セミナー＠先端研
2017.10.18

Prospect of strangeness nuclear physics at J-PARC (personal view)

J-PARCでのストレンジネス核物理の展望

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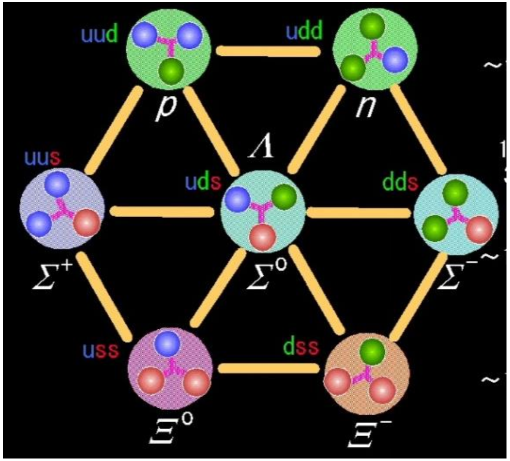
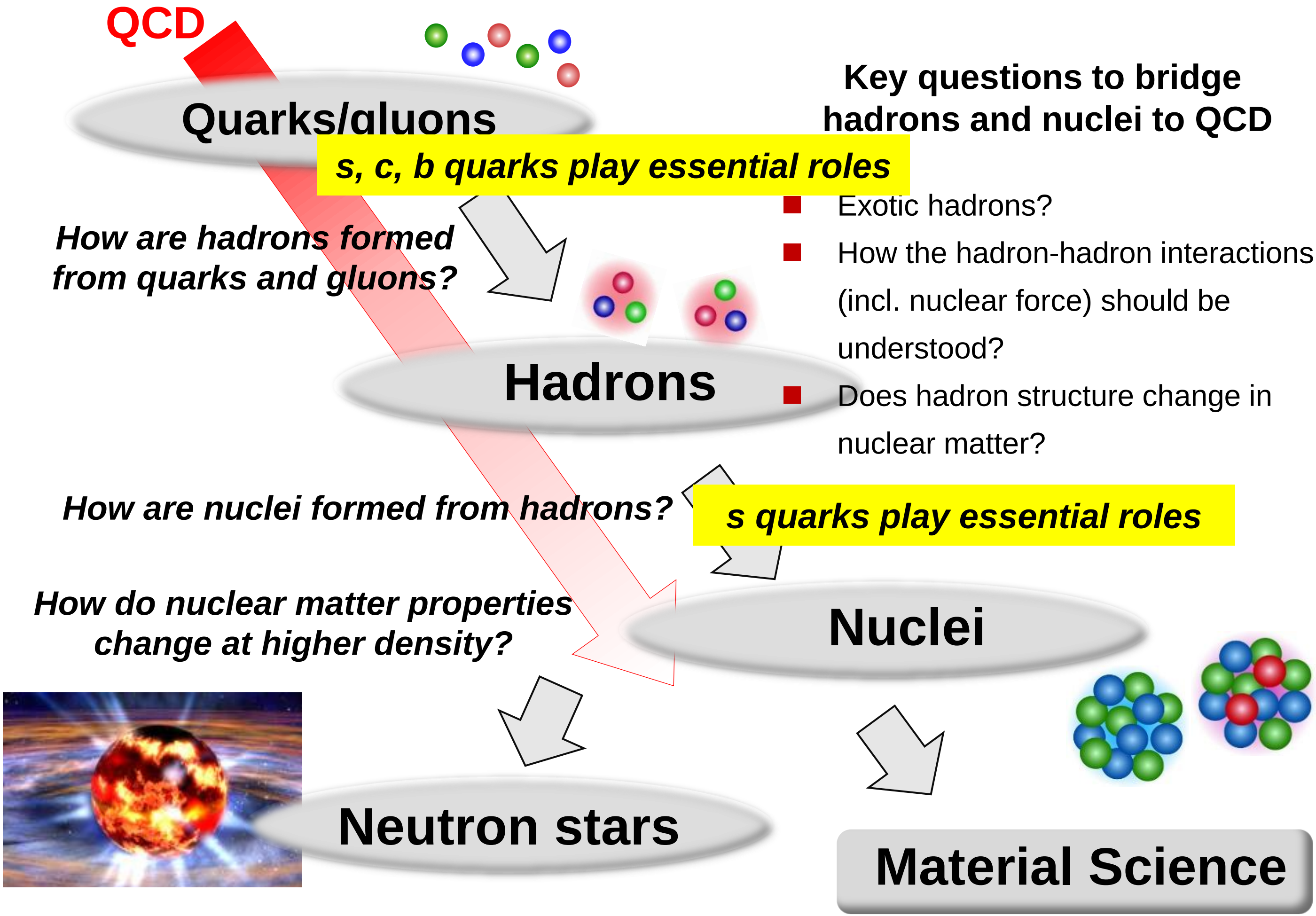
1. Introduction

--- why strangeness?



Basic questions in low energy QCD



Key questions in nuclear force

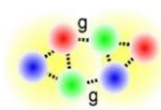
- Origins of the short range forces such as repulsive core and LS force?
- The short-range strong repulsion almost cancelled by the long-range strong attraction. Why?
- How should we understand Baryon-Baryon forces in a unified way?
- How is the high density matter in neutron stars?

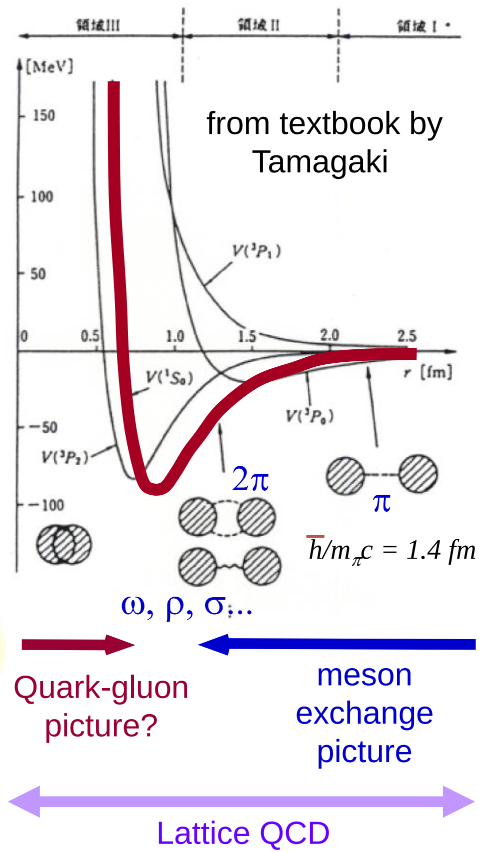
=> Give answers

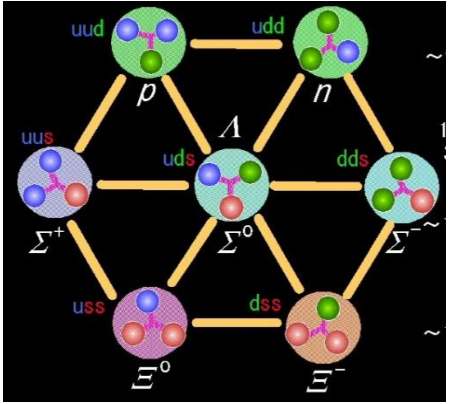
by adding s quarks and extending

NN -> BB forces

nuclear matter -> baryonic matter







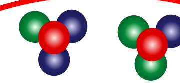
How well do we know BB interactions ?

Due to short lifetimes (10^{-10} s) of hyperons(Y) YN interactions have been studied using hypernuclei rather than YN scattering experiments

Exp's running or planned at J-PARC etc.

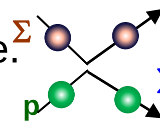
- **ΛN** attractive (U_{Λ}=-30 MeV)
  The same in neutron matter?
  Effect of ΛN-ΣN mixing?

n-rich Λ hypernuclei



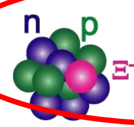
Charge sym. breaking in Λ hypernuclei

- **ΣN** looks strongly repulsive.
  How large repulsion?



$\Sigma^{\pm}$-p scattering

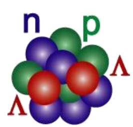
- **ΞN** unknown => Attractive
  How large attraction? H dibaryon?



Ξ hypernuclei

Ξ atoms

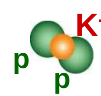
- **ΛΛ** weakly attractive
  Effect of ΛΛ-ΞN coupling?



ΛΛ hypernuclei

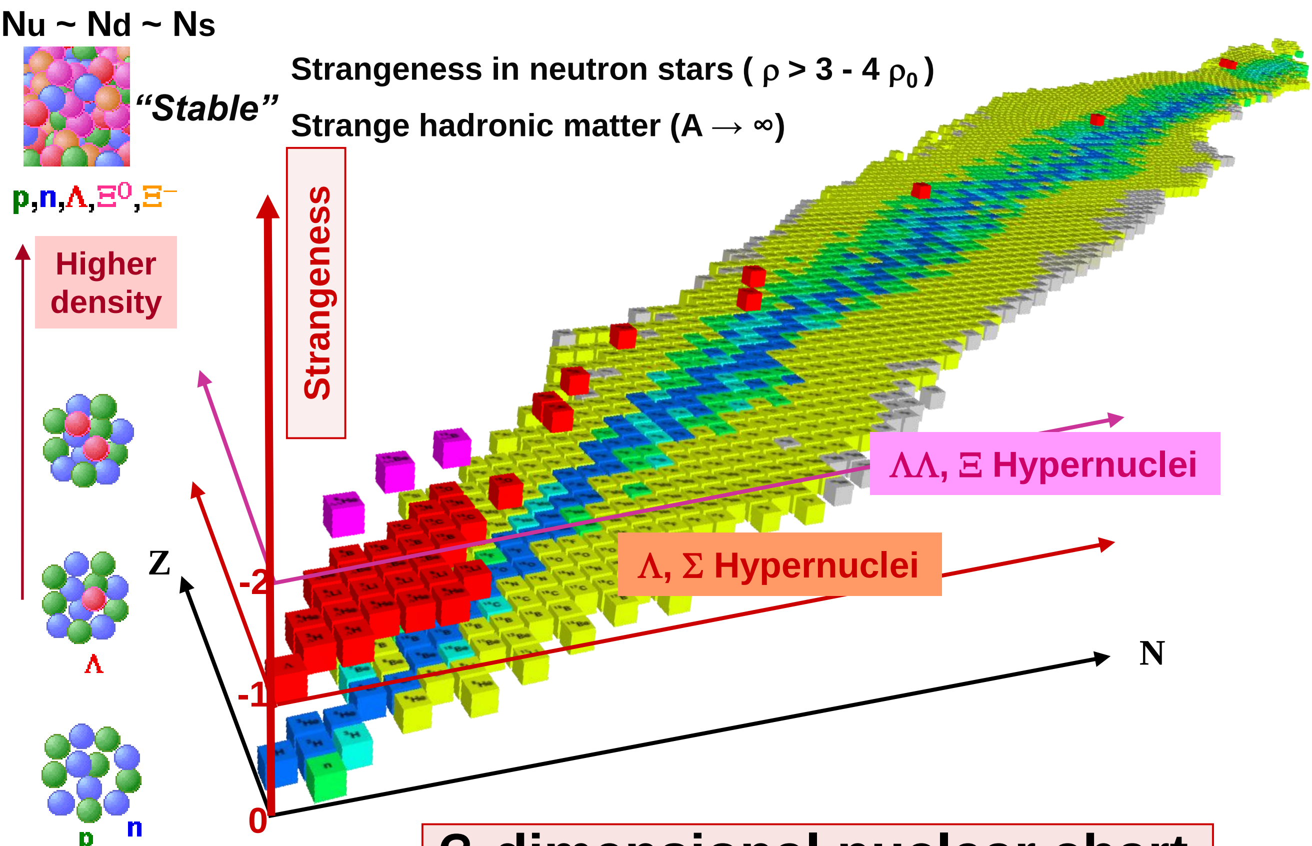
H dibaryon?

