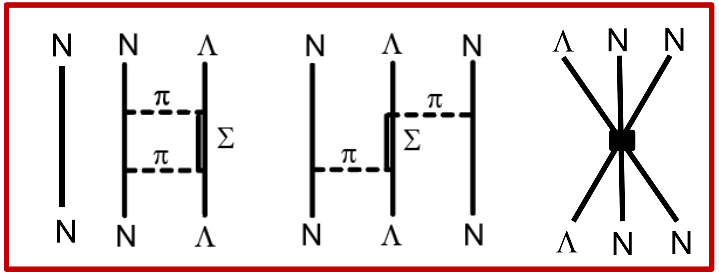
But, YN int. in nuclei is significantly different from YN. Int in free space

- **High quality YN scattering experiments**

$\Sigma^{\pm}$p 0.44-0.80 GeV/c dσ/dΩ (J-PARC E40)

Λp 0.3-0.65 GeV/c dσ/dΩ (SPring-8) -> under data taking

0.4-0.8 GeV/c Pol.Λ -> dσ/dΩ, Analyzing Power, Depolarization (J-PARC E86, future)



- **Femtoscopy**

Λp <~ 0.3 GeV/c via pp coll. @√s=13 TeV (ALICE) -> (ALICE Run3)

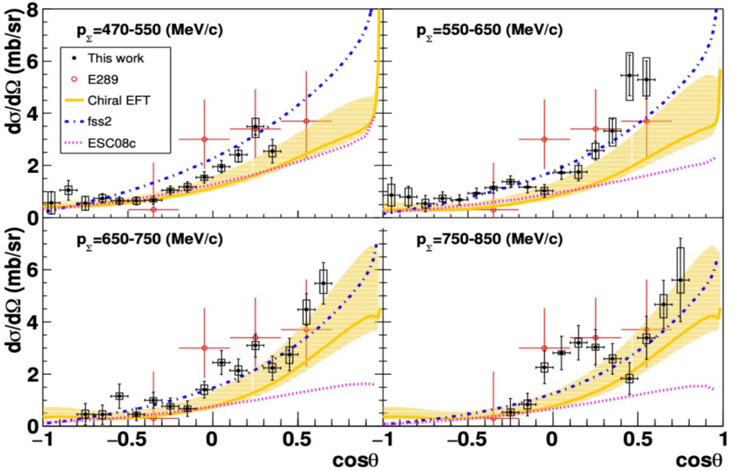
- **Hypertriton (loose pnΛ system)** Precise B_{Λ} , τ data from STAR, ALICE, J-PARC, MAMI,…

$\Sigma^{\pm}p$ scattering at J-PARC

Σ^{-} p elastic

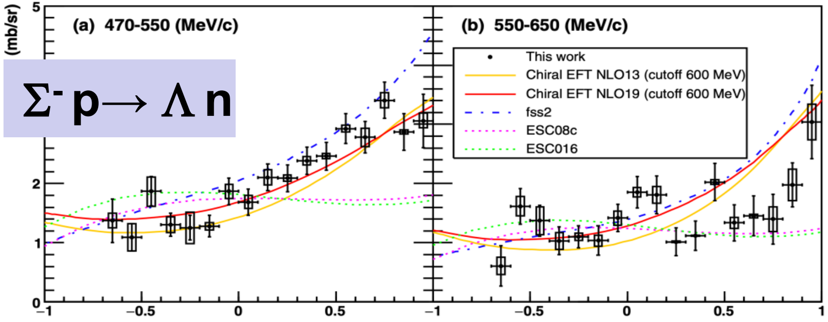
Σ^{-}p elastic scattering

K. Miwa et al., PRC 104, 045204 (2021)

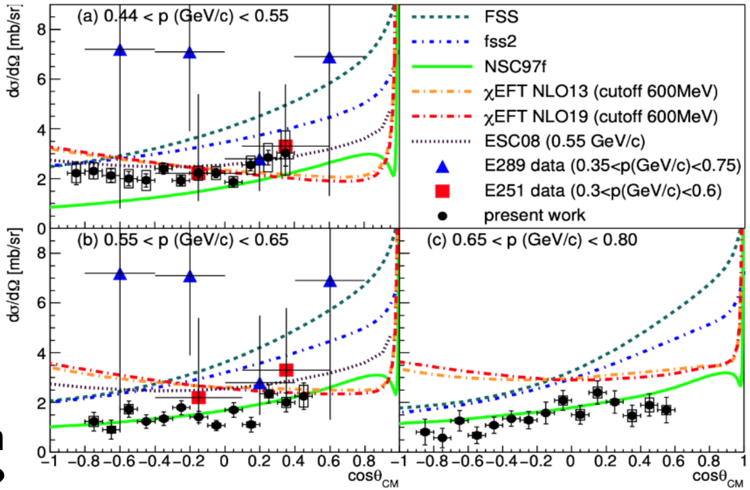


K. Miwa et al., PRL 128, 072501 (2022)

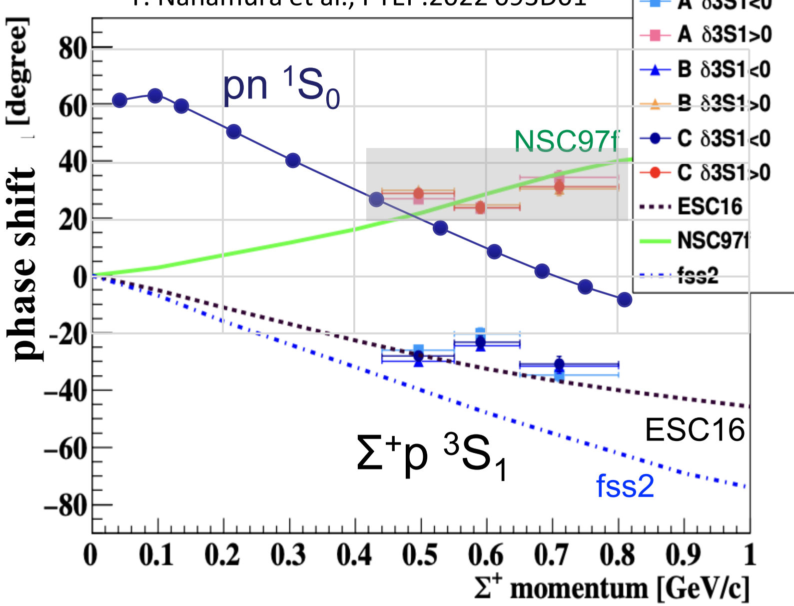
$\Sigma^{-}p \rightarrow \Lambda n$ inelastic scattering



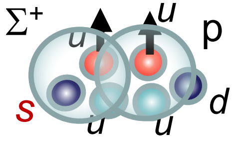
Σ^{+} p elastic



T. Nanamura et al., PTEP.2022 093D01



Σ^{+}-p (spin=1)



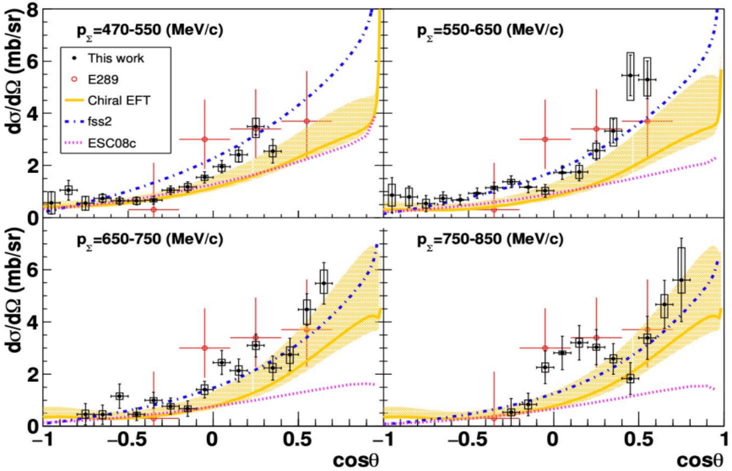
Strong repulsion by quark Pauli ??

