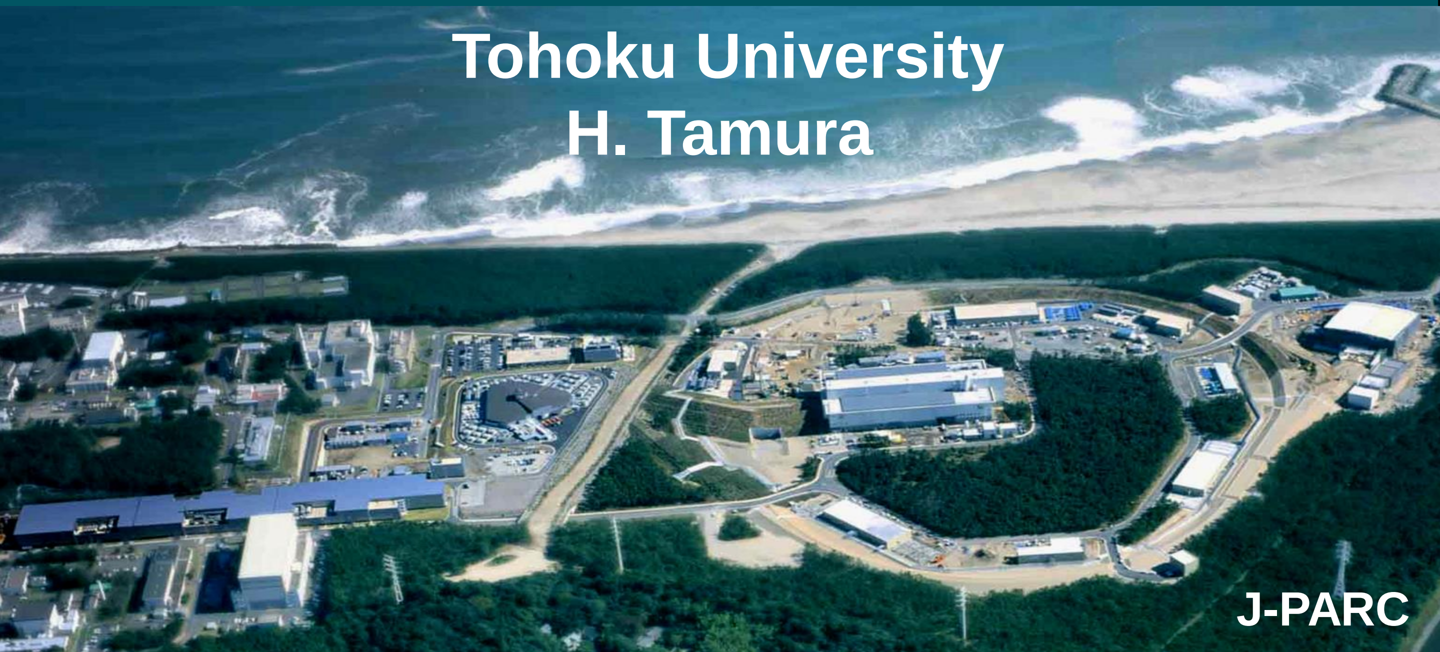
EMMI workshop
2017.11.7

Hypernuclear physics with kaon (and pion) beams

Tohoku University
H. Tamura



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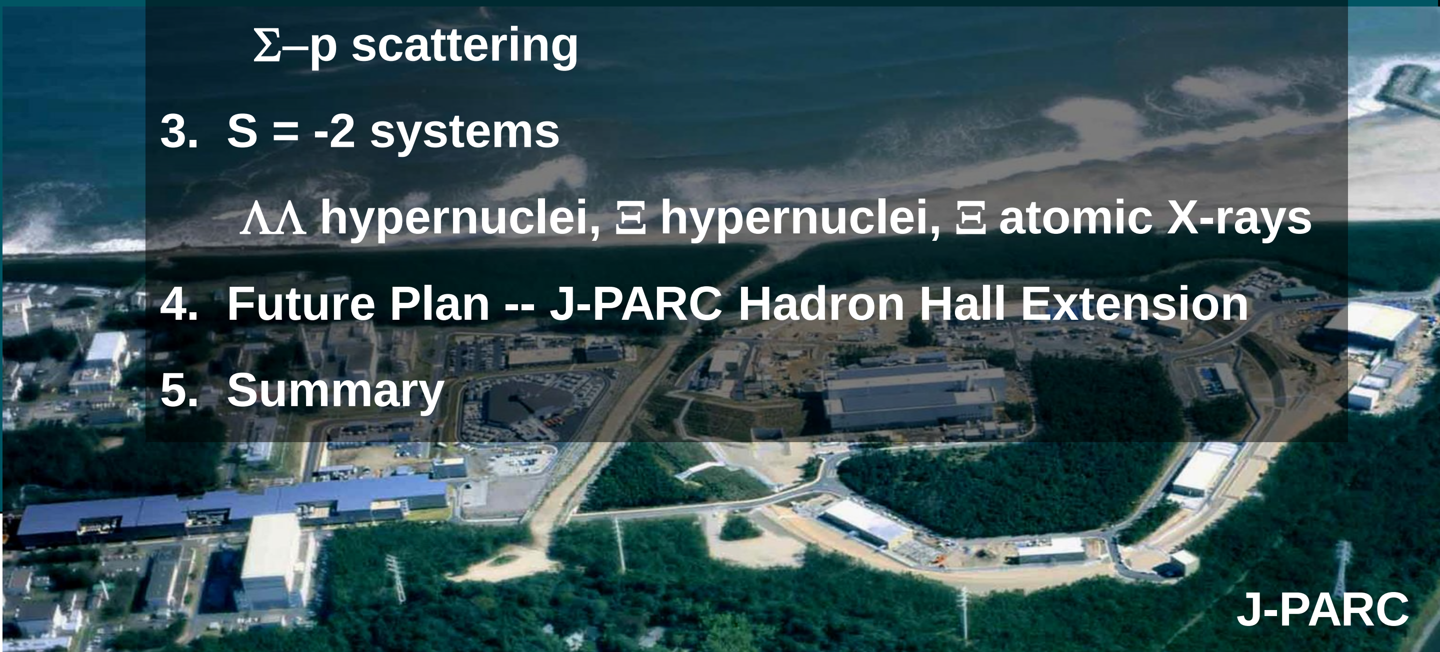
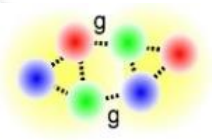


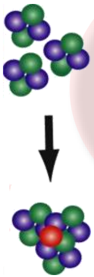
1. Introduction

Motivation: Strangeness makes nuclear physics deeper and wider

BB interactions



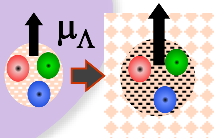
Unified understanding of BB forces by u,d ->u, d, s
Short-range forces by quark pictures
Test lattice QCD calculations



Impurity effect in nuclear structure

Changes of size, deformation, clustering.
Nuclear structure study using hyperons

Behavior and properties of baryons in nuclei



Baryon mixing
3-body forces
Modification of baryons

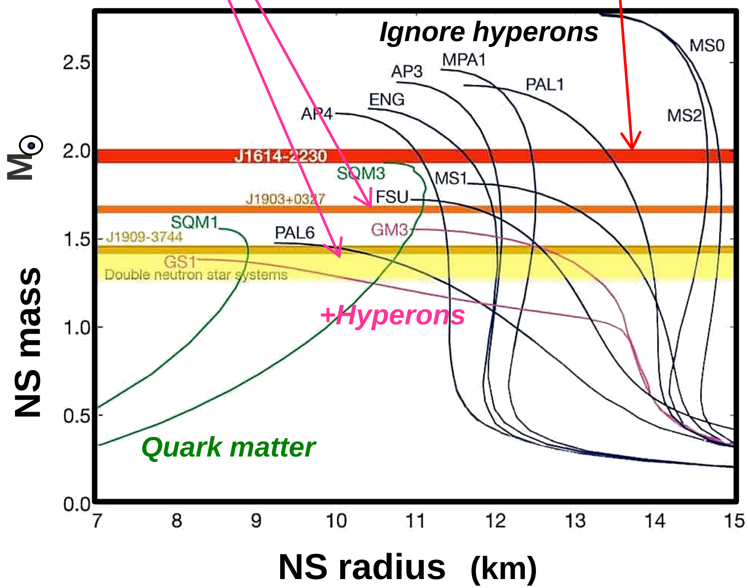
Clues to understand hadrons and nuclei from quarks

Cold and dense nuclear matter with strangeness

"Hyperon puzzle" in neutron stars

- Hyperons (Λ at least) should appear at ρ ~ 2-3 ρ_0
  EOS's with hyperons or kaons too soft => cannot support M > 1.5 M_{sun}
- Heavy NS's (~2.0 M_{sun}) were observed.