- **K^{bar}N** strongly attractive
  How large attraction in nuclear matter?



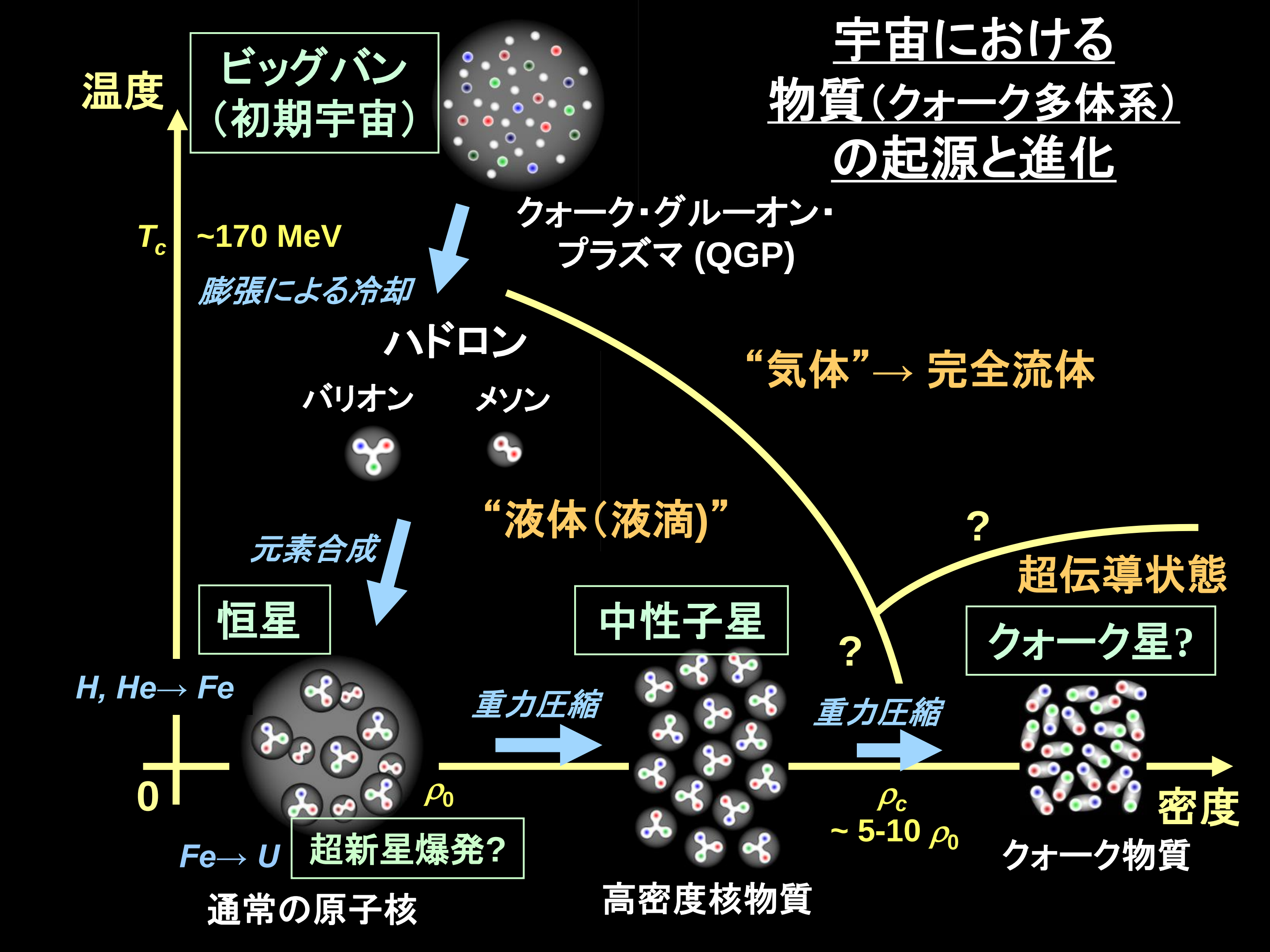
K-nucleus
K atoms

World of matter made of u, d, s quarks

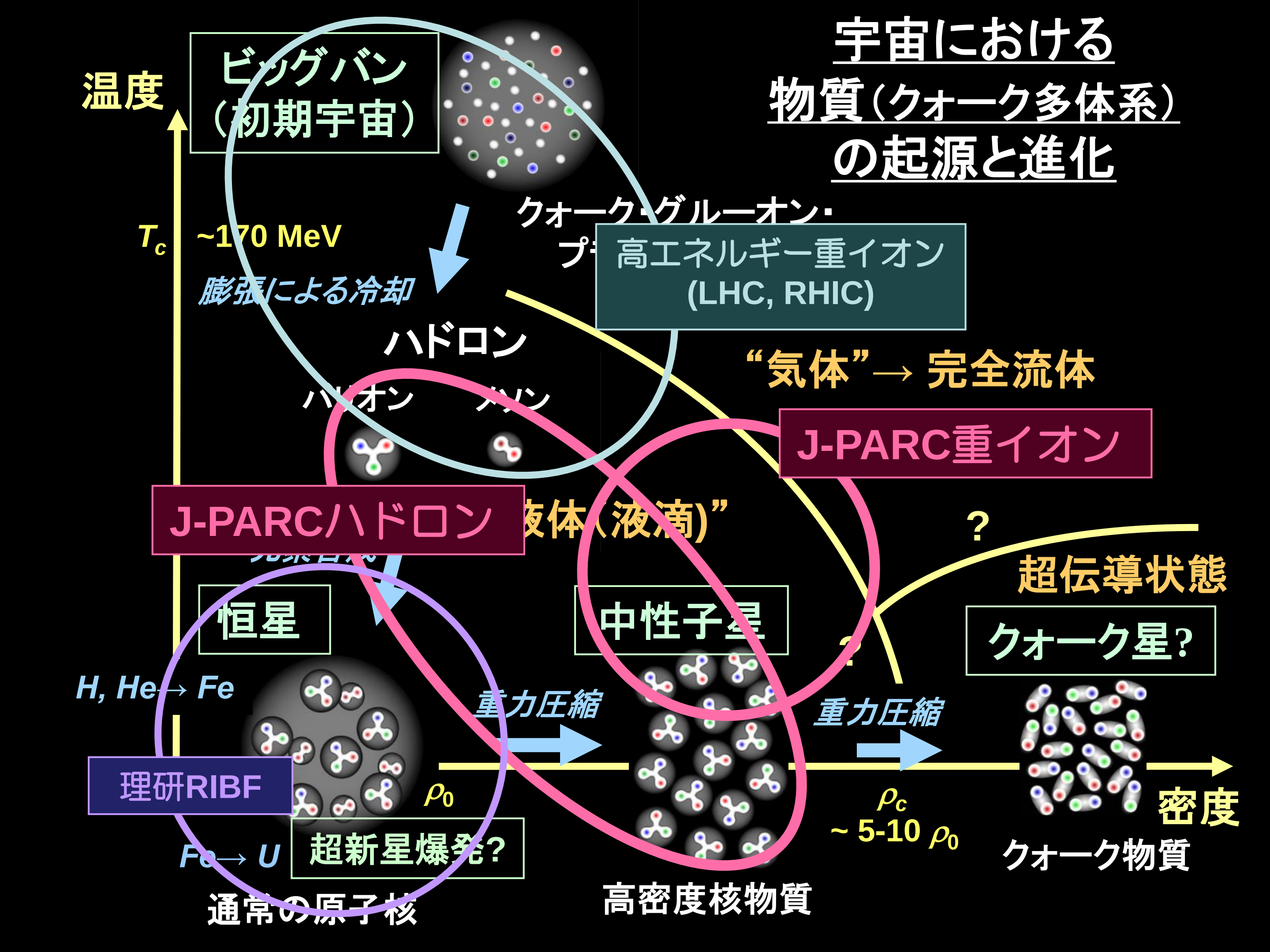


3-dimensional nuclear chart

by M. Kaneta inspired by HYP06 conference poster



宇宙における
物質（クォーク多体系）
の起源と進化
温度
ビッグバン
（初期宇宙）
クォーク·グルーオン·
プラズマ (QGP)
T_c
~170 MeV
膨張による冷却
ハドロン
バリオン
メソン
"気体"→ 完全流体
"液体（液滴)"
元素合成
?
超伝導状態
恒星
中性子星
クォーク星?
?
H, He→ Fe
重力圧縮
重力圧縮
0
ρ_0
ρ_c
~ 5-10 ρ_0
密度
Fe→ U
超新星爆発?
クォーク物質
通常の原子核
高密度核物質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?
超伝導状態
恒星
中性子星
クォーク星?
H, He→ Fe
重力圧縮
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理研RIBF
ρ_0
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~ 5-10 ρ_0
密度
クォーク物質
Fe→ U
超新星爆発?
通常の原子核
高密度核物質