$\Sigma^{\pm}p$ scattering at J-PARC

$\Sigma^- p$ elastic

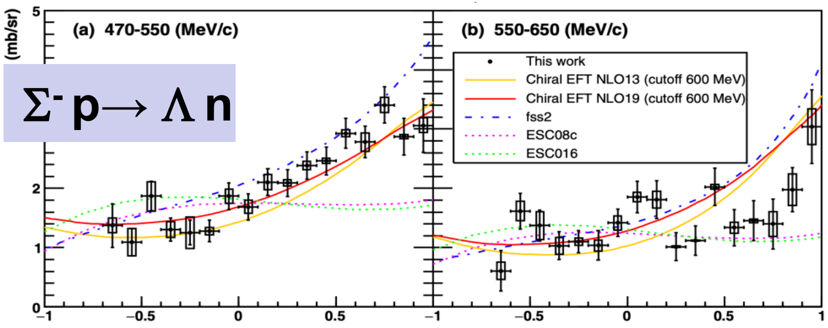
Σ^-p elastic scattering

K. Miwa et al., PRC 104, 045204 (2021)

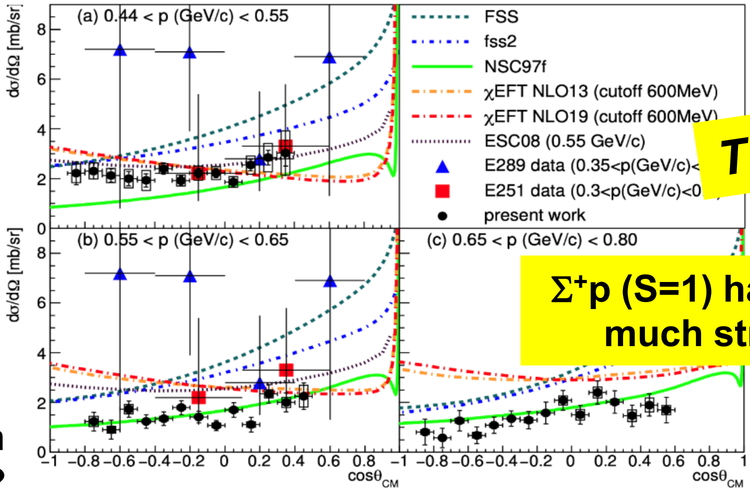


K. Miwa et al., PRL 128, 072501 (2022)

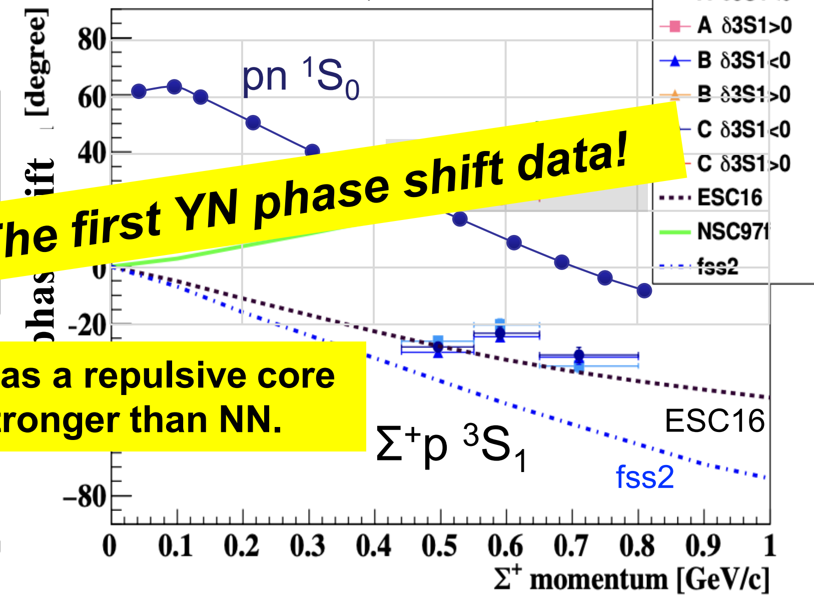
$\Sigma^-p \rightarrow \Lambda n$ inelastic scattering



$\Sigma^+ p$ elastic



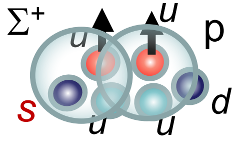
T. Nanamura et al., PTEP.2022 093D01



The first YN phase shift data!

Σ^+p (S=1) has a repulsive core much stronger than NN.

Σ^+-p (spin=1)



Strong repulsion by quark Pauli ??

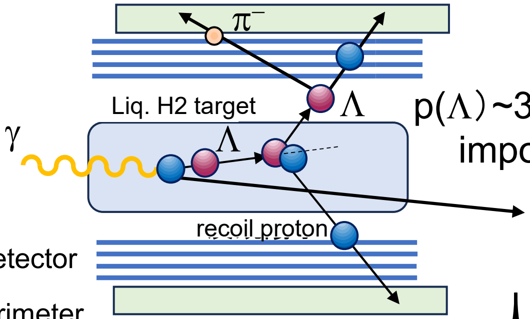
Slide from Miwa

Present and future : Λp scattering

γ beams @Spring-8 (runnig now)

Momentum tagged Λ via γp→K⁺Λ reaction

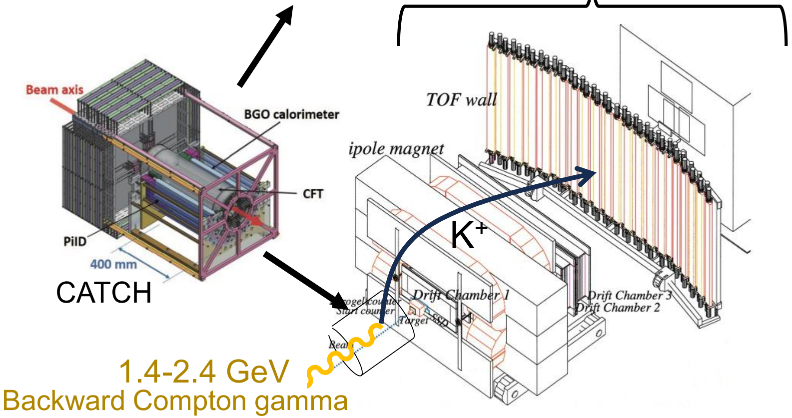
YN scattering detector system (CATCH)



p(Λ)~300~700 MeV/c important for NS

Fiber detector

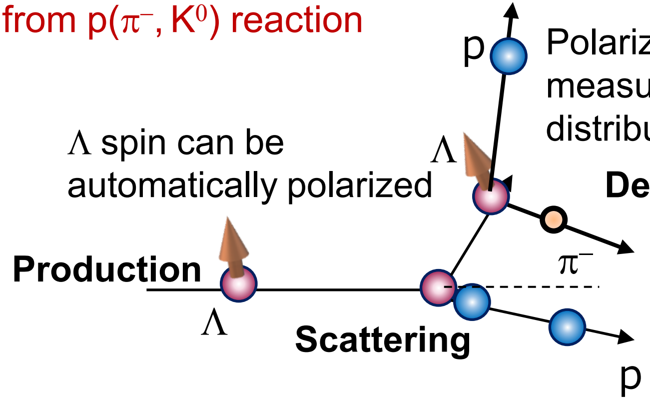
BGO calorimeter



1.4-2.4 GeV
Backward Compton gamma

K- beam@J-PARC HEFex (K1.1 line) (E86)