PSR J1614-2230 (2010) 1.97±0.04 M_{sun}
PSR J0348-0432 (2013) 2.01±0.04 M_{sun}



=> Unknown repulsion at high ρ

- Strong repulsion in three-body force including hyperons,
  NNN, YNN, YYN, YYY ?
  Chiral EFT is successful in NNN force.
  Extension to include hyperons requires **high quality YN scattering data.**
- Phase transition to quark matter ?
  (quark star or hybrid star)

We need to know YN, YY, K^{bar}N interactions both <u>in free space</u> and <u>in nuclear medium</u>

Are all hyperons bound in nuclei?

✔ Λ 40 Λ hypernuclei from $^{3}_{\Lambda}H$ to $^{208}_{\Lambda}Pb$ with ~80 excited states have been experimentally produced.

U_{Λ} = -30 MeV (c.f. U_N = -50 MeV)

-> Should appear $\rho \sim$ 2-3 ρ_0 in neutron stars

✗ Σ No bound systems observed (one exception: $^{4}_{\Sigma}He$)
Potential looks strongly repulsive.

U_{Σ} ~ +30 MeV

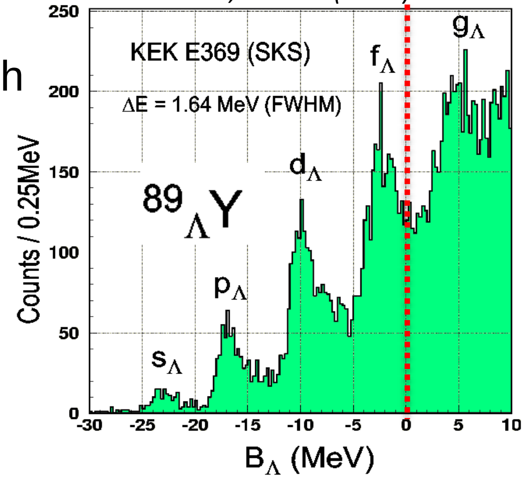
-> Does not appear in neutron stars

How strong is the repulsion?

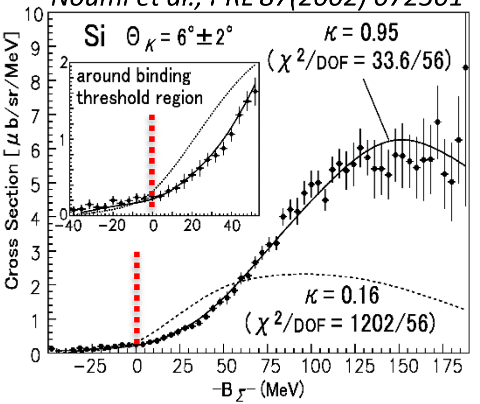
ΣN scattering experiment necessary

? Ξ No definite data exists

Hotchi et al., PRC 64 (2001) 044302



Noumi et al., PRL 87(2002) 072301



Comparison of hypernuclear production methods

K^- / π^+ beams (from protons) : (K^-,π^-), (π^+,K^+)

CERN-PS, BNL-AGS, KEK-PS, J-PARC

Secondary/weak beams ; thick targets

-> Limited resolution in reaction spectroscopy

Large cross section -> Less background, relatively large yield

n => Λ : energy calibration difficult

=> Coincidence experiments of Λ hyp. (γ-ray, weak decays)

S= -2 systems by (K^-,K^+)

DAΦNE

Electron (photon) beams: $(e,e'K^+)$

Jlab, MAMI

Primary/strong beams; thin target -> Excellent resolution

p => Λ : precise energy calibration

Less yield, accidental background

=> High resolution Λ hyp. spectroscopy, Precise mass determination

HI beams

GSI

Indirect reaction, ID from weak decay via invariant mass

-> Various hypernuclear species, Combinatorial background

=> Lifetime, Magnetic moment, Exotic hypernuclei

LHC, RHIC

Comparison of hypernuclear production methods

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S= -2 systems by (K^-,K^+)

DAΦNE

The three methods are complementary.

Electron (photon) beams: ( )

Jlab, MAMI

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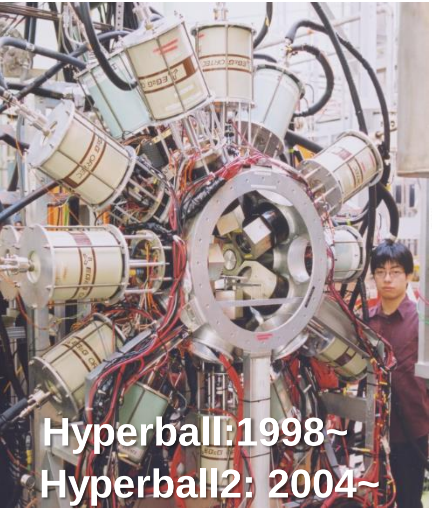
GSI

LHC, RHIC

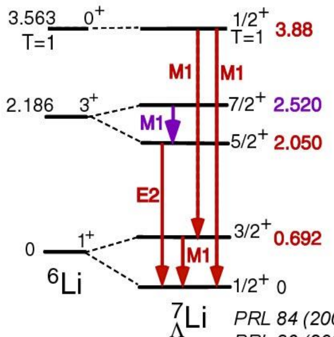
2. S=-1 systems

γ-ray spectroscopy of Λ hypernuclei

Hypernuclear γ-ray data (2015)

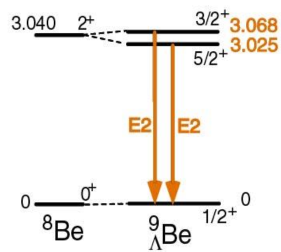


^{7}Li (π^+,K$^+\gamma$) KEK E419



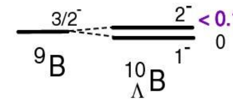
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

^{9}Be (K$^-$,$\pi^-\gamma$) BNL E930('98)



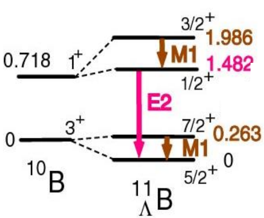
PRL 88 (2002) 082501
NPA 754 (2005) 58c

^{10}B (K$^-$,$\pi^-\gamma$) BNL E930('01)



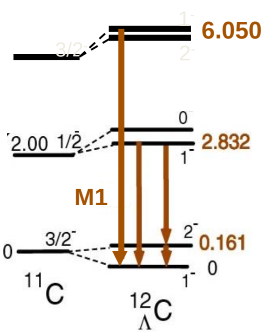
NPA 754 (2005) 58c

^{11}B (π^+,K$^+\gamma$) KEK E518



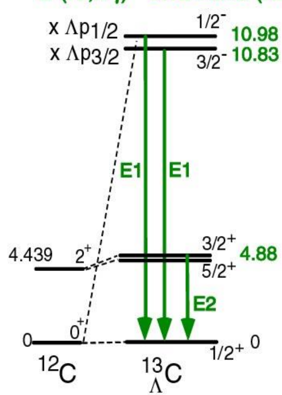
NPA 754 (2005) 58c

^{12}C (π^+,K$^+\gamma$) KEK E566



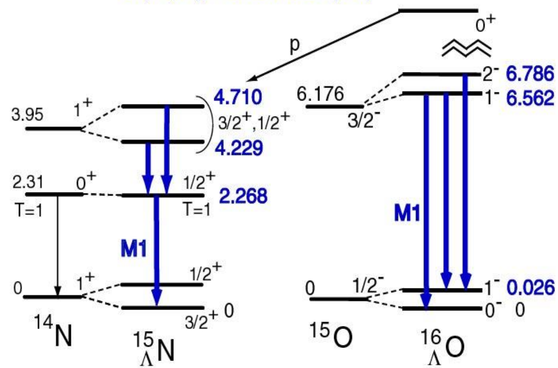
EPJ A33 (2007) 243
PTEP (2015) 081D01

^{13}C (K$^-$,$\pi^-\gamma$) BNL E929 (NaI)



PRL 86 (2001) 4255
PRC 65 (2002) 034607

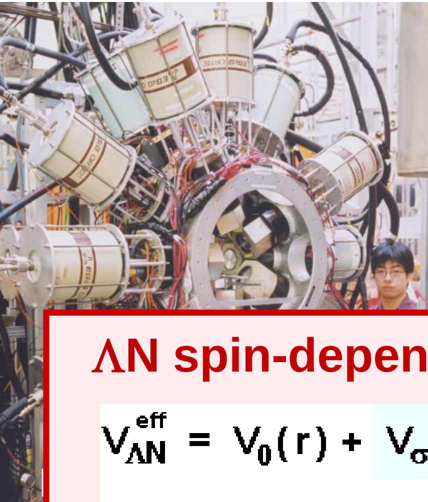
^{16}O (K$^-$,$\pi^-\gamma$) BNL E930('01)