Recent results and plans on Strangeness NP

- ■ *(Partly) took data*
- ■ *running*
- ■ *Under preparation*

S=-1 hypernuclei

J-PARC E13/E63

■ γ spectroscopy of Λ hypernuclei

${}^{4}_{\Lambda}$He γ-ray observed *${}^{4}_{\Lambda}$H γ-ray, ${}^{7}_{\Lambda}$Li B(M1), ..*

■ Λ hypernuclear spectroscopy via (e,e'K^+)

JLab

${}^{7}_{\Lambda}$He, ${}^{10}_{\Lambda}$Be, ${}^{12}_{\Lambda}$B high res. Spect. *${}^{40}_{\Lambda}$K, ${}^{48}_{\Lambda}$K*

■ Decay pion spectroscopy of Λ hypernuclei

MAMI

${}^{4}_{\Lambda}$H mass from ${}^{4}_{\Lambda}$H -> ^{4}He + π^-

■ Lifetime of light Λ hypernuclei via HI beams

GSI, STAR, ALICE

Surprisingly short ${}^{3}_{\Lambda}$H lifetime

S=-2 hypernuclei

J-PARC E07

■ Emulsion experiments

Ξ^--^{14}N bound state observed KEK

■ ■ Ξ hypernuclear spectroscopy

${}^{12}_{\Xi}$Be observed J-PARC E05

■ ■ Ξ atom X rays J-PARC E03/E07

■ Unbound H dibaryon search

J-PARC E42

S=-1 YN scattering

■ Σ p scattering J-PARC E40

$\Sigma^{\pm}p \to \Sigma^{\pm}p$, $\Sigma^{-}p \to \Lambda n$: $d\sigma/d\Omega$

K^{bar} nuclei

J-PARC E15

■ K^-pp via ^{3}He(K^-,n) *K-pp spectrum measured*

■ K^-pp via d(π^+,K^+) *K-pp like bump observed*

J-PARC E27

■ K-pp studies (HADES) GSI

■ ■ K-N, N-Nucleus (KLOE/AMADEUS)

DAΦNE

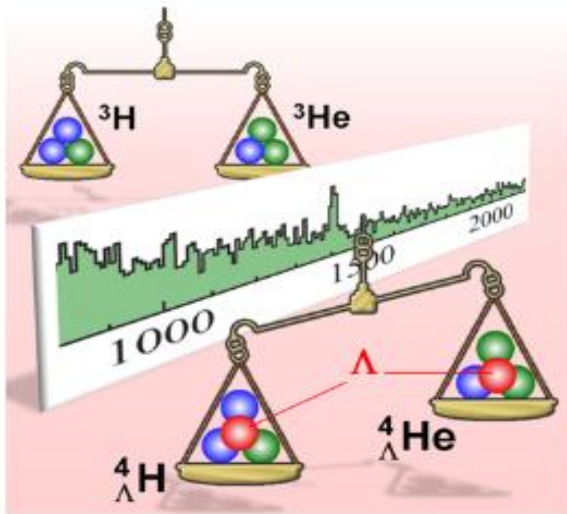
■ ■ K-d, K-He atom X rays

DAΦNE, J-PARC E57/E62

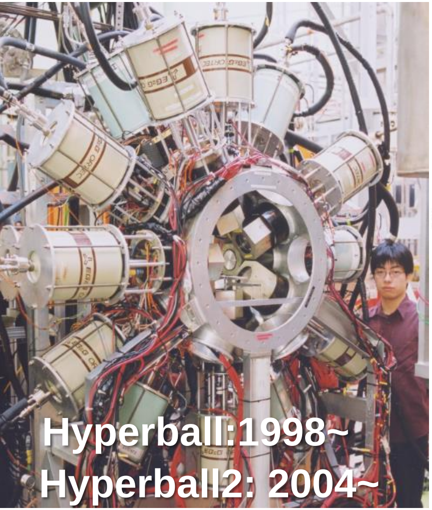
2. Recent results at J-PARC

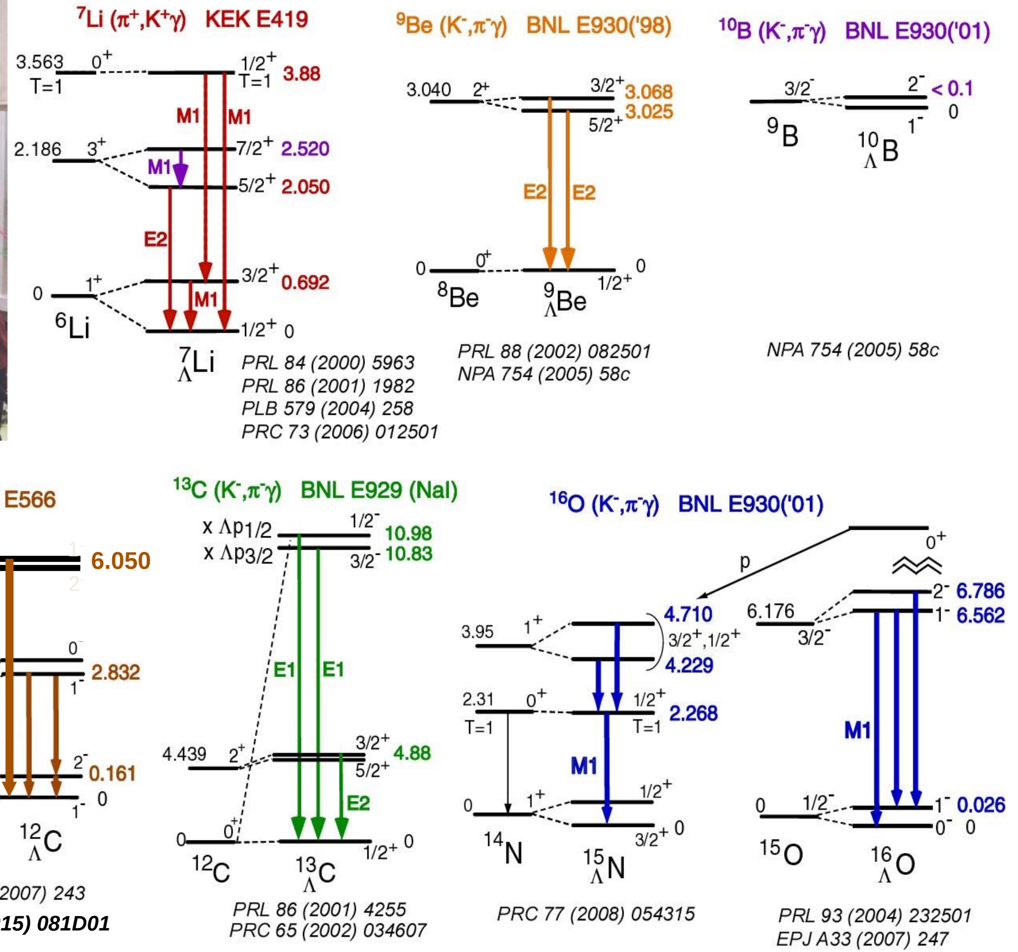
2.1 γ spectroscopy of Λ hypernuclei

-- Charge symmetry breaking--

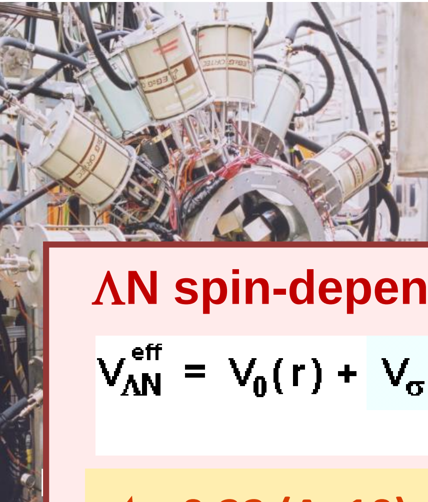


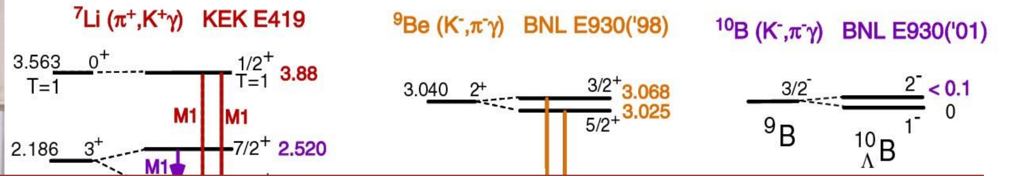
Hypernuclear γ-ray data (2012)





Hypernuclear γ-ray data (2012)





ΛN spin-dependent interaction strengths determined:

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

Δ (V_σ), S_Λ (V_Λ), S_N (V_N), T (V_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)