Measure spin observables with polarized Λ beam from p(π⁻, K⁰) reaction



Production

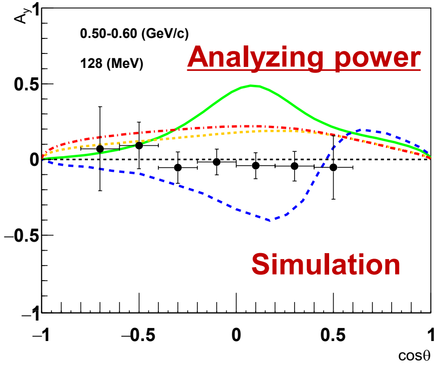
Scattering

Decay

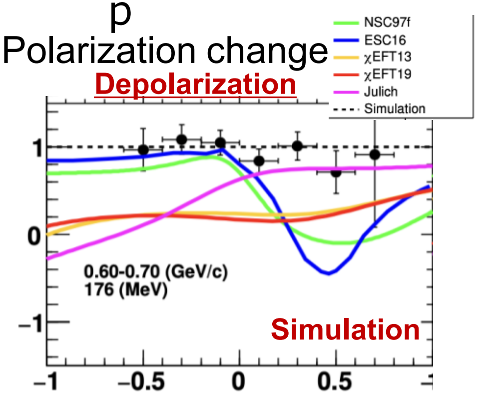
Λ spin can be automatically polarized

Polarization can be measured from angular distribution of p

- Left-Right asymmetry



- Polarization change



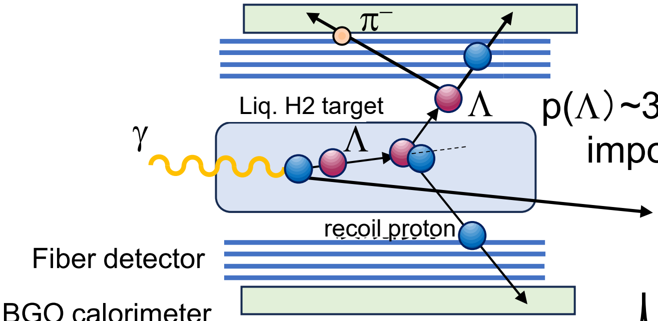
Slide from Miwa

Present and future : Λp scattering

γ beams @Spring-8 (runnig now)

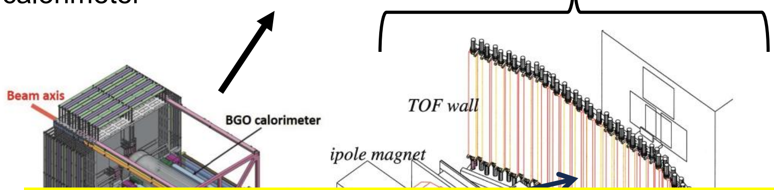
Momentum tagged Λ via γp→K⁺Λ reaction

YN scattering detector system (CATCH)



p(Λ)~300~700 MeV/c important for NS

K⁺

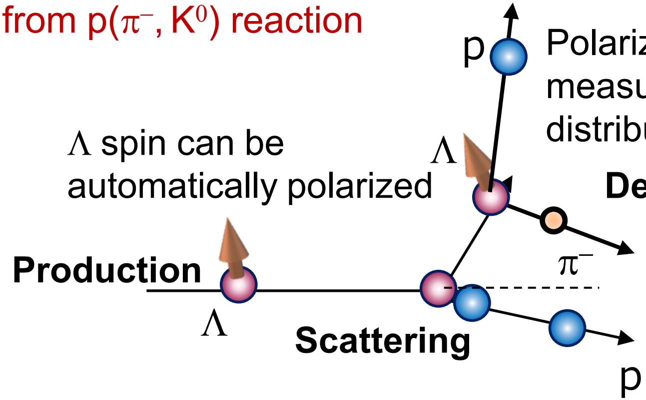


=> ΛN int. for large p(Λ) and p-wave

=> ΛNN strength can be obtained by comparing with hypernuclear data of U_0^Λ = -30 MeV.

K- beam@J-PARC HEFex (K1.1 line) (E86)

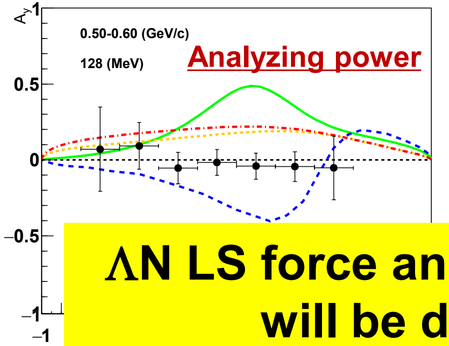
Measure spin observables with polarized Λ beam from p(π⁻, K⁰) reaction

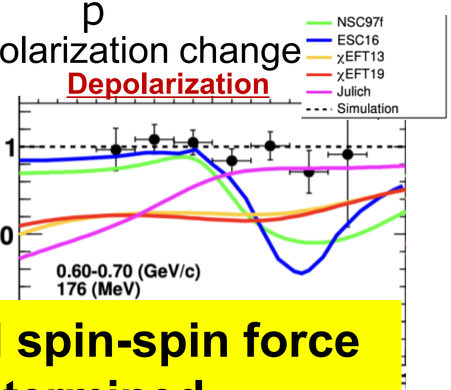


Polarization can be measured from angular distribution of p

Λ spin can be automatically polarized

- Left-Right asymmetry
- Polarization change





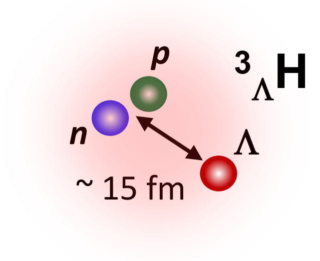
ΛN LS force and spin-spin force will be determined

3. Precise light Λ hypernuclear data

(Hypertriton and CSB)

The benchmark, Hypertriton ($^3_\Lambda$H = pnΛ)

Precise data of few-body systems are particularly important.



- We long believed:
  B_Λ~ 130 keV (old emulsion)
  => radius ~$(2\mu B_\Lambda)^{-1/2}$ ~ 15 fm
  => τ ~ $\tau_{\Lambda(\text{free})}$ (263 ps)
- Previous data of τ, much shorter than τ_Λ (free), look inconsistent with the small B_Λ.
- Hypertriton's B_Λ is an important benchmark for ΛN interaction in free space (but with a little effect of ΛNN 3BF.