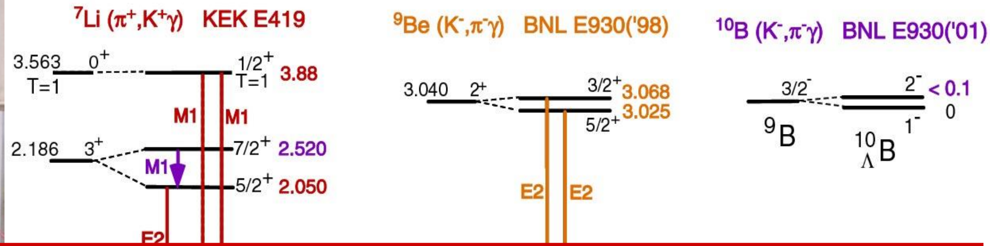


PRC 77 (2008) 054315

PRL 93 (2004) 232501
EPJ A33 (2007) 247

Hypernuclear γ-ray data (2015)





ΛN spin-dependent interaction strengths determined:

$$V^{eff}_{\Lambda N} = V_0(r) + V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\, \vec{l}_{\Lambda N} \vec{s}_\Lambda + V_N(r)\, \vec{l}_{\Lambda N} \vec{s}_N + V_T(r)\, S_{12}$$

Δ $\quad S_\Lambda$ $\quad S_N$ $\quad T$

Δ = 0.33 (A>10), 0.42 (A<10), S_Λ = -0.01, S_N = -0.4, T =0.03 MeV

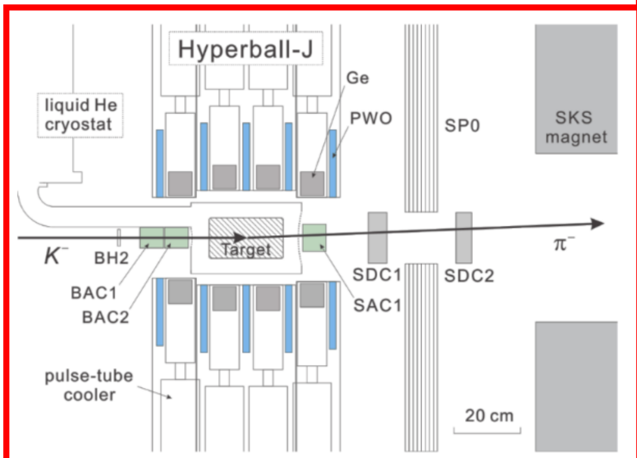
- **Almost all these p-shell levels are reproduced by this parameter set. (D.J. Millener)**
- **Feedback to BB interaction models. Nijmegen ESC08 model is almost OK. (But ΛN-ΣN force is not well studied yet.)**

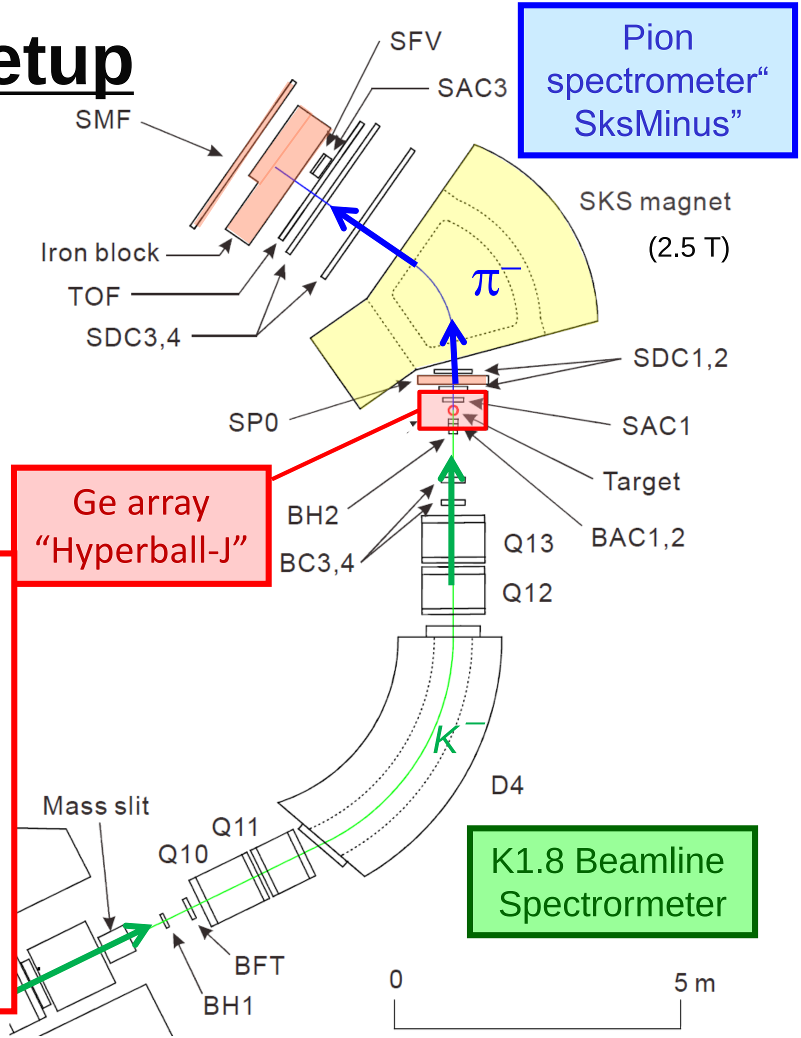
=> go to s-shell and sd-shell

J-PARC E13 Setup

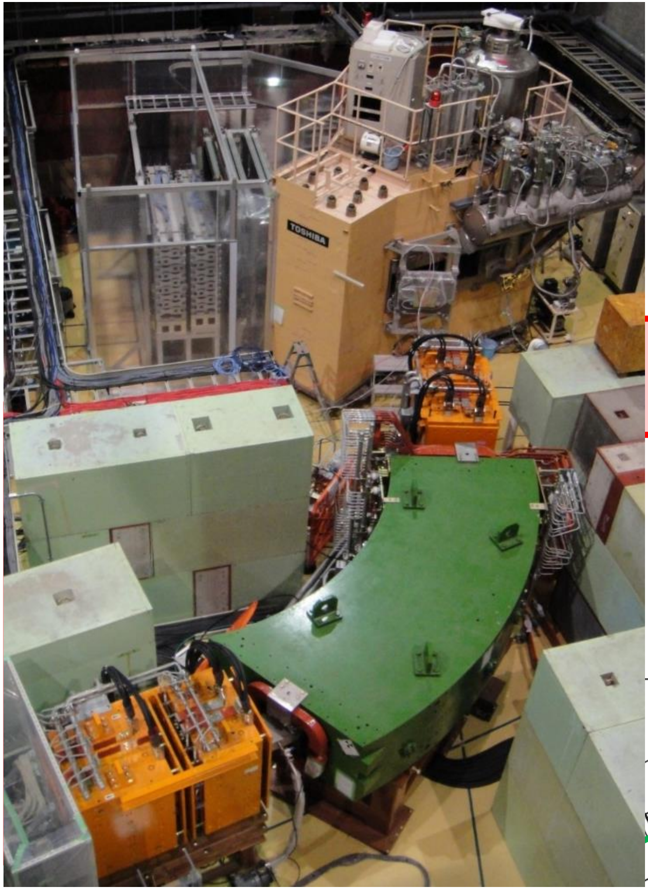
$$ {}^{A}Z\,(K^-,\pi^-)\,{}^{A}_{\Lambda}Z^* \;\rightarrow {}^{A}_{\Lambda}Z+\gamma $$

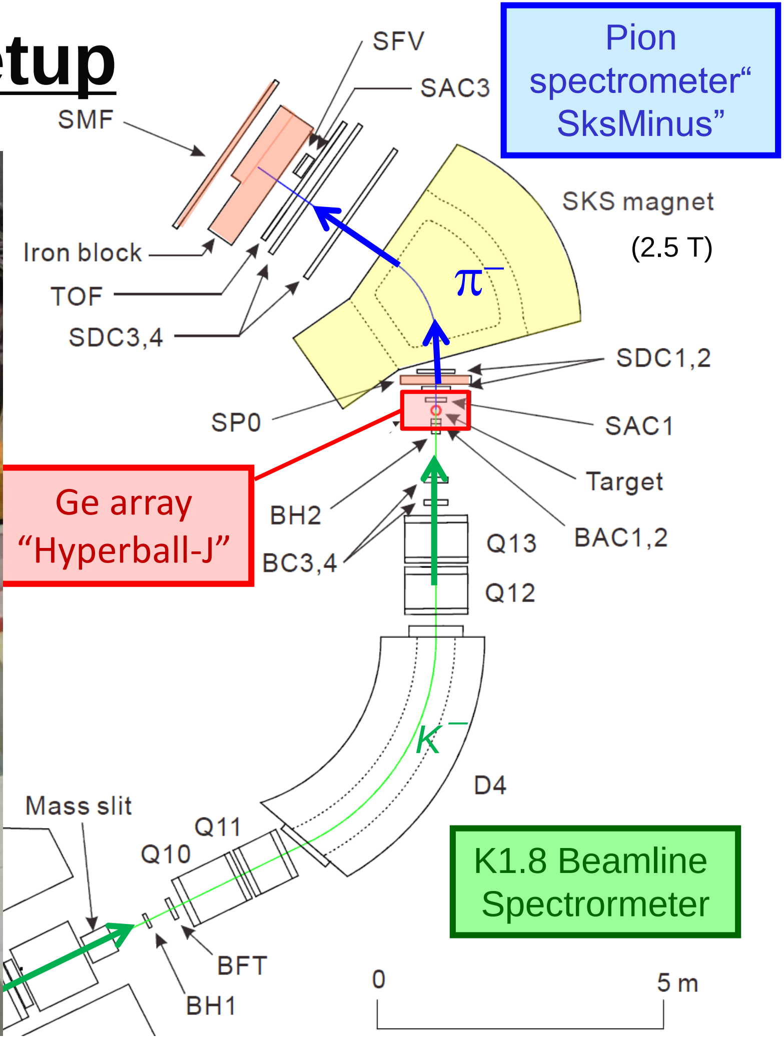
- Tag production of hypernuclei
- Detect γ-rays from hypernuclei