NPA 754 (2005) 58c

EPJ A33 (2007) 243

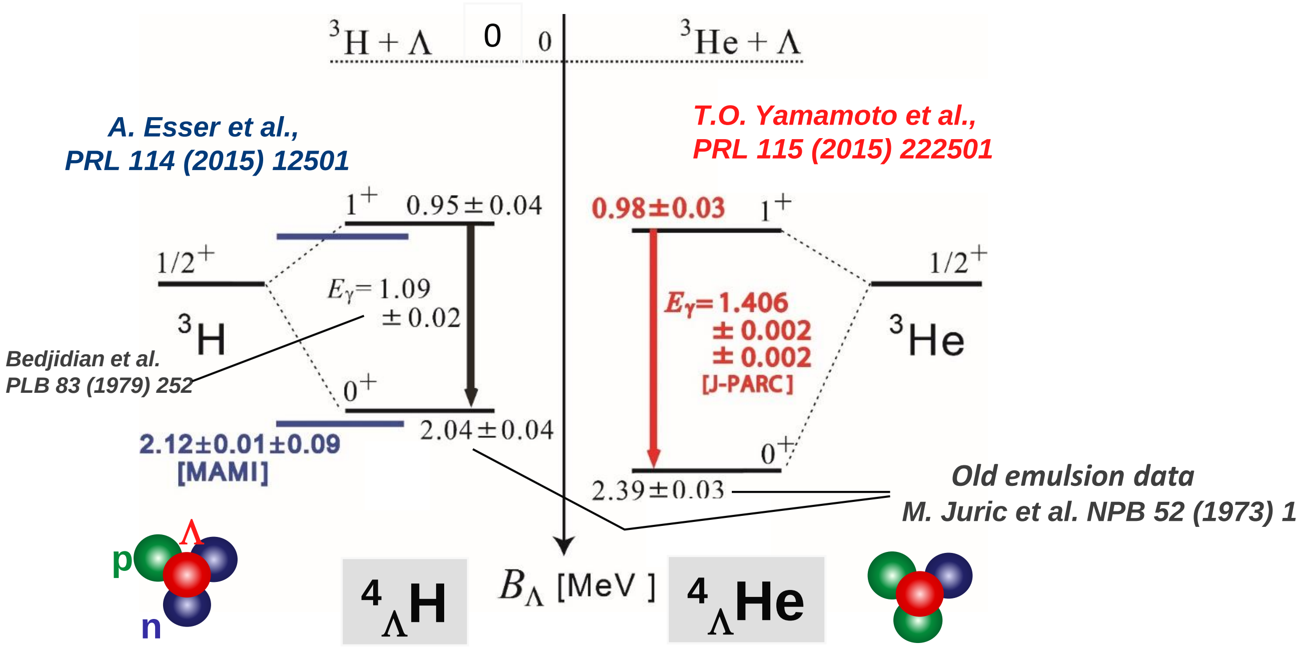
PTEP (2015) 081D01

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

PRC 77 (2008) 054315

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

Charge Symmetry Breaking in A=4 hypernuclei



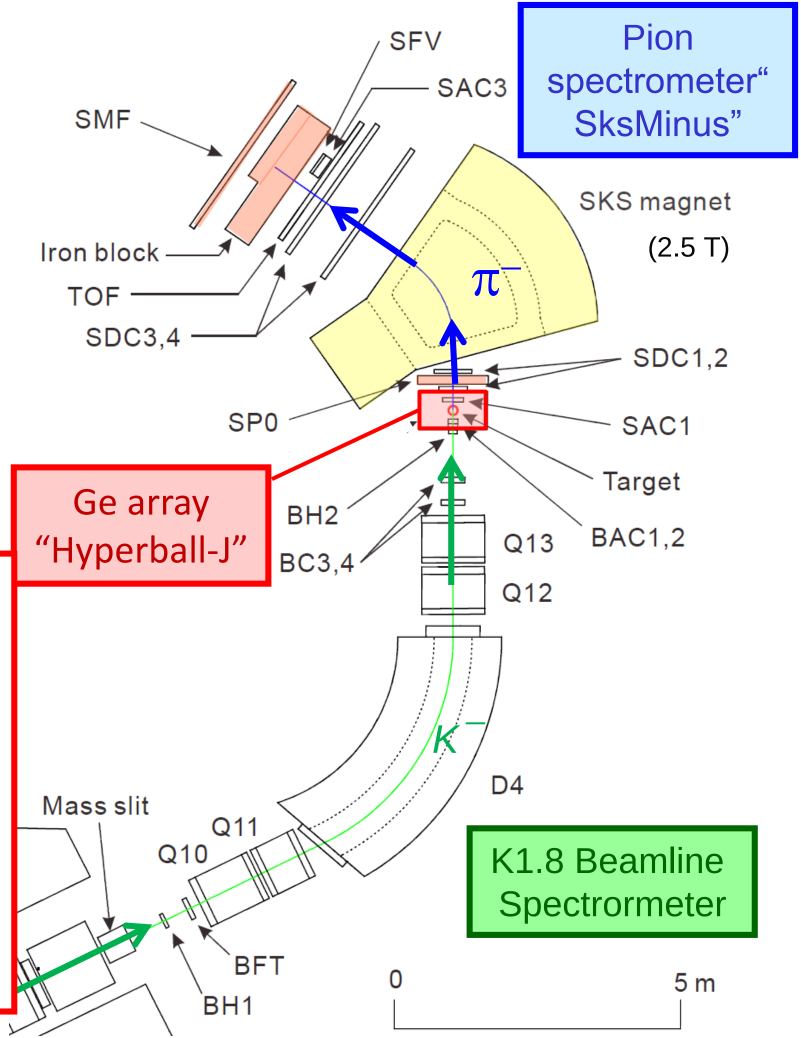
cf. B(^{3}H) - B(^{3}He) – EM effect ~70 keV

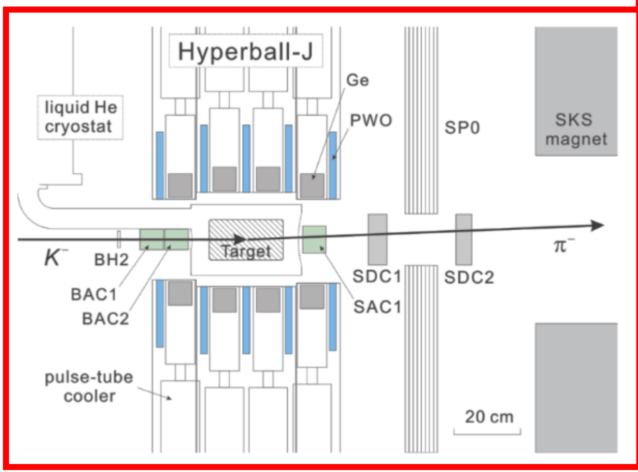
CSB effect in ΛN force (pΛ ≠ nΛ) is much than in NN force (pp ≠ nn)

E13 Setup

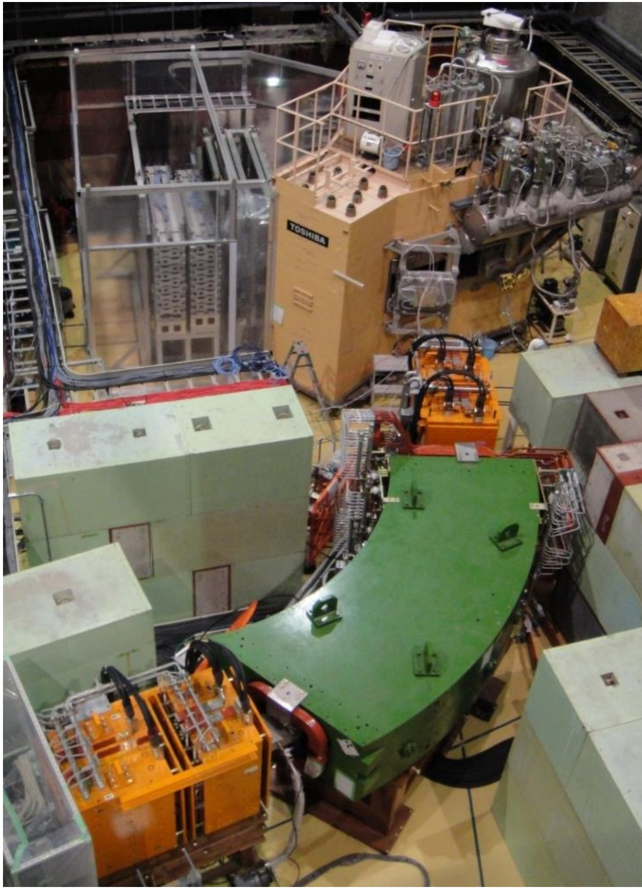
$$ {}^{A}Z\,(K^-,\pi^-)\,{}^{A}_{\Lambda}Z^* \to {}^{A}_{\Lambda}Z + \gamma $$

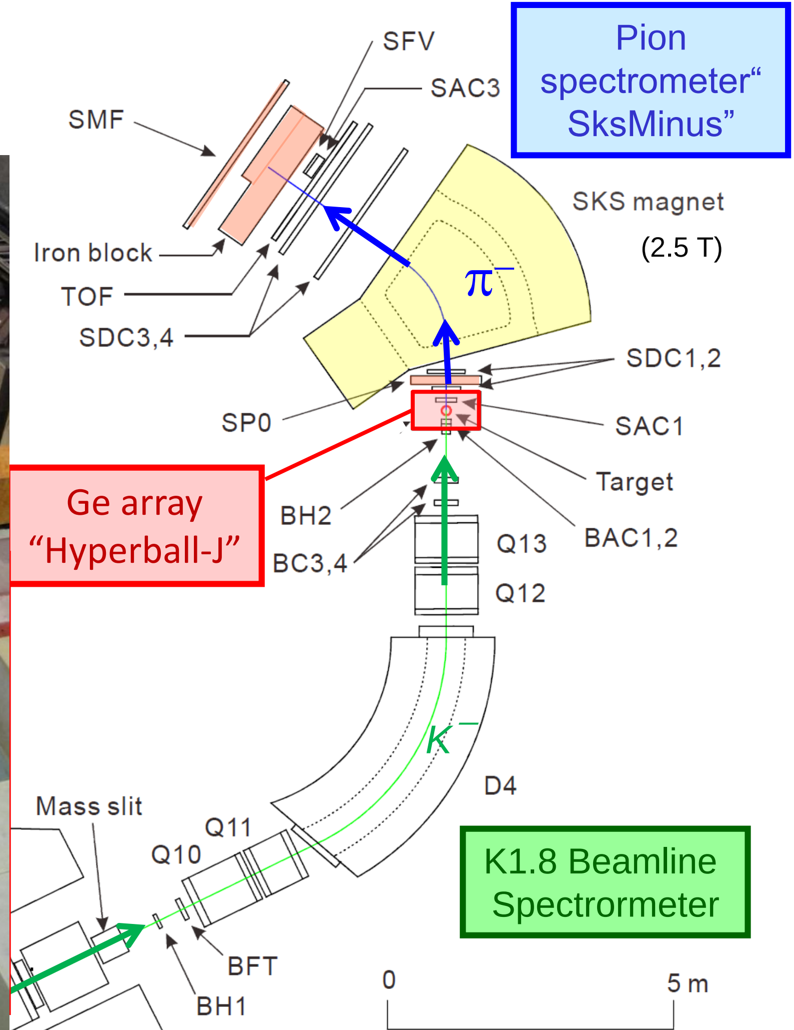
- Tag production of hypernuclei
- Detect γ-rays from hypernuclei