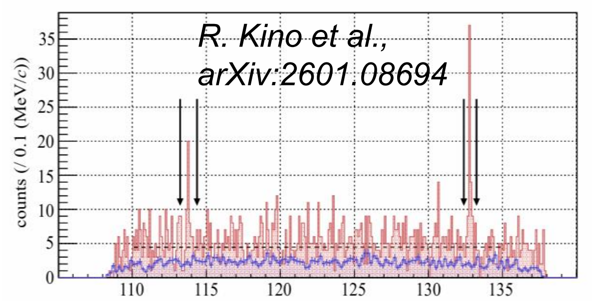
New data after 2018

Experiment	Reaction	Method	τ ($^3_\Lambda$H) ps	$B_\Lambda(^3_\Lambda H)$ MeV
STAR	HI (Au+Au) √s=3GeV	decay length inv. mass	221±15±19	0.41±0.12±0.11
ALICE	HI (Pb+Pb) √s=5TeV	decay length inv. mass	253±11±6	0.102±0.063 ±0.067
HADES	HI (Ag+Ag) √s=2.55GeV	decay length	256±22±36 (preliminary)	-
WASA-FRS	HI (^{6}Li+^{12}C) 2GeVA	decay length	under analysis	under analysis
J-PARC E73	^{3,4}He(K$^-$,π^0)	decay π^- timing	Under analysis	-
J-PARC E07	K$^-$ on emulsion	decay π^- range	$^3_\Lambda$H -> ^{3}He π^-	0.23±0.11 ±0.05
MAMI	^{7}Li(e,K$^+$)	decay π^- momentum	-	0.523±0.013± 0.075

Status of hypertriton binding energy

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

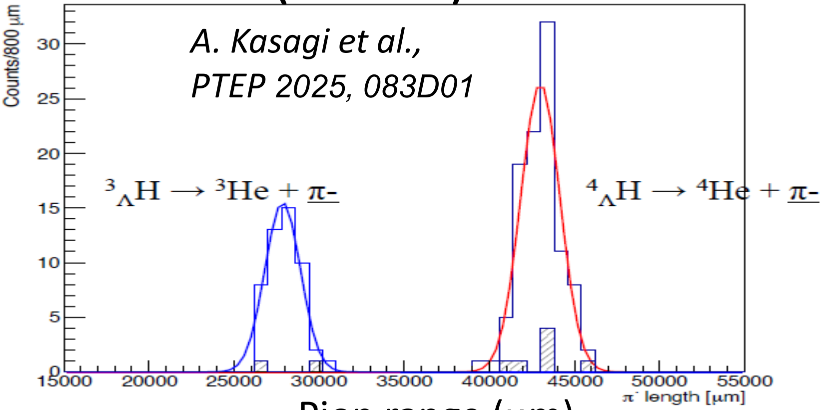
MAMI A1 (decay pion spectroscopy)



R. Kino et al., arXiv:2601.08694

Pion momentum (MeV/c)

J-PARC E07 (emulsion)



A. Kasagi et al., PTEP 2025, 083D01

Pion range (μm)

B_{Λ} value

MAMI (decay π)

arXiv:2601.08694

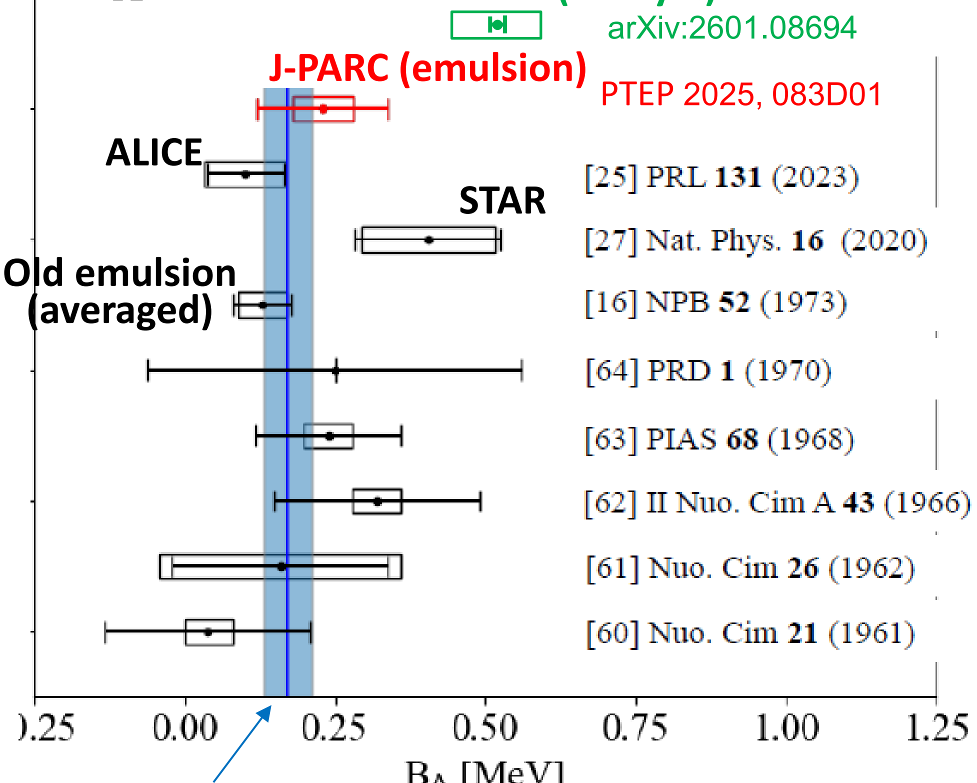
J-PARC (emulsion)

PTEP 2025, 083D01

ALICE

STAR

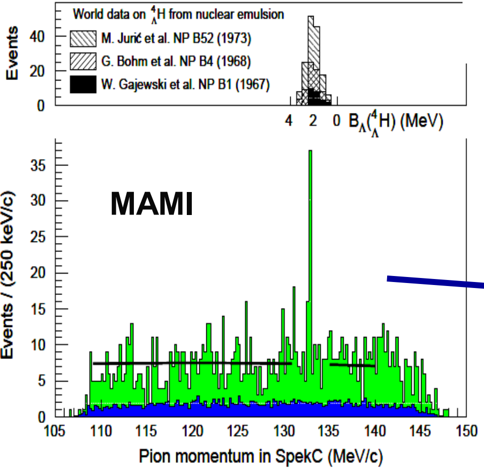
Old emulsion (averaged)



0.172 ± 0.040 MeV

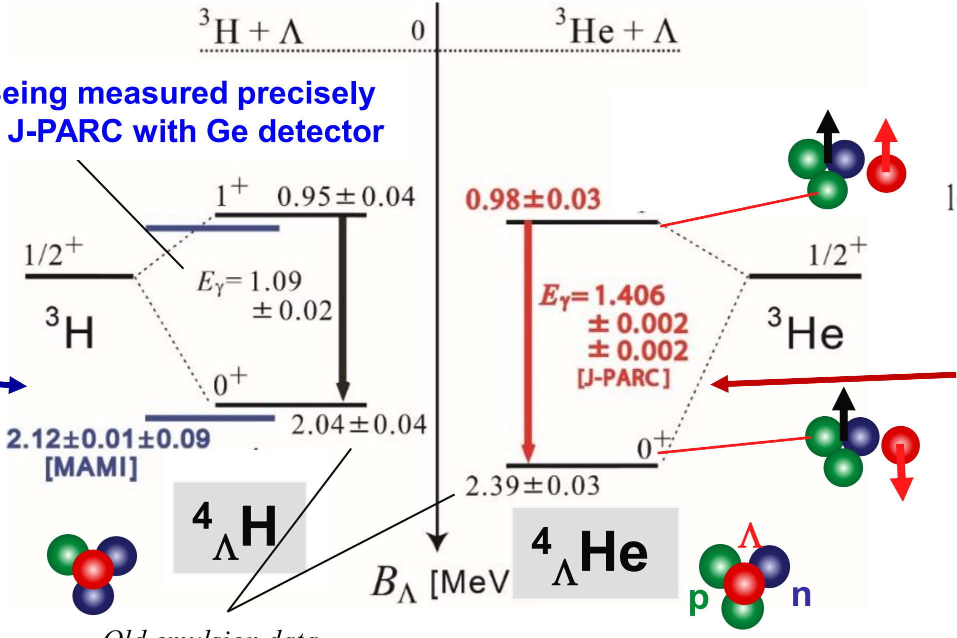
Charge Symmetry Breaking in A=4 hypernuclei