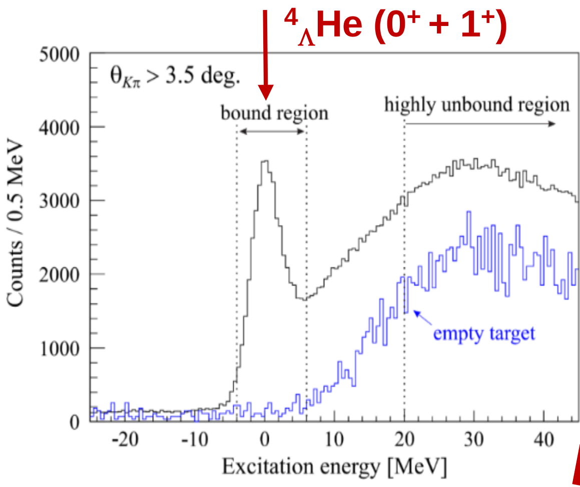
J-PARC E13 Setup



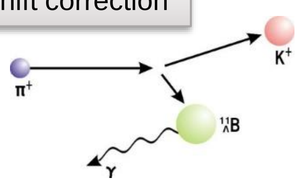


Result

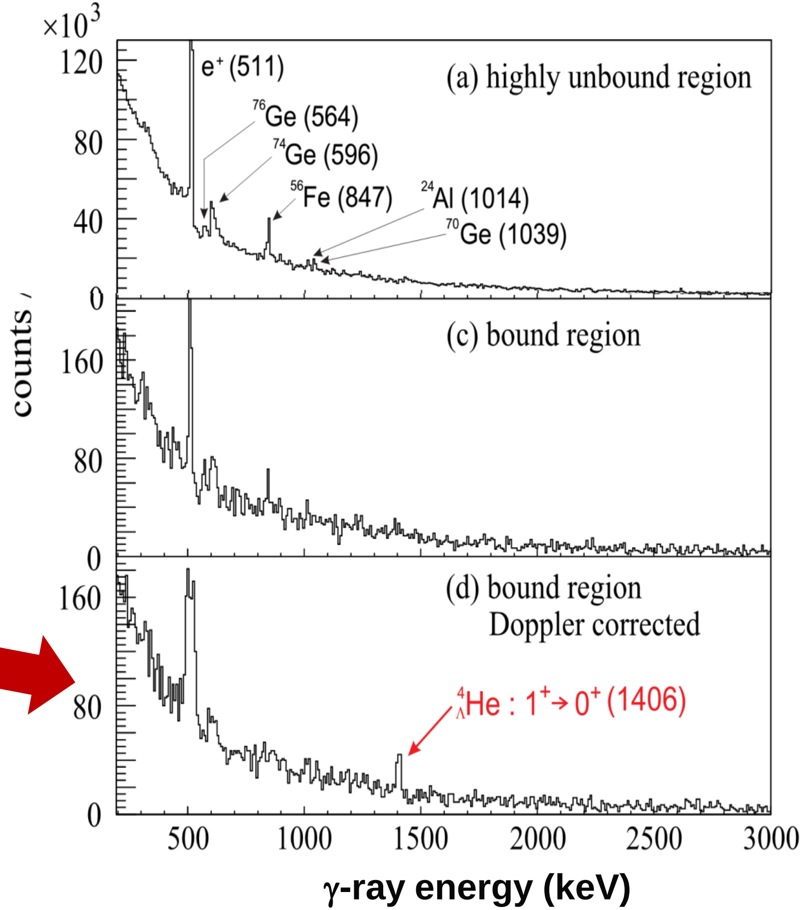
$^{4}He(K^{-},\pi^{-})$ missing mass



Doppler shift correction

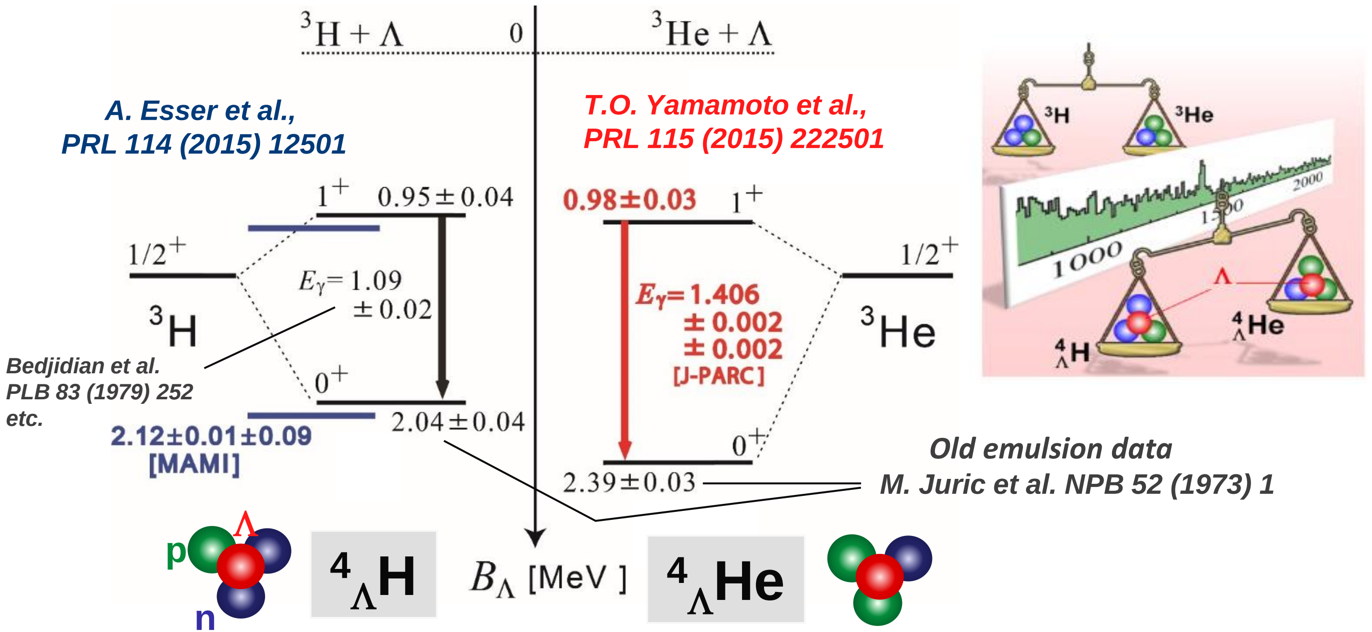


$$E_{corrected} = \frac{E_{measured}}{\gamma(1 + \beta\cos\theta_{\gamma})}$$



A peak observed at
1406±2±2 keV

Charge Symmetry Breaking in A=4 hypernuclei



A large CSB effect in ΛN force (pΛ ≠ nΛ) confirmed.

<u>Spin dependence</u> in CSB effect *cf.* B(^{3}H) - B(^{3}He) – EM effect ~70 keV