E13 Setup



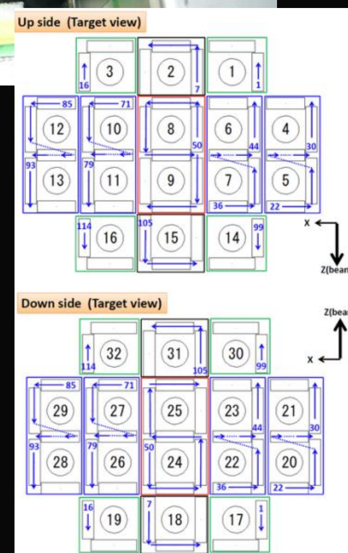

Pion spectrometer“ SksMinus”
SFV
SAC3
SMF
SKS magnet
(2.5 T)
Iron block
TOF
SDC3,4
π^-
SDC1,2
SP0
SAC1
Target
Ge array “Hyperball-J”
BH2
BC3,4
BAC1,2
Q13
Q12
K^-
D4
Mass slit
Q11
Q10
K1.8 Beamline Spectrometer
BFT
BH1
0
5 m

Hyperball-J

Pulse-tube refrigerator

Ge cooled down to ~70K (c.f. 92K w/LN2) to reduce radiation damage

Fast background suppressor made of PWO

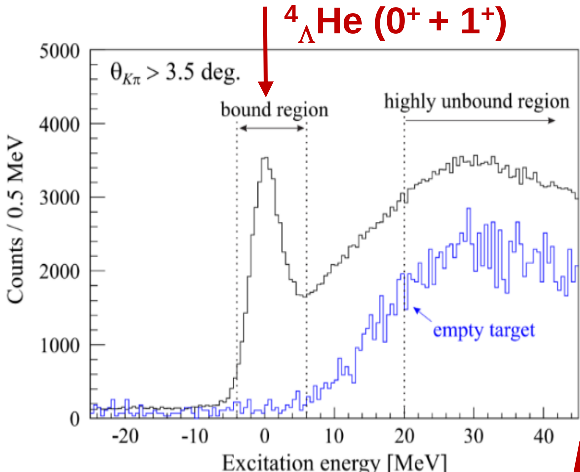


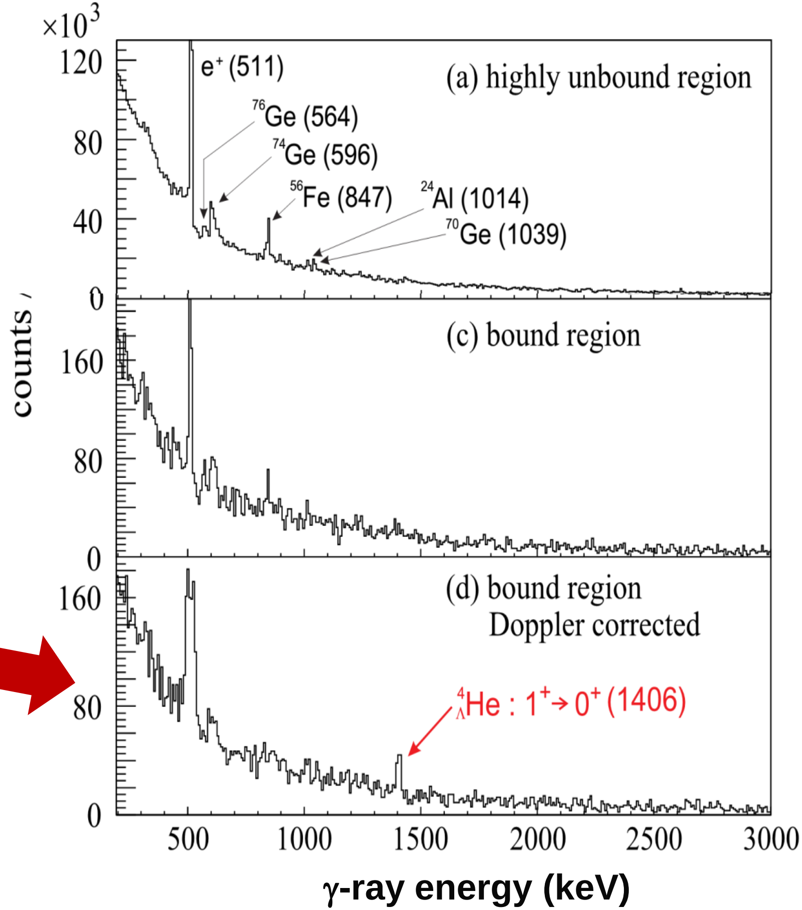
ΔE= 3.1(1) keV at 1.33 MeV
Eff. = 5.4% @1 MeV
with 28 Ge(re=60%)

T. Koike et al., NIM A770 (2015) 1

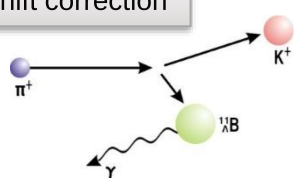
Result

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





Doppler shift correction

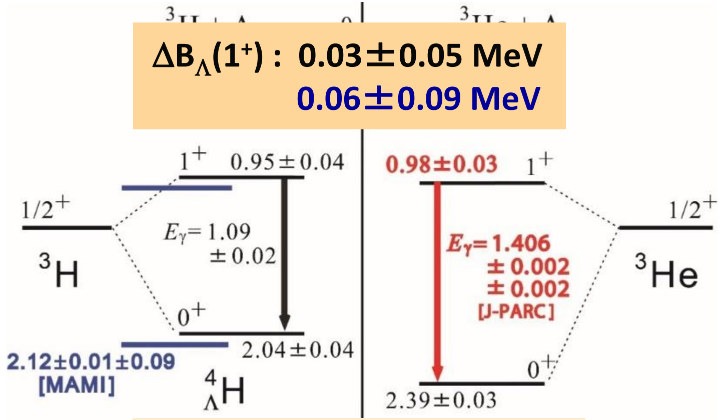


$$E_{corrected} = \frac{E_{measured}}{\gamma(1+\beta cos\theta_{\gamma})}$$

A peak observed at
1406±2±2 keV

What does it mean?

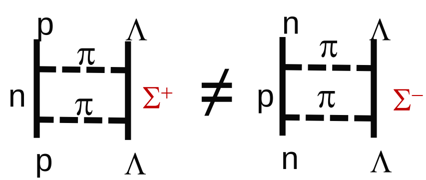
$\Delta B_\Lambda(1^+)$: 0.03±0.05 MeV
0.06±0.09 MeV



$\Delta B_\Lambda(0^+)$: 0.35±0.05 MeV
0.26±0.09 MeV

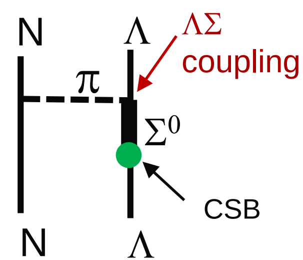
- **Existence of a large CSB effect confirmed only from γ-ray data**
- **Suggesting the old emulsion data reliable from MAMI data**
- **Large <u>spin dependence</u> in CSB effect**

- Ab-initio calc. including $\Sigma^+\Sigma^-$ mass difference + CSB in BB force (Nijmegen SC97e) =>$\Delta B_\Lambda(0^+)$ ~70 keV.
  Nogga et al., PRL 88 (2002) 172501



- CSB in ΛN force seems to be sensitive to ΛΣ coupling (Scaler ΛΣ coupling -> ~250 keV) *A. Gal, PLB 744 (2015) 352*

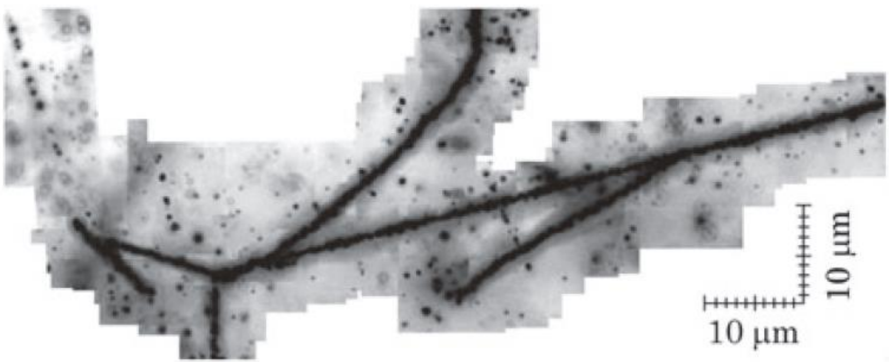
- ChEFT force makes situation better.
  D. Gazda and A. Gal, PRL 116 (2016) 122501



-> CSB is a good probe to test BB interactions

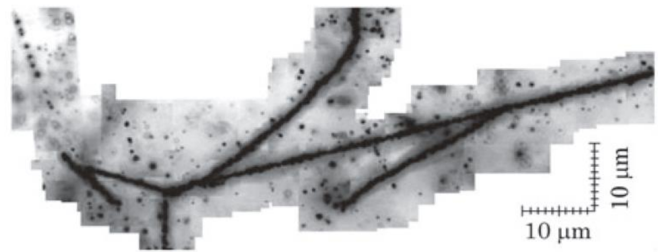
2. Recent results

2.2 Ξ hypernuclei and Ξ atoms



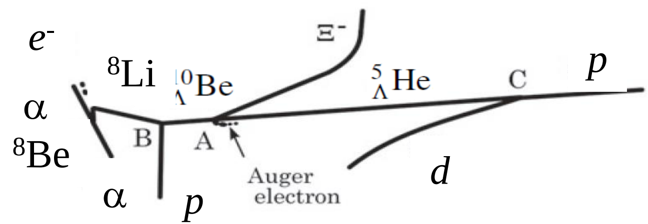
Discovery of Ξ-nuclear bound system

"Kiso event"



Newly developed
"Overall scanning method"
applied to KEK E373 emulsions

K. Nakazawa et al. PTEP 2015, 033D02
物理学会論文賞



uniquely identified as

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

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

${}^{10}_{\Lambda}\mathrm{Be}$ production : in the ground state — in the highest excited state

$3D$ atomic state of the Ξ^-–${}^{14}\mathrm{N}$ system (0.17 MeV)