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

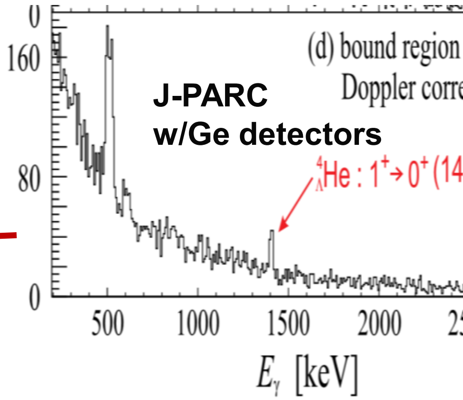


$^4{}_\Lambda H \rightarrow {}^4He + \pi^-$

Being measured precisely at J-PARC with Ge detector



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



$B_\Lambda({}^4{}_\Lambda He(0^+))$ - $B_\Lambda({}^4{}_\Lambda H(0^+))$ ~ 300 keV >> $B({}^3H)$-$B({}^3He)$ ~70 keV (w/o EM effect)

A large Charge Symmetry Breaking (Λp ≠ Λn) is confirmed.
The CSB effect has a spin dependence.

Not theoretically understood yet.
ΛN-ΣN coupling could be responsible?

CSB in p-shell hypernuclei can be a key
=> (e,e'K$^+$) @Jlab <-> (π^+,K$^+$) @J-PARC

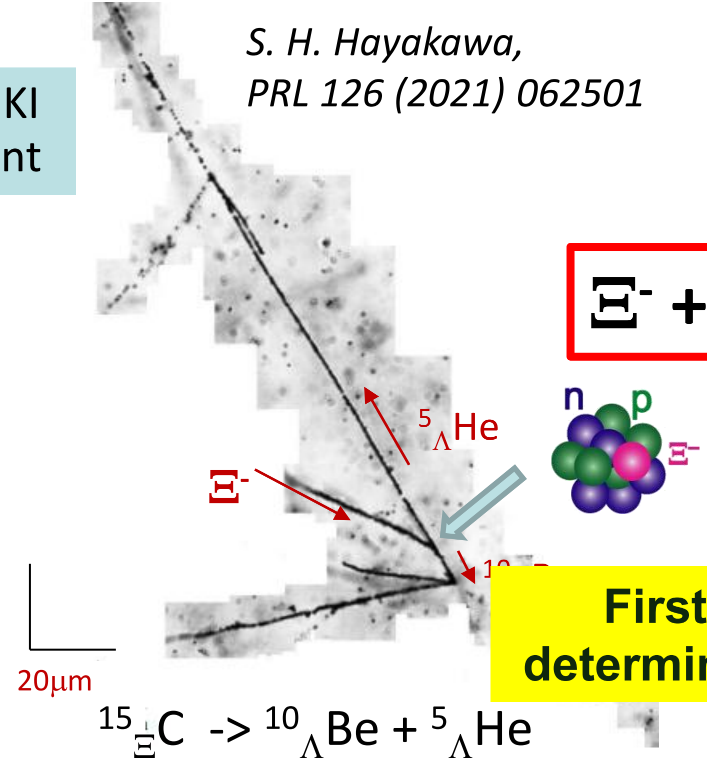
4. Ξ hypernuclei and ΞN interaction

Ξ-hypernuclei in emulsion (J-PARC E07)

$K^- + \text{“p”} \rightarrow \Xi^- + K^+$, then Ξ^- is stopped in emulsion and captured by C, N, O nuclei.

IBUKI event

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



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

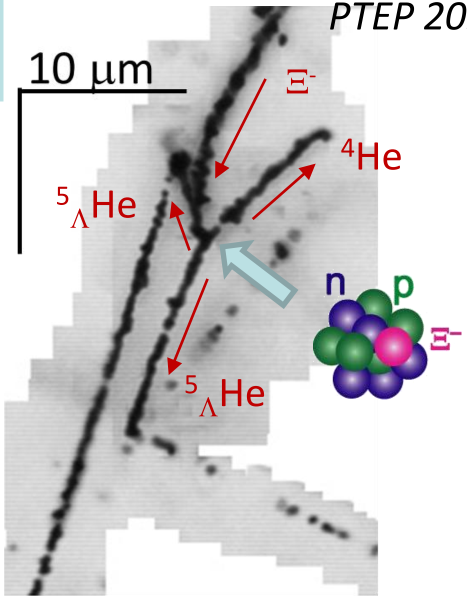
First precise determination of B_{Ξ}

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

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

IRRAWADDY event

M. Yoshimoto et al.,
PTEP 2021, 073D02

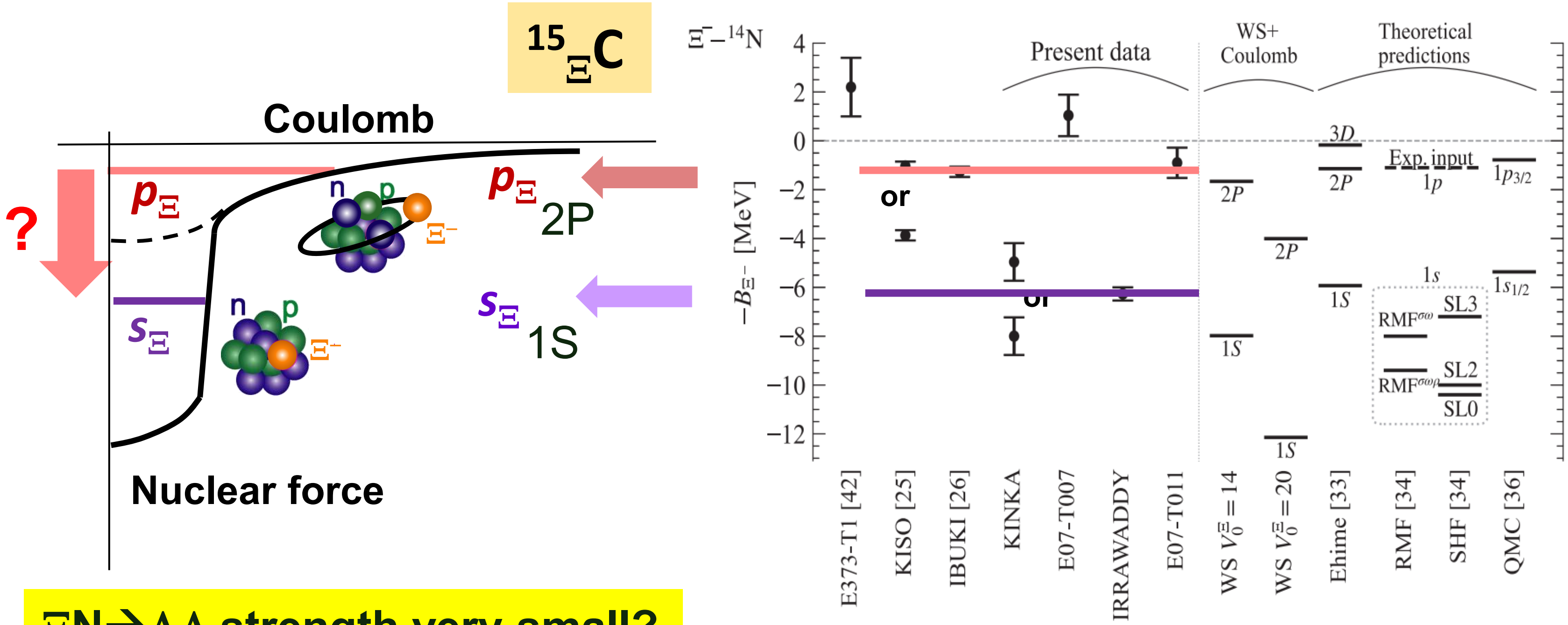


$^{15}_{\Xi}C \rightarrow {}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + {}^{4}He + n$

$B_{\Xi^-} = 6.27 \pm 0.27$ MeV

Observation of *p*- and *s*-state Ξ hypernuclei (?)