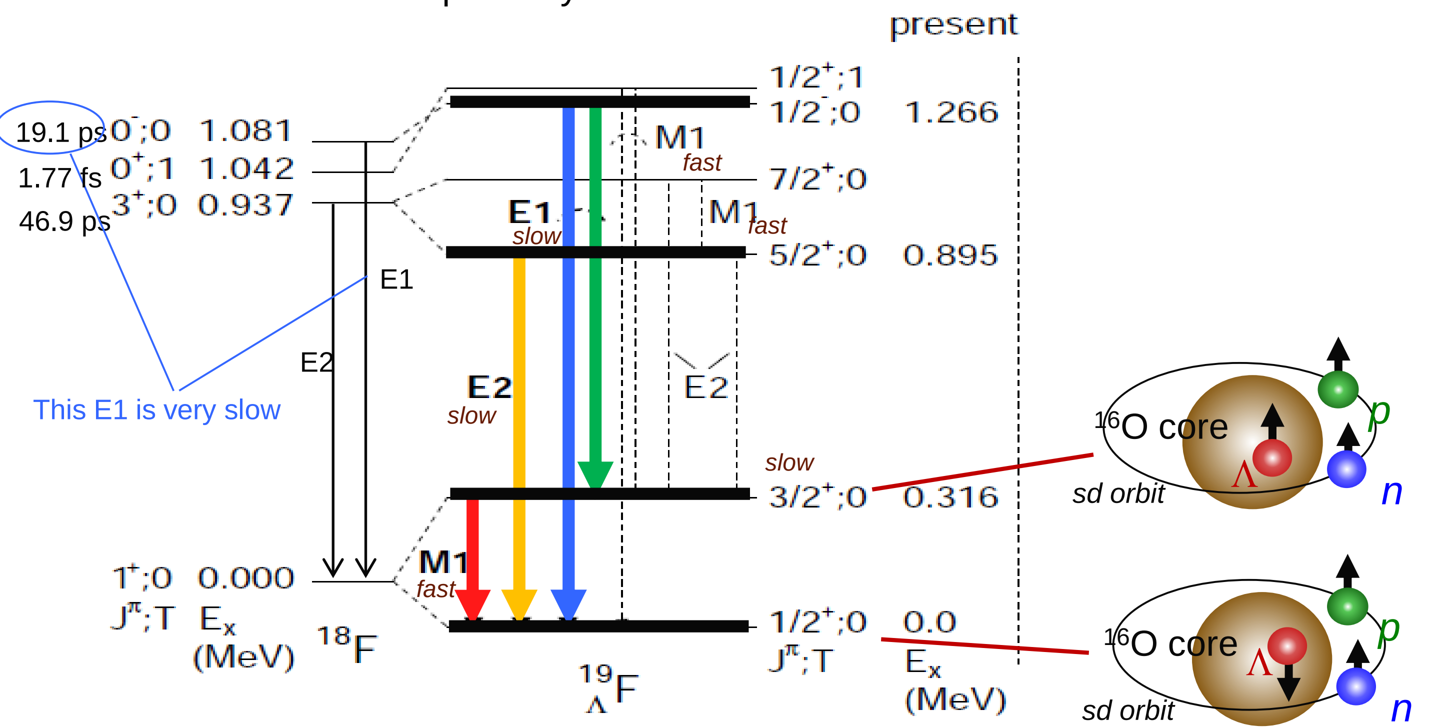
Previous theoretical works failed to understand it.

A.Gal suggests it can be explained with a YN force with different Σ–Λ coupling.

A. Gal, PLB 744 (2015) 352, D. Gazda and A. Gal, PRL 116 (2016) 122501

Level scheme of $^{19}_{\Lambda}F$ (J-PARC E13 result)

Assigned from the peak width (Doppler broadening or not) and the expected yield.



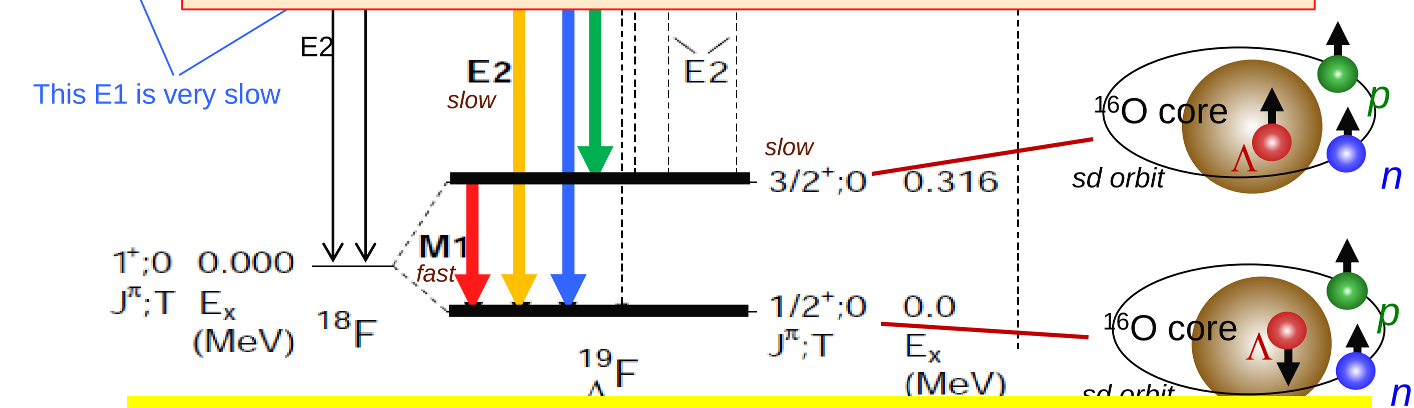
fast: Doppler broadening (< 1 ps)

slow: No Doppler broadening (> 1 ps)

Level scheme of $^{19}_{\Lambda}$F (J-PARC E13 result)

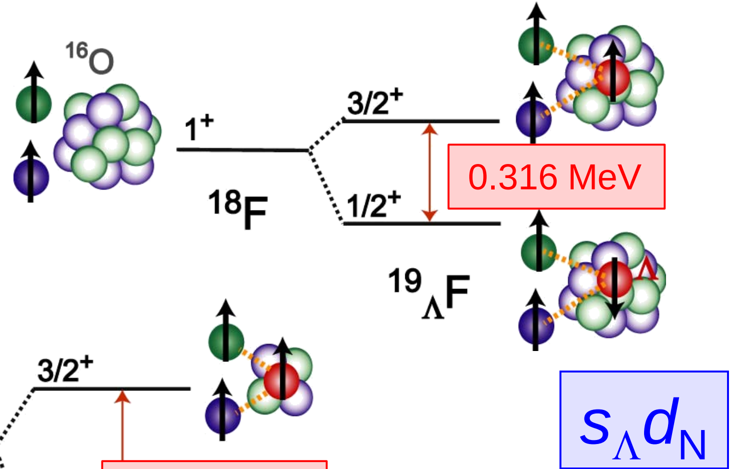
Shell model calculations for g.s. doublet ($3/2^+$,$1/2^+$) spacing

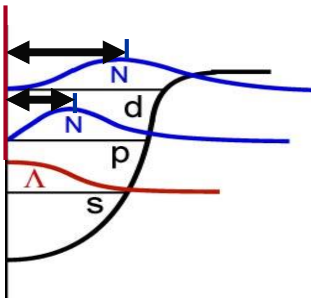
Millener	305 keV	Effective spin-spin interaction strength from p-shell hypernuclear data (Δ=0.33 MeV)
Umeya	419 keV	NSC97f
	245 keV	NSC97e
Exp.	315.5 ± 0.4 +0.6/-0.5 keV	

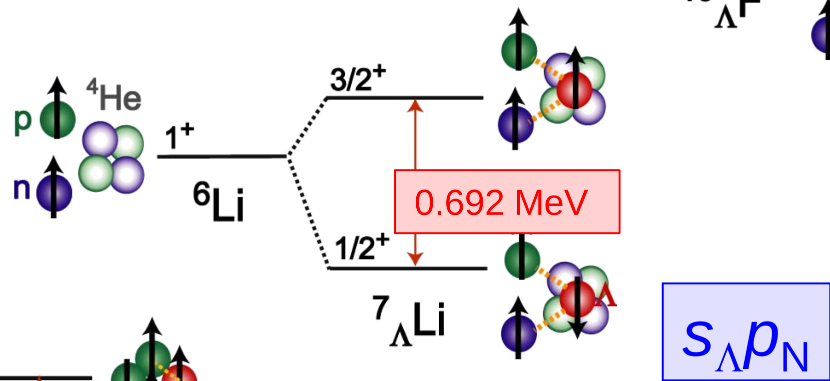


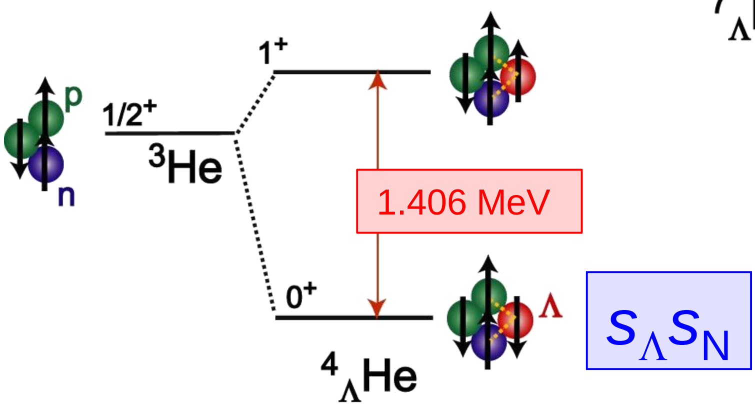
The theoretical frameworks and the inputs (ΛN interaction strength and range) are good even for heavier hypernuclei.