The first evidence for a deeply bound Ξ state -> Ξ⁻-nucleus is attractive

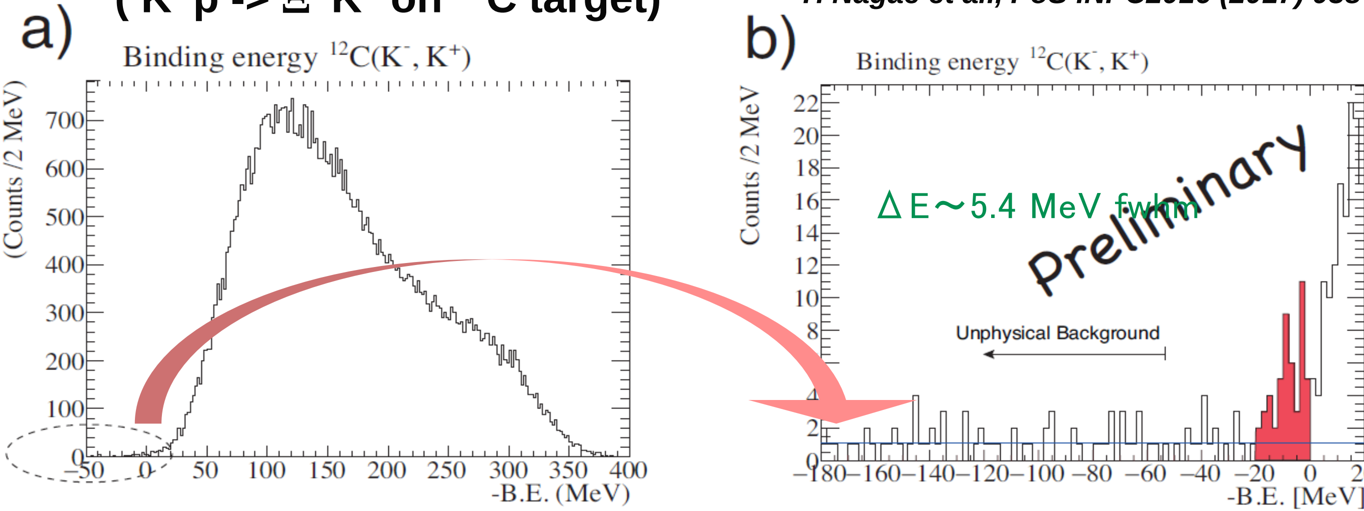
Ξ-Hypernuclear Spectroscopy via (K^-,K^+) Reaction

Nagae et al., J-PARC E05

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

(K^- p -> Ξ^- K^+ on ^{12}C target)

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



Rather deep bound states

If U_Ξ is as deep as U_Λ , both Λ and Ξ^- should appear at $\rho \sim 2\ \rho_0$

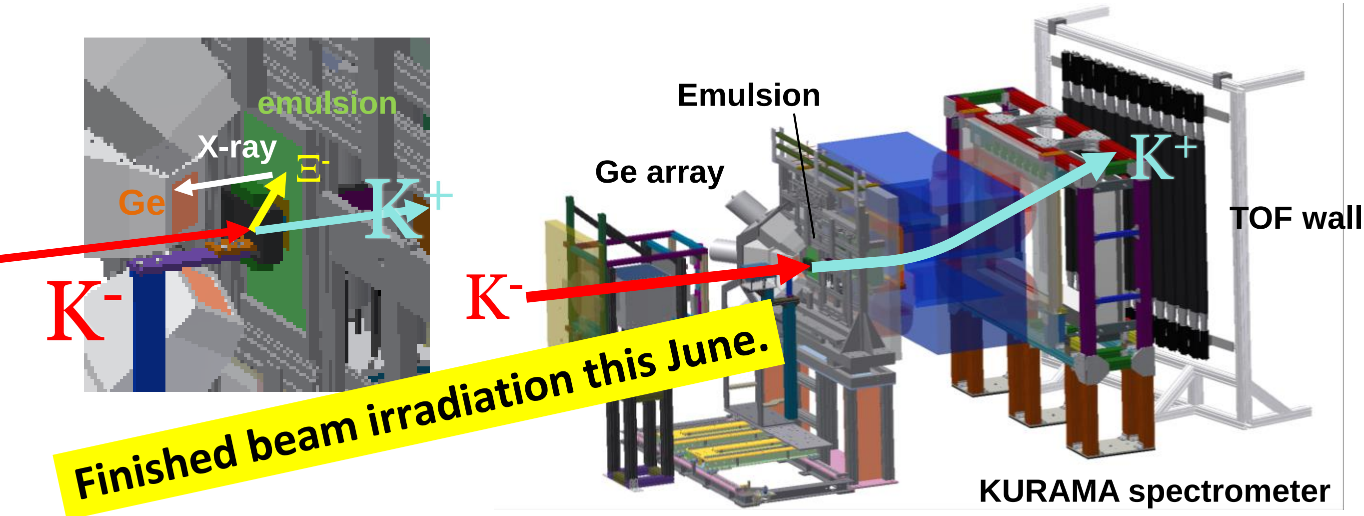
-> **”Hyperon puzzle” more difficult to solve.**

Extremely strong three-body YNN force necessary,
or, deconfined quark matter exists?

More S=-2 events with emulsion

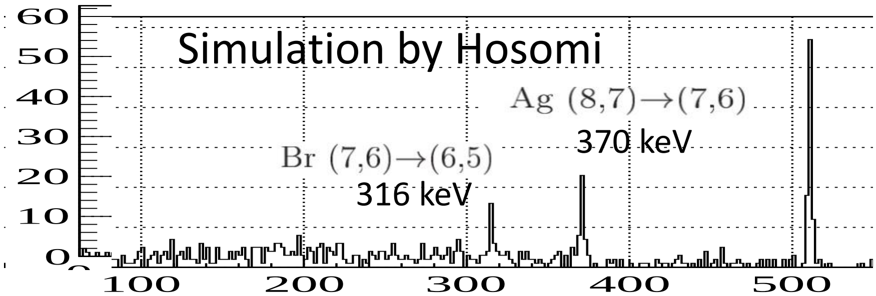
J-PARC E07
K. Nakazawa et al.

- **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 with Ge detectors**
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Ξ^- absorbed events identified from emulsion image–> no background

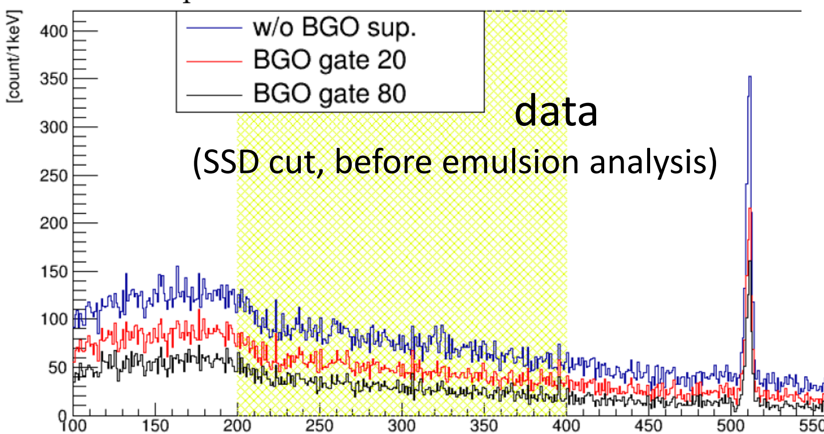


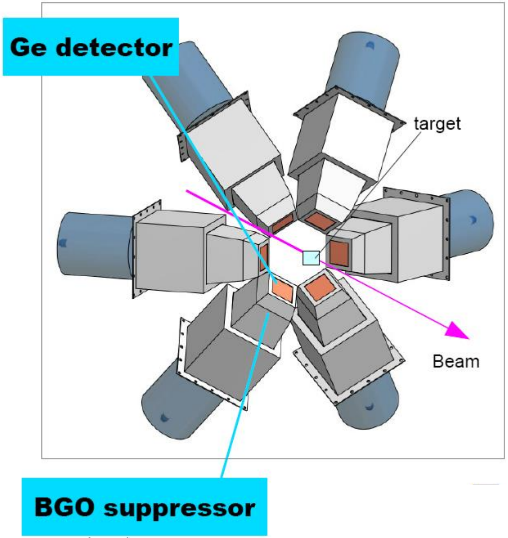
Slide by M. Fujita

X-ray spectrum



▼Ge ADC spectra





	(n,l)	X-ray Energy [keV]
Ag	(9,8)→(8,7)	254.7
	(8,7)→(7,6)	371.5
Br	(8,7)→(7,6)	206.0
	(7,6)→(6,5)	317.4

▲Ξ^- atom X-ray energy

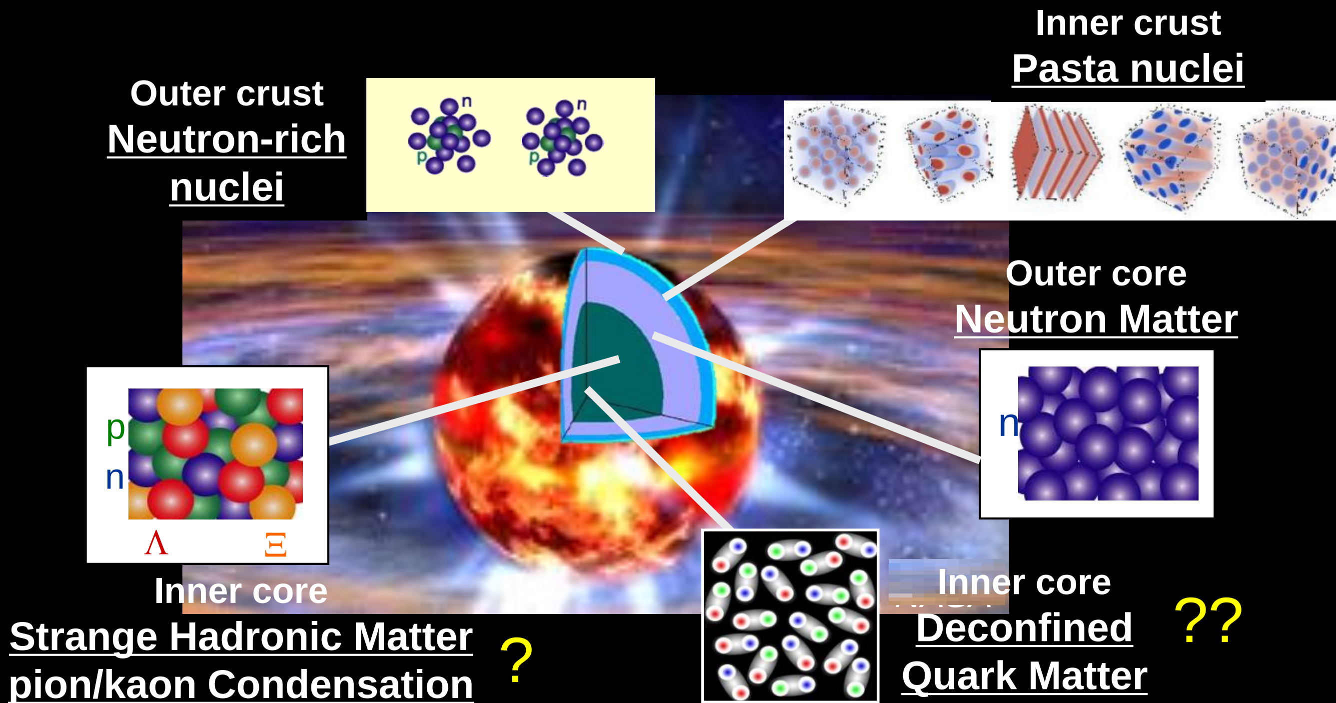
=> E03(Tanida): direct coincidence without using emulsion