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



ΞN→ΛΛ strength very small?

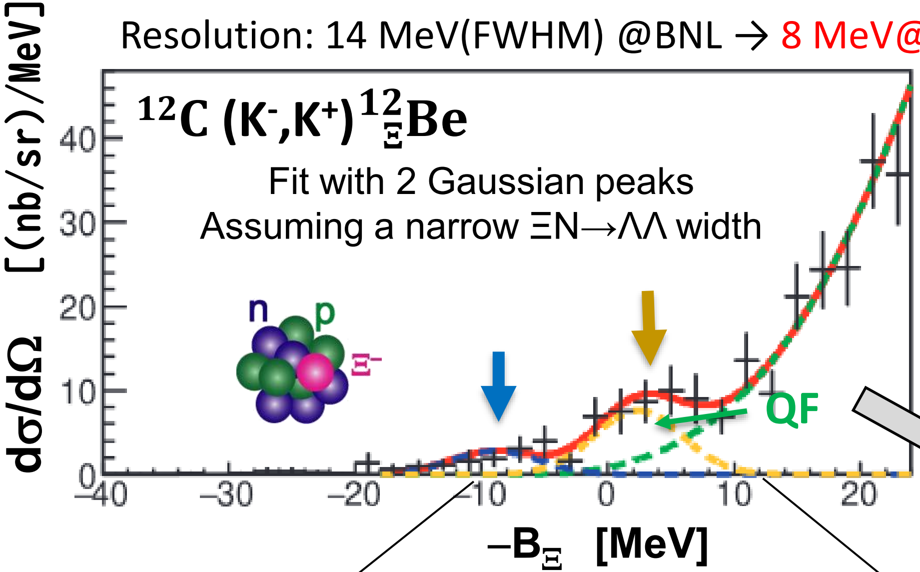
Meson exch.(Nijmegen) int. : Ξ absorption from 3D, 4%-0.3% from 2P orbits

Lattice (HAL QCD): ~ 1/10 of Nijmegen -> 2P/3D absorption comparable, but 1Sabsorption still negligible

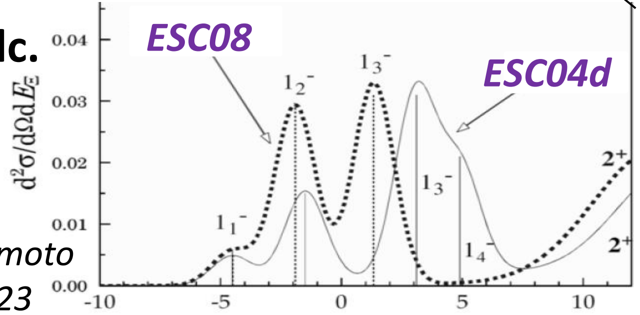
^{12}C (K$^-$,K$^+$) $^{12}_{\Xi}$Be missing-mass spectroscopy

(J-PARC E05)

Resolution: 14 MeV(FWHM) @BNL → 8 MeV@J-PARC E05



DWIA calc.



T.Motoba, S.Sugimoto
NPA835 (2019) 223

Y. Ichikawa et al.,
PTEP 2024 (2024) 091D01

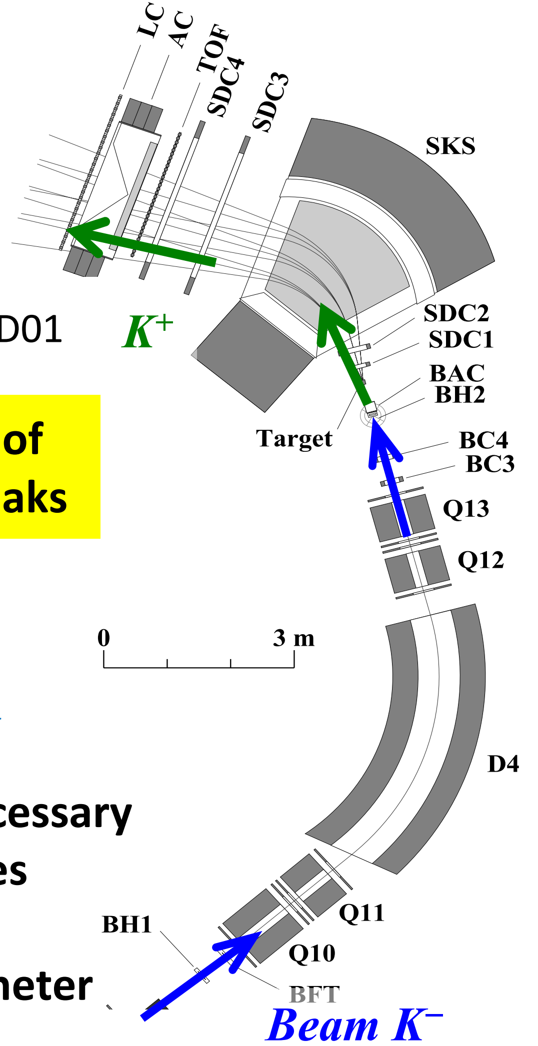
First observation of Ξ-hypernuclear peaks

B$_\Xi$ values

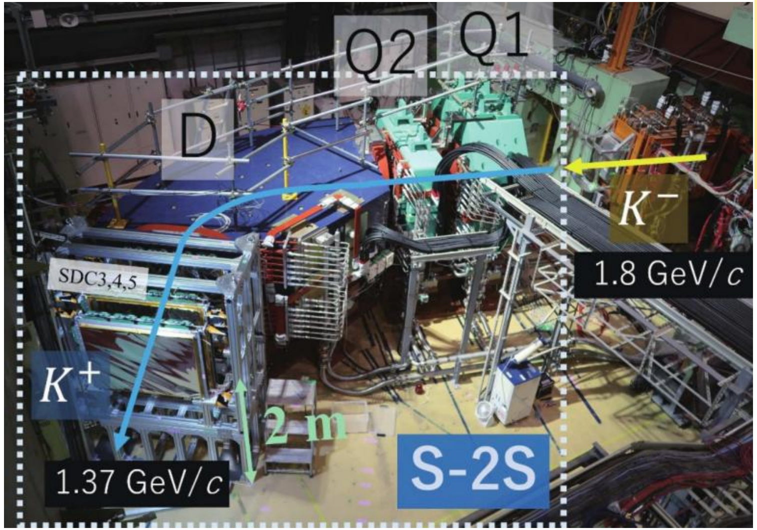
$-2.4 \pm 1.3^{+2.8}_{-1.2}$ MeV

$8.9 \pm 1.4^{+3.8}_{-3.1}$ MeV

Better resolution necessary to identify states
➔ J-PARC E70
w/ a new spectrometer