A-dependence of ΛN interaction strength









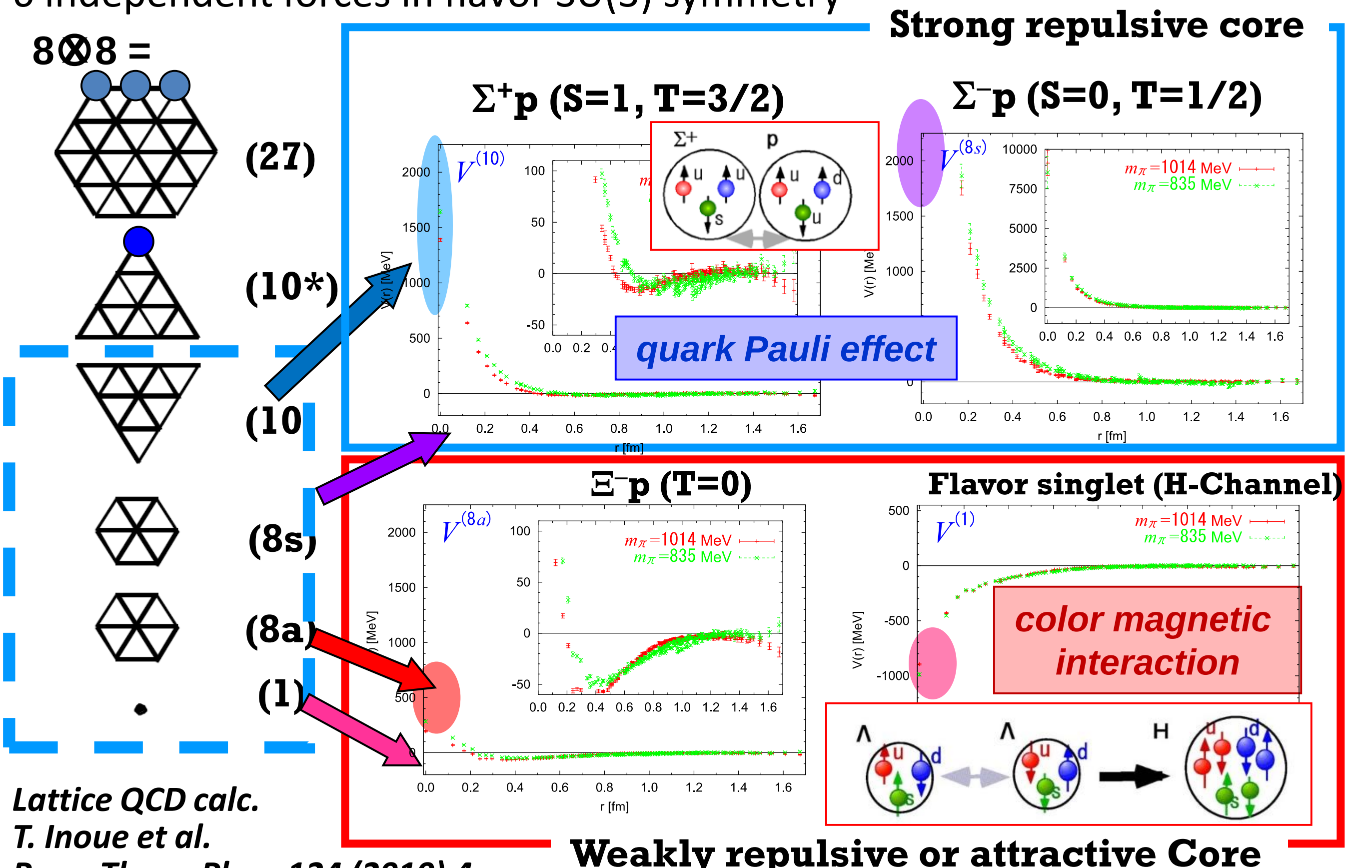
These splittings are understood well consistently.

2. S=-1 systems

Σ-p scattering

Baryon Baryon interaction by Lattice QCD

6 independent forces in flavor SU(3) symmetry



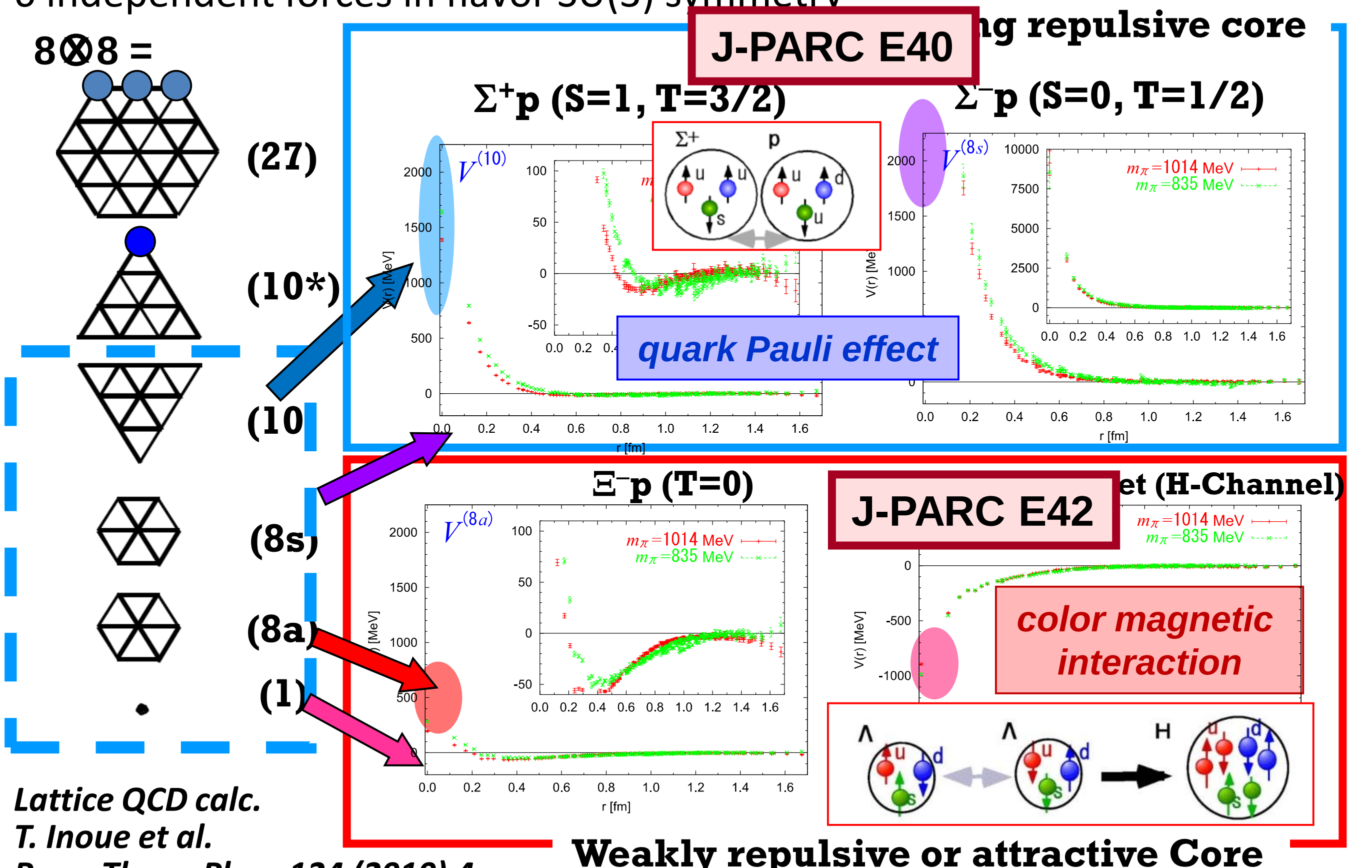
Lattice QCD calc.
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

Slide by Koji Miwa

Baryon … QCD

The same behavior was predicted by Oka-Yazaki's Quark Cluster Model

6 independent forces in flavor SU(3) symmetry

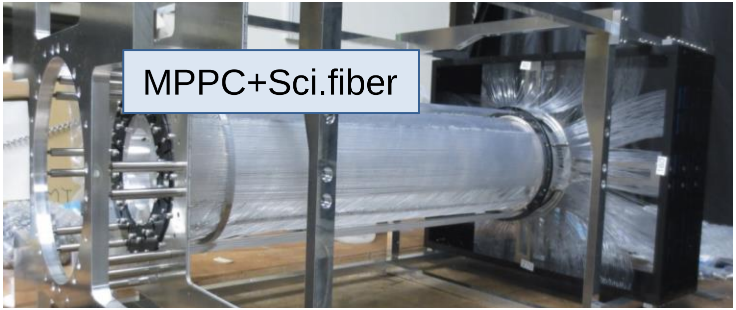


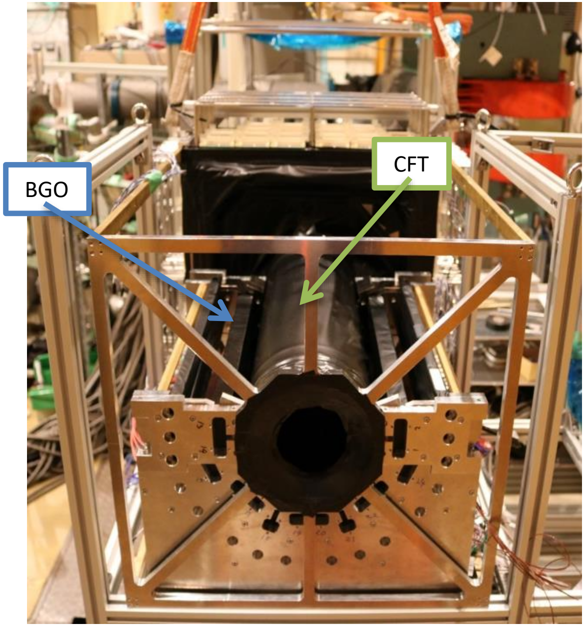
Lattice QCD calc.
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