3. Future prospect

3.1 Hyperon puzzle and density dependence of YN interaction

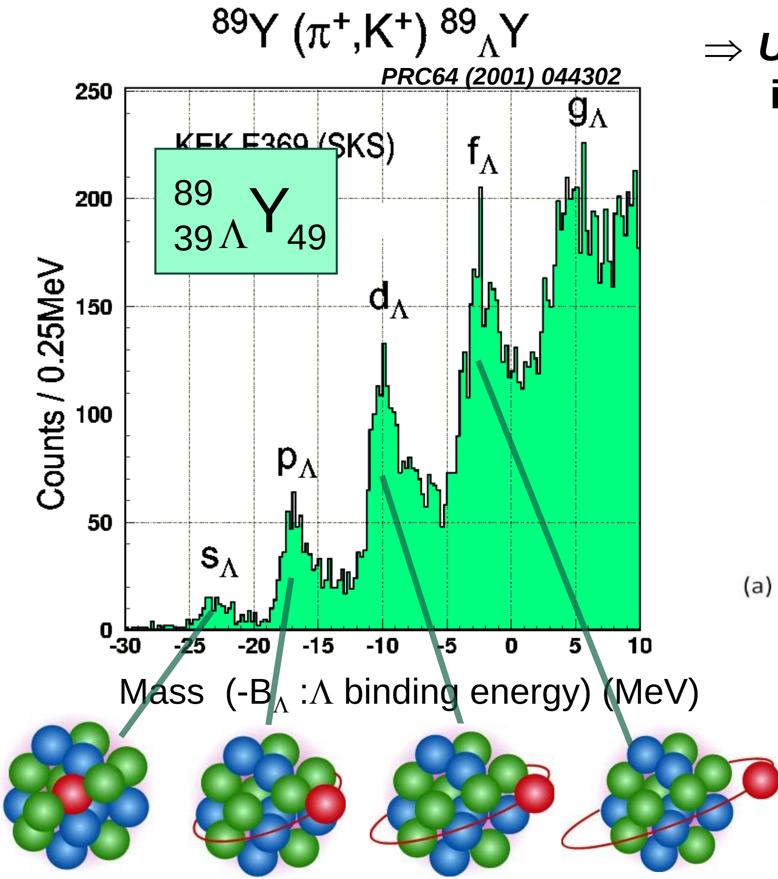
Mysteries of Neutron Star Matter



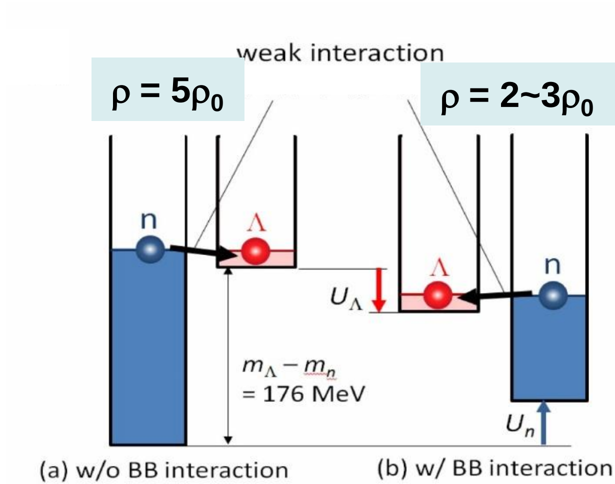
Inner Core: Various possibilities

But at least Λ hyperon should appear at $\rho = 2\sim3\ \rho_0$

Attractive ΛN interaction and hyperon mixing



⇒ $U_\Lambda(\rho_0)$ = -30 MeV (~2/3 of U_N) is well established.



Fermi gas model

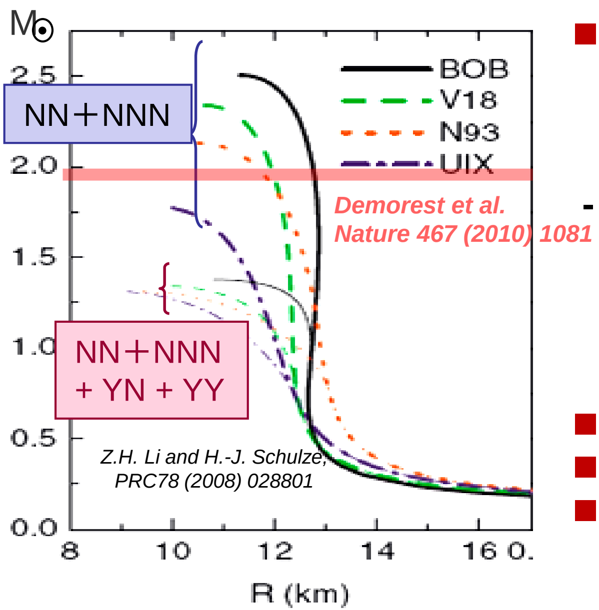
=> Λ must appear at ρ = 2~3 ρ$_0$

Hyperon puzzle

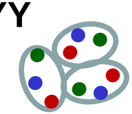
- At least Λ should appear at ρ = 2.0~2.5 ρ_0
- When hyperons or K^{bar} appear, EOS becomes too soft to support massive NS with >1.5$M_{\odot}$

<—> Reliable observation of two NSs with~2.0$M_{\odot}$

Present nuclear physics has been (semi-)phenomenologically made using experimental data around ρ_0 only -> No predictable power for $\rho > \rho_0$



How to solve?



- Introduce repulsion in YNN, YYN, YYY as well as NNN
  - Density dep. in coupling constants
  - ρ^4 term in RMF, Multi-Pomeron exch.
- How to fix their strengths is a problem
  - Same as NNN?
  - Use HI collision data
  - ChEFT framework
  - Lattice QCD?
- Relativistic effect, Pauli in baryon mixing
- Quark Meson Coupling model
- Phase transition to quark matter or quark/hadron crossover (hybrid matter)

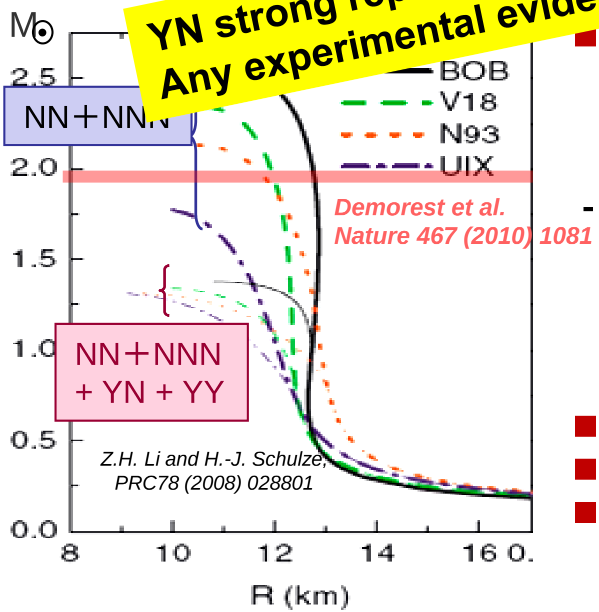
Hyperon puzzle

- At least Λ should appear at ρ = 2.0~2.5 ρ_0
- When hyperons or K^{bar} appear, EOS becomes too soft to support massive NS with >1.5$M_{\odot}$

<—> Reliable observation of two NSs with~2.0$M_{\odot}$

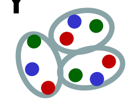
Present nuclear physics has been (semi-)ph… …nade using experimental data aroun… …ower for $\rho > \rho_0$

YN strong repulsion at high density really exists?
Any experimental evidence?



How to solve?

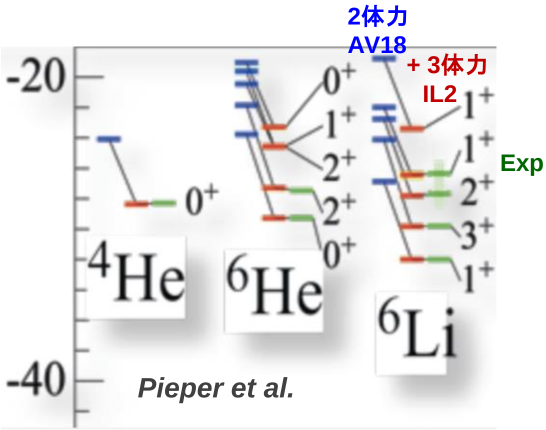
- Introduce repulsion in YNN, YYN, YYY as well as NNN
  - Density dep. in coupling constants
  - ρ^4 term in RMF, Multi-Pomeron exch.



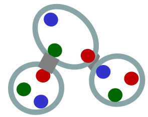
- How to fix their strengths is a problem
  - Same as NNN?
  - Use HI collision data
  - ChEFT framework
  - Lattice QCD?