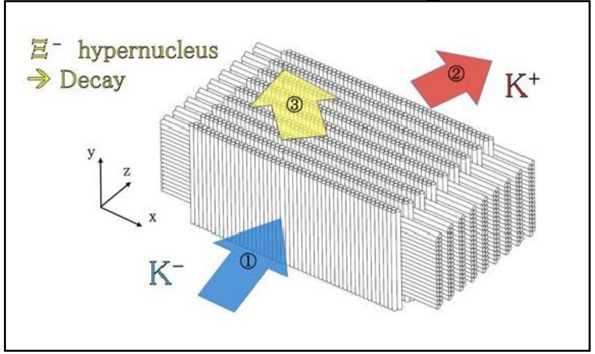
New experiments have been finished

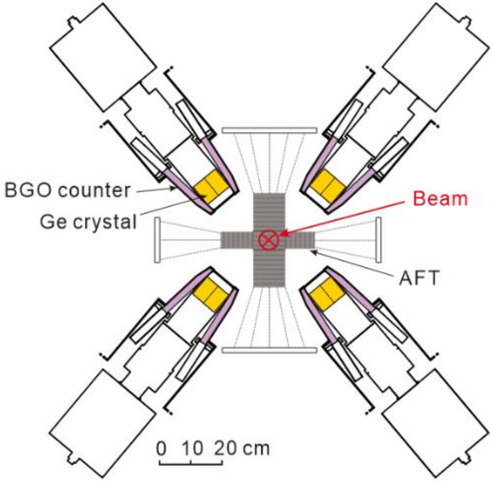


E70:
^{12}C(K-,K+)$^{12}{}_{\Xi}$Be
w/ a new spectrometer

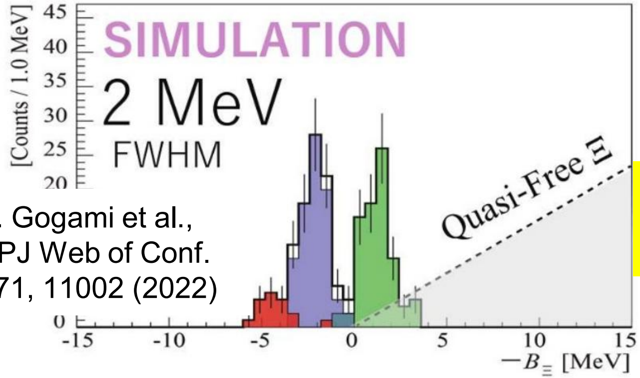
E96:
^{12}C Ξ atomic X-rays

Active Fiber Target



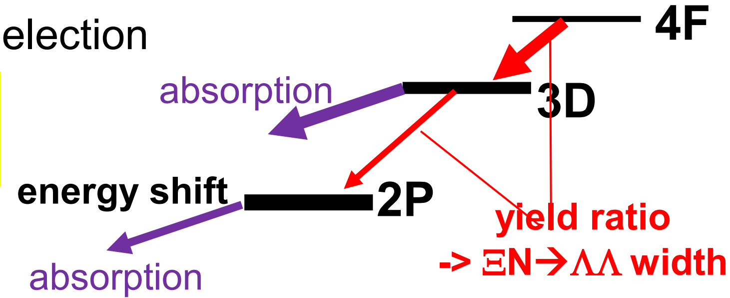


Energy loss correction
Stopped Ξ selection



T. Gogami et al.,
EPJ Web of Conf.
271, 11002 (2022)

Data-taking finished.
Under analysis.



absorption

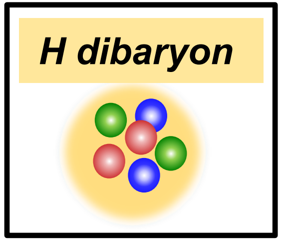
energy shift

absorption

yield ratio
-> ΞN→ΛΛ width

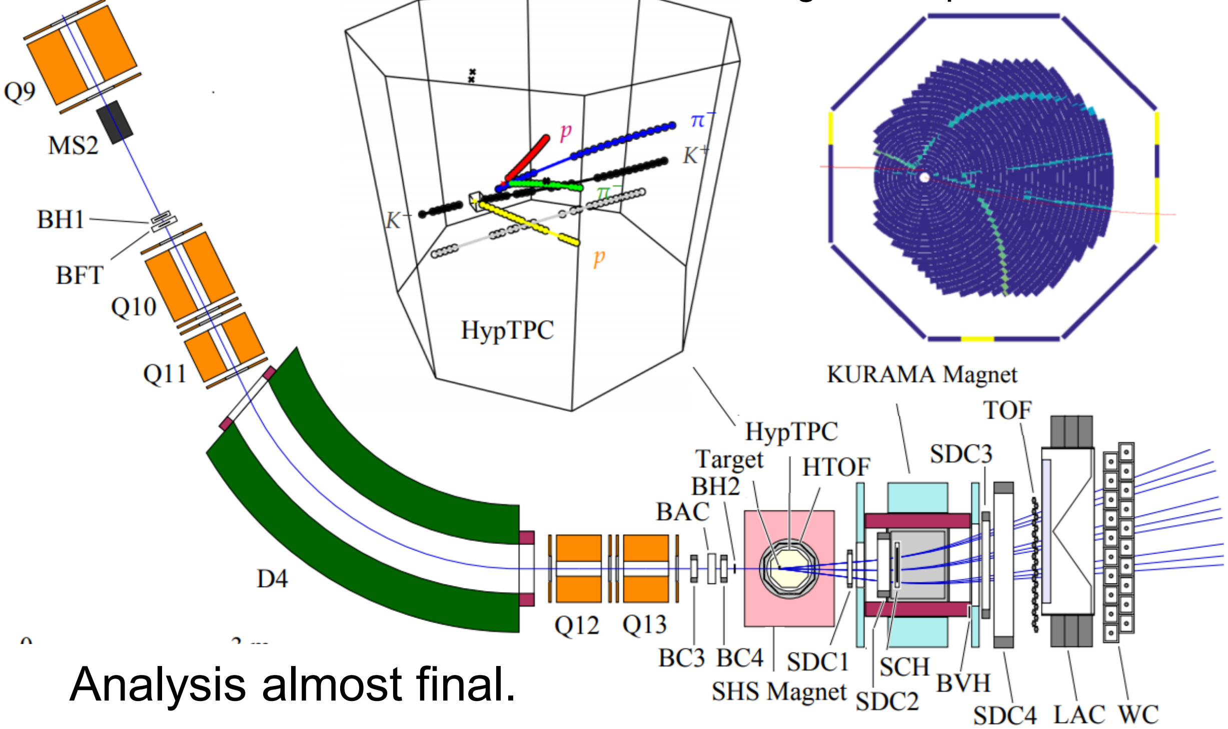
Study of H-dibaryon and ΞN interaction by $(K^-,K^+\Lambda\Lambda)$

(J-PARC E42, J.K. Ahn et al.)



Above ΛΛ threshold
Detect H→ΛΛ

TPC for high-rate operation



Analysis almost final.