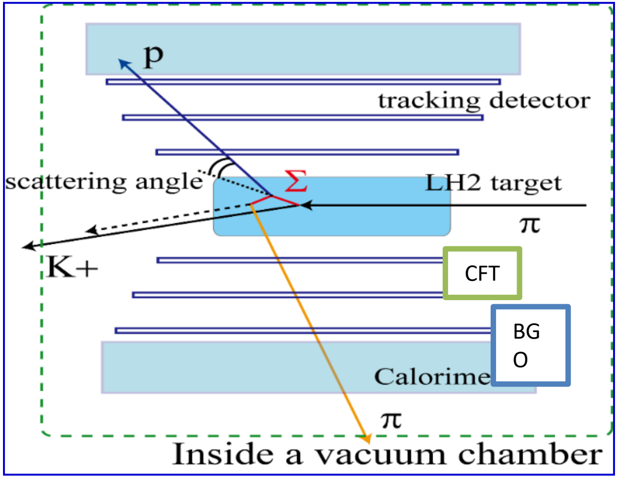
$\Sigma^{\pm}$p Scattering Experiment

J-PARC E40 (Miwa et al.)

- 1.3 GeV/c π^{+-} p -> $K^+ \Sigma^{+-}$ reaction
- Σ^{+-} track not directly measured
- Measure proton momentum vector -> kinematically complete







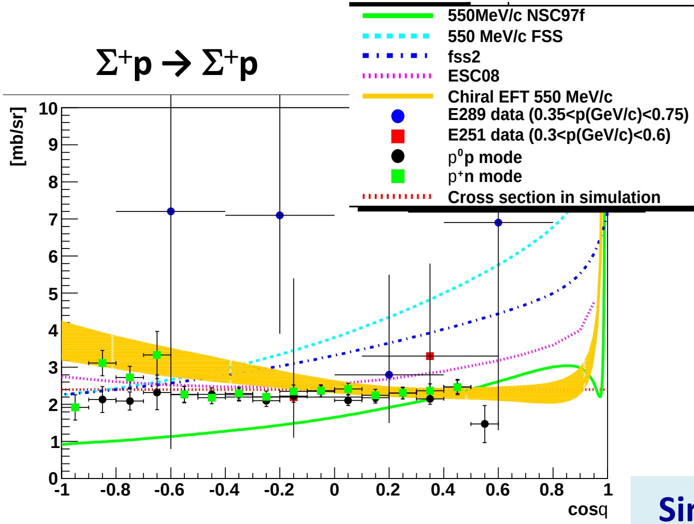
$\Rightarrow$ **$d\sigma/d\Omega$ for Σ^+p, Σ^-p, Σ^-p->Λn**
(p_Σ = 400-700 MeV/c)
=> confirm quark Paul effect

Run from Feb. 2018 at J-PARC

Slide by K. Miwa

Expected accuracy

$\Sigma^+p \rightarrow \Sigma^+p$



ds/dΩ : 2.4mb/sr isotropic (assumed)

- 20,000 scattering events
- derive dσ/dΩ for 3 momentum ranges

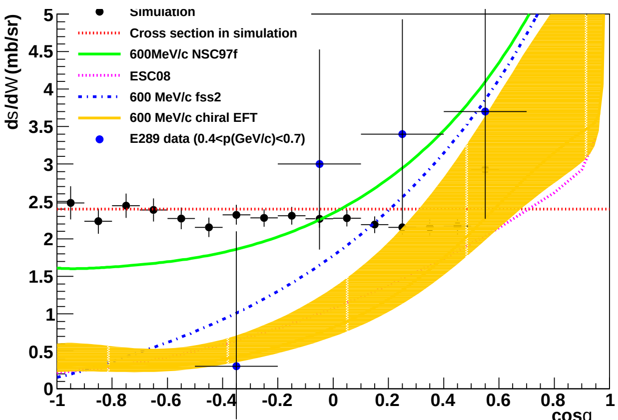
– Σ^-p : ±0.11 (stat.) ±0.15 (syst.) mb/sr

– Σ^+p : ±0.15 (stat.) ±0.15 (syst.) mb/sr

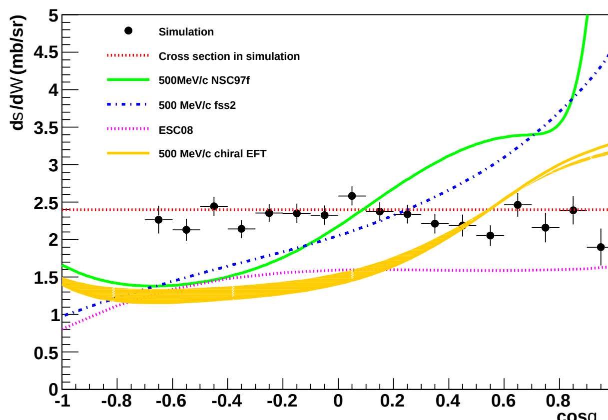
for 2.4 mb/sr

Simulation for p_Σ = 0.5 – 0.6 (GeV/c)

$\Sigma^-p \rightarrow \Sigma^-p$



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

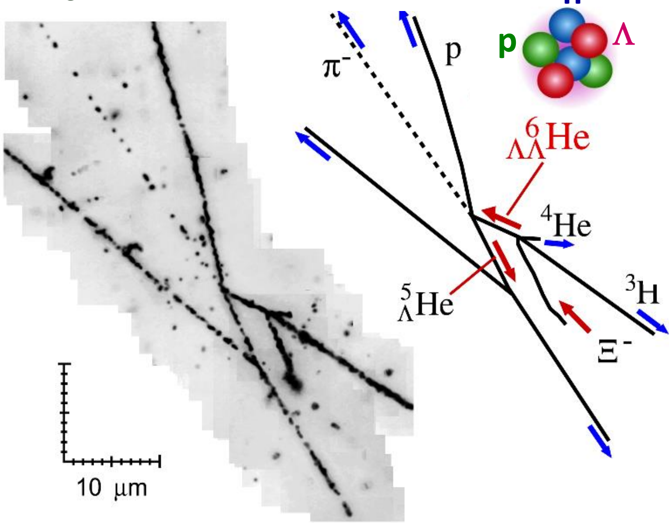


3. S=-2 Systems

Emulsion Results (KEK E373)

New analysis!

Nagara event



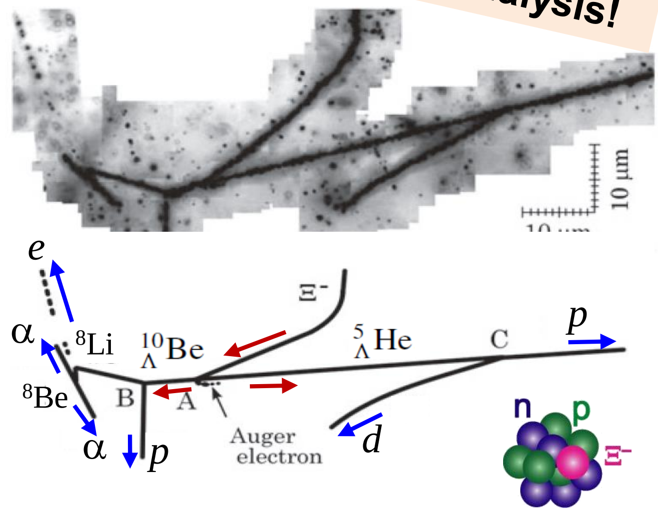
$^{6}_{\Lambda\Lambda}$He -> $^{5}_{\Lambda}$He + p + π^{-}

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

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

Λ-Λ is weakly attractive

Kiso event



$$\Xi^- + {}^{14}\mathrm{N} \to {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