- Relativistic effect, Pauli in baryon mixing
- Quark Meson Coupling model
- Phase transition to quark matter or quark/hadron crossover (hybrid matter)

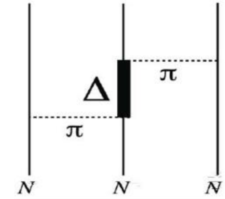
Property of 3-body nuclear force (NNN)



Illinois型3体力（2π exchange, 藤田・宮沢型）

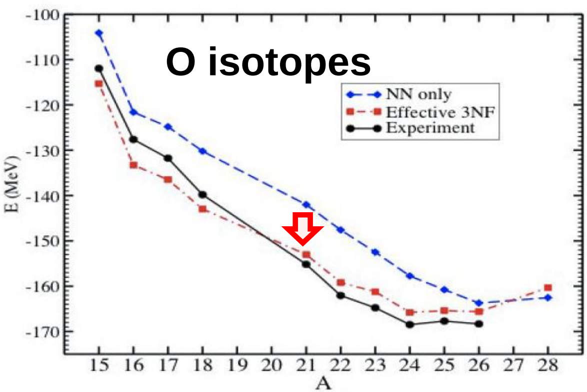


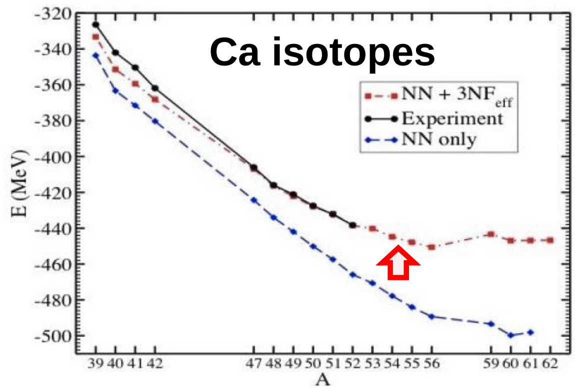
ハドロンは内部構造が
あるので「3体力」がある



軽い核（低密度）では、引力的
～藤田・宮沢型

重い核（高密度～ρ_0）では、斥力的
＋相対論的効果

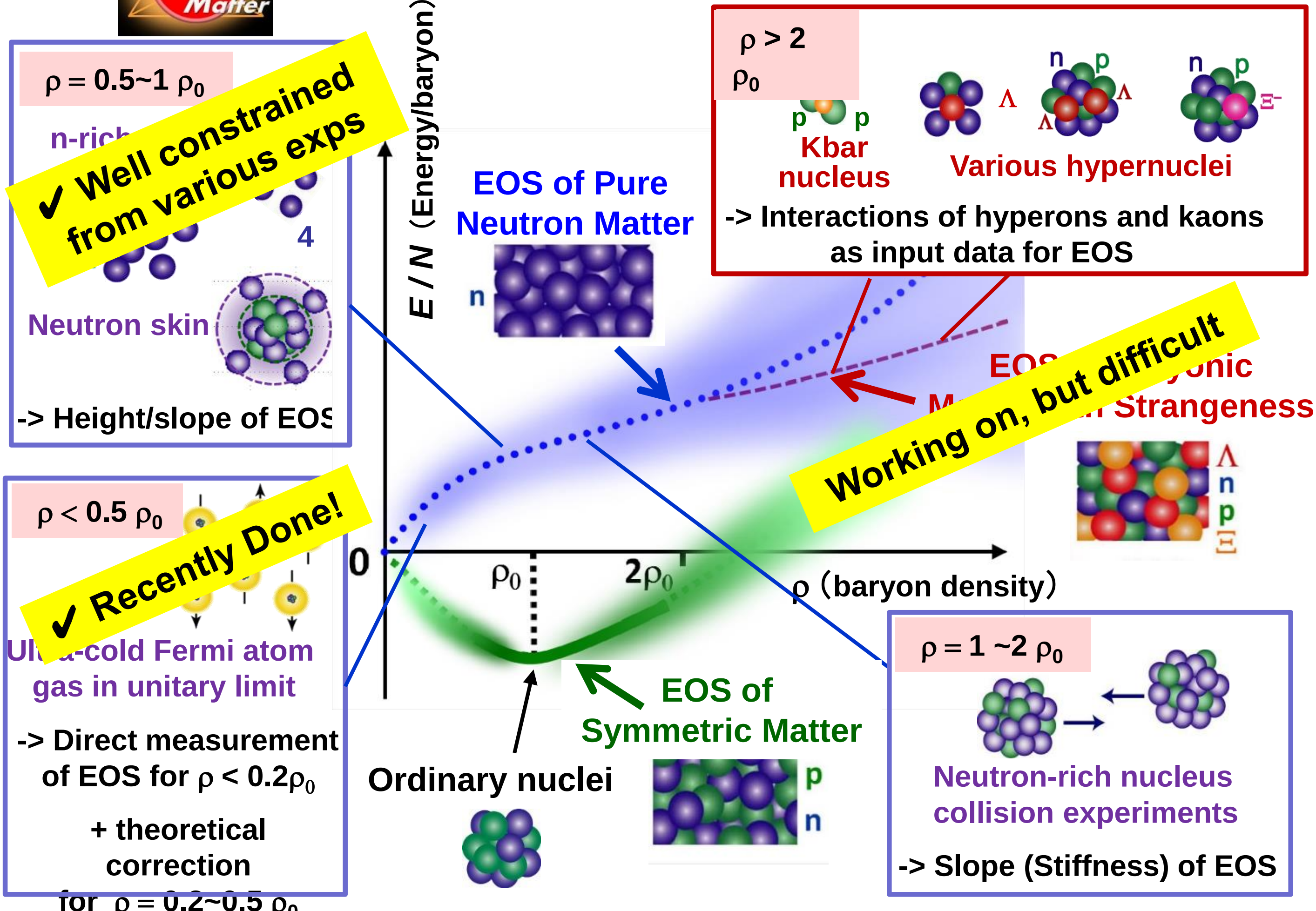




Chiral effective field theoryによる3体力

G. Hagen et al., PRL 109 (2012) 032502

Equation Of State from Experiments



Equation Of State from Experiments

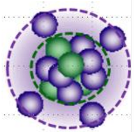
$\rho = 0.5\sim1\ \rho_0$

n-rich

✔ Well constrained from various exps

4

Neutron skin



-> Height/slope of EOS

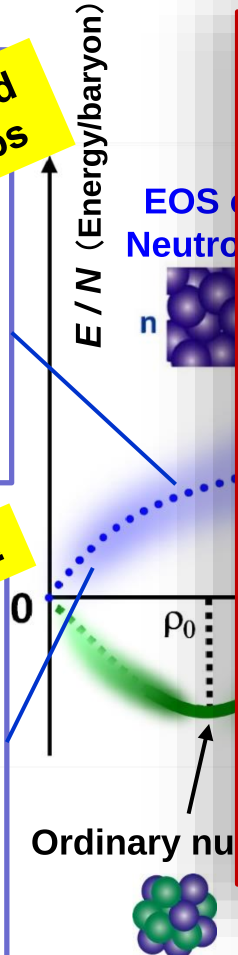
$\rho < 0.5\ \rho_0$

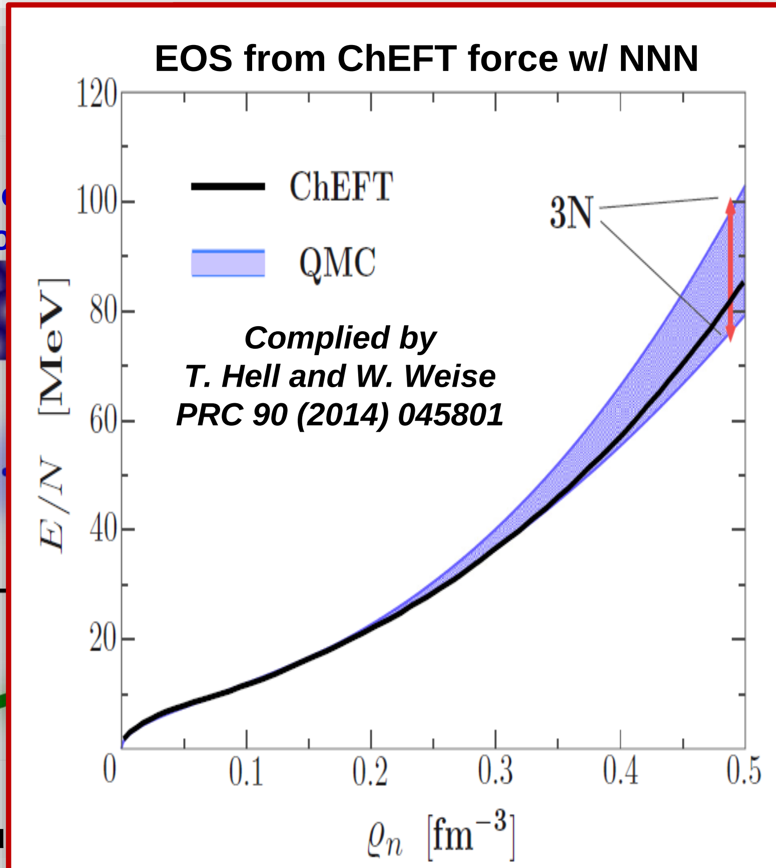
✔ Recently Done!

Ultra-cold Fermi atom gas in unitary limit

-> Direct measurement of EOS for $\rho < 0.2\rho_0$

+ theoretical correction for $\rho = 0.2\sim0.5\ \rho_0$



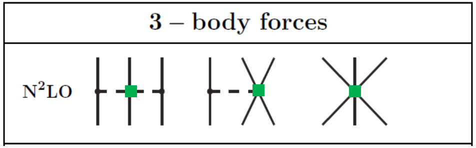


-> Slope (Stiffness) of EOS

How to experimentally approach this problem?

Ch-EFT interactions with hyperons (Extension to $SU(3)_f$)

Haidenbauer, Weise, et al.



But contact terms cannot be determined well

=> High statistics scattering data necessary

Interactions both in free space → input to ChEFT and many-body theories
and in nuclear matter
are necessary

Density-dependent int. (= 3-body forces)

- **YN int. in free space :**

  => YN scattering experiments, Precise data of few body hypernuclei

  E40 (Miwa): $\Sigma^{\pm}$p scattering

  Beyond E40: Λp scattering, spin observables

- **YN int. in nuclear matter :**

  => Precise data of Λ's single particle energies (B_Λ) for medium-heavy HN