W.S. Jung et al.,
PTEP 2025 (2025) 091D01

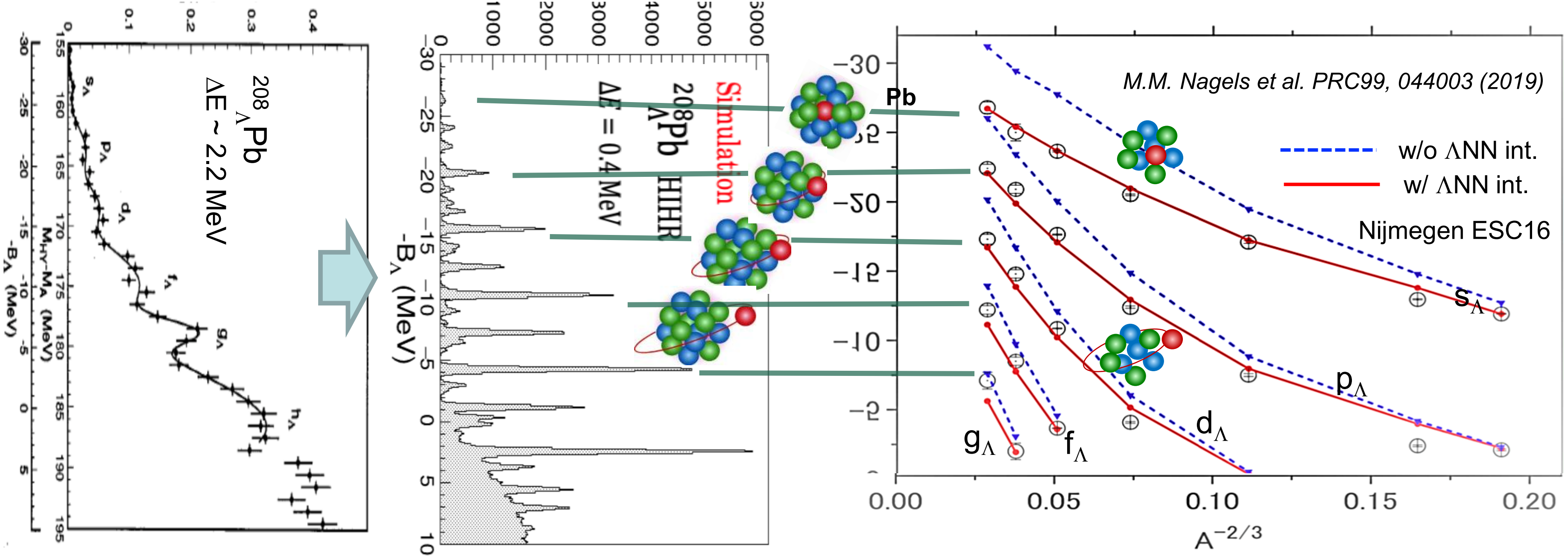
- $\Xi^- p \rightarrow \Xi^0 n$, ΛΛ cross sections were derived from Ξ^- escape rate and ΛΛ yield.
- $\sigma(\Xi^- p \rightarrow \Lambda\Lambda) \sim 1.1$ mb much smaller than meson exch. model predictions.
  $\Gamma_\Xi \lesssim 0.7$ MeV -> narrow Ξ hypernuclear states
- ΛΛ invariant mass spectrum for H dibaryon search will be published soon.

5. Hypernuclear spectroscopy for ΛNN interaction

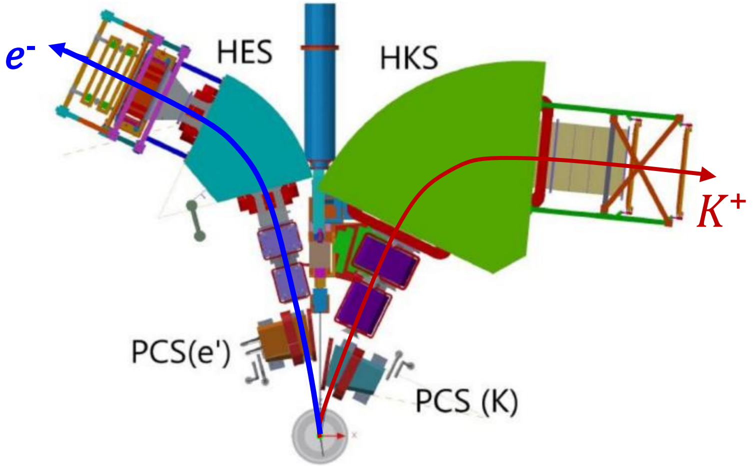
How can we extract YNN 3-body force effect ?

Single particle energies of Λ in hypernuclei => sensitive to ΛN density dep. (= ΛNN 3BF)

- Λ is distinguishable from nucleons. No Pauli from nucleons.
- We know the local density where the Λ is located.
- Different mass numbers, orbitals -> probe different densities



Experimental Plans



JLab @Hall C

E12-15-008: ^{40,48}Ca$(e,e'K^+)$ ${}^{40,48}_{\Lambda}$K

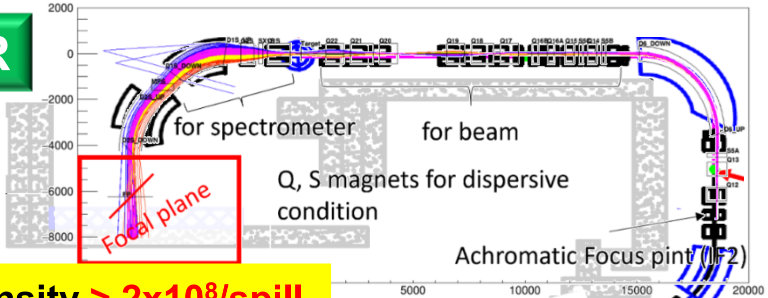
E12-18-013: ^{208}Pb $(e,e'K^+)$ ${}^{208}_{\Lambda}$Tl

T=1 ΛNN force => Λnn force in NS

J-PARC @HIHR line

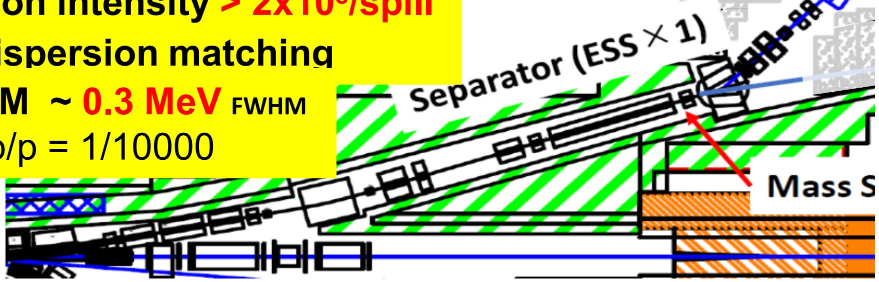
at the extended Hadron Facility

HIHR



P84: (π^+,K^+) …${}^{12}_{\Lambda}$C, ${}^{28}_{\Lambda}$Si, ${}^{40}_{\Lambda}$Ca, ${}^{51}_{\Lambda}$V, ${}^{89}_{\Lambda}$Y, ${}^{139}_{\Lambda}$La, ${}^{208}_{\Lambda}$Pb

ΔM < 400 keV (FWHM)



Pion intensity > 2×10^8/spill
Dispersion matching
ΔM ~ 0.3 MeV FWHM
Δp/p = 1/10000

Together with ΛN scattering exp. (E86 @K1.1), those B_{Λ} values give info. on ΛNN strength.

6. Summary

1. In order to elucidate the nuclear force and to solve the hyperon puzzle in NS, we need YN/YY interactions, both in free space and in nuclear matter, and extract information on YNN 3BF.
2. Recent high-quality $\Sigma^{\pm}p$ scattering data at J-PARC are being used to improve the interaction models. High-quality Λp scattering experiments are following.
3. Light hypernuclear data, ${}^{3}_{\Lambda}H$ binding energy/lifetime and Charge Symmetry Breaking in ${}^{4}_{\Lambda}H$/ ${}^{4}_{\Lambda}He$, have been collected.
4. Ξ hypernuclear data in emulsion and (K^{-},K^{+}) spectroscopy indicate an attractive Ξ-nucleus potential with a narrow ΞN-$\Lambda\Lambda$ width.
5. To investigate ΛNN interaction, precise Λ hypernuclear spectroscopy exp's are planned at Jlab and at the extended J-PARC Hadron Facility.