The first clear ΛΞ hypernucleus

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

K. Nakazawa et al. PTEP 2015, 033D02

Ξ-N is attractive

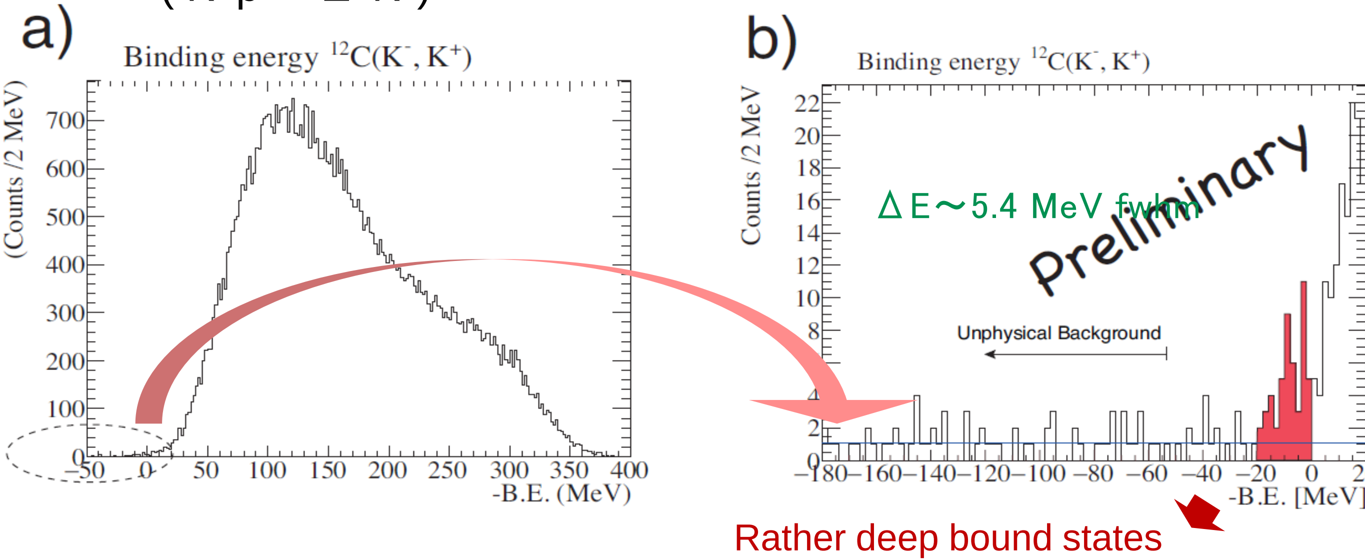
Ξ-Hypernuclear Spectroscopy via (K^-,K^+) Reaction

$^{12}C\,(K^-,K^+)\,^{12}_{\Xi}Be$ with SKS spectrometer

Nagae et al., J-PARC E05

$(K^- p \to \Xi^- K^+)$

T. Nagae et al., PoS INPC2016 (2017) 038



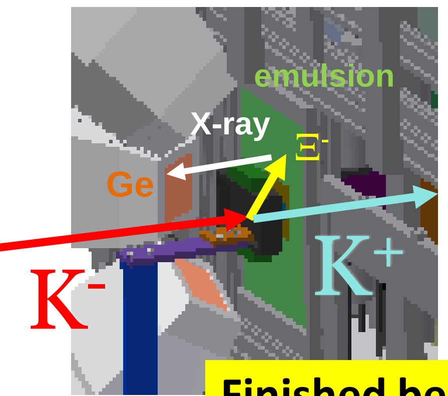
If U_Ξ is as deep as U_Λ(-30MeV), Ξ^- should appear first at $\rho \sim 2\,\rho_0$ in NS.

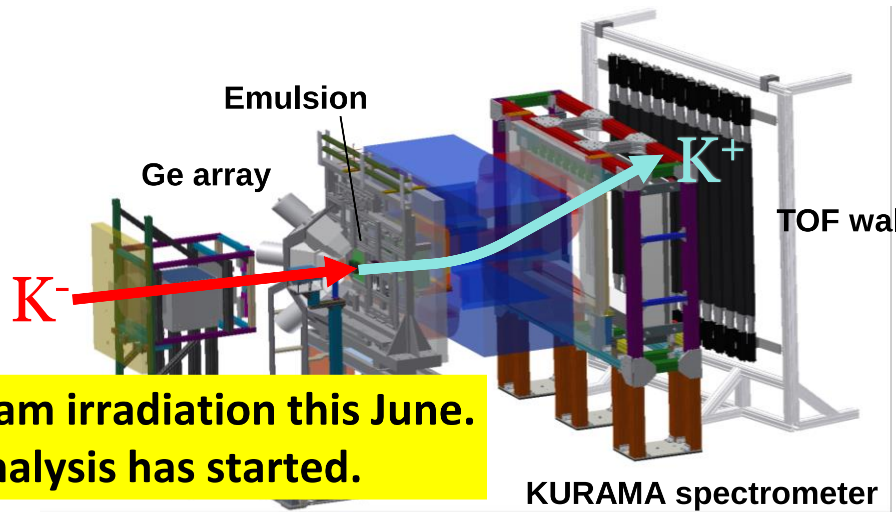
-> "Hyperon puzzle" more difficult to solve?

More S=-2 events with emulsion

J-PARC E07
K. Nakazawa et al.

- **Collect ~10^2 $\Lambda\Lambda$ hypernuclear events from ~10^4 Ξ^-_{stop}**
  - Confirm $\Lambda\Lambda$ int. and extract $\Lambda\Lambda$–ΞN effect
  - More Ξ-nuclear events -> Ξ-N interaction
- **Measure Ξ^- -atomic X-rays (Ag, Br) with Ge detectors**
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Ξ^- absorbed events identified from emulsion image–> no background





Finished beam irradiation this June.
Emulsion analysis has started.

4. Future Plan
J-PARC Hadron Hall Extension

Extension Plans of J-PARC Hadron Hall

S= -1 Systems

High precision
Λ hypernuclear spectroscopy

- < 2.0 GeV/c
- 1.8x10^8 pion/spill
- x10 better Δp/p

γ-ray spectroscopy
weak decays
ΛN scattering

- < 1.2 GeV/c
- ~10^6 K^-/spill

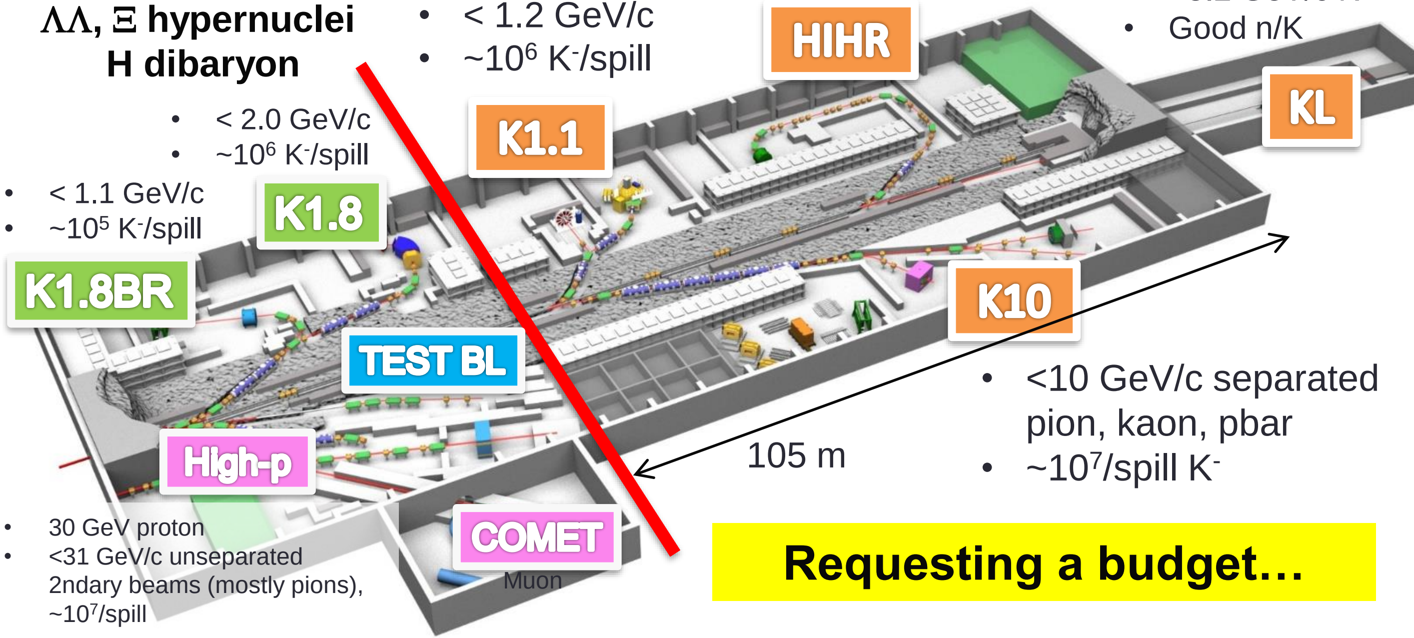
S= -2 Systems

ΛΛ, Ξ hypernuclei
H dibaryon

- < 2.0 GeV/c
- ~10^6 K^-/spill

- < 1.1 GeV/c
- ~10^5 K^-/spill

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K



- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

Requesting a budget…

5. Summary

- Kaon(pion) beams, electron(photon) beams, heavy ion beams are all complementary to each other.
- Present status at J-PARC:
  - γ-ray spectroscopy of $^{4}_{\Lambda}$He and $^{19}_{\Lambda}$F confirmed CSB in A=4 and revealed spin-spin splitting in sd-shell hypernucleus
  - Ξ–nucleus bound systems have been observed in old emulsion (Ξ^{-}-^{14}N) and in ^{12}C(K^-,K^+) $^{12}_{\Xi}$Be spectrum
  - New emulsion experiment for more $\Lambda\Lambda$ and Ξ hypernuclei + Ξ-atomic X-rays has been successfully performed.
  - $\Sigma^{\pm}$p scattering experiment will start soon.
- J-PARC hadron Hall extension is planned to construct new kaon beam lines and a high-reolution pion beam line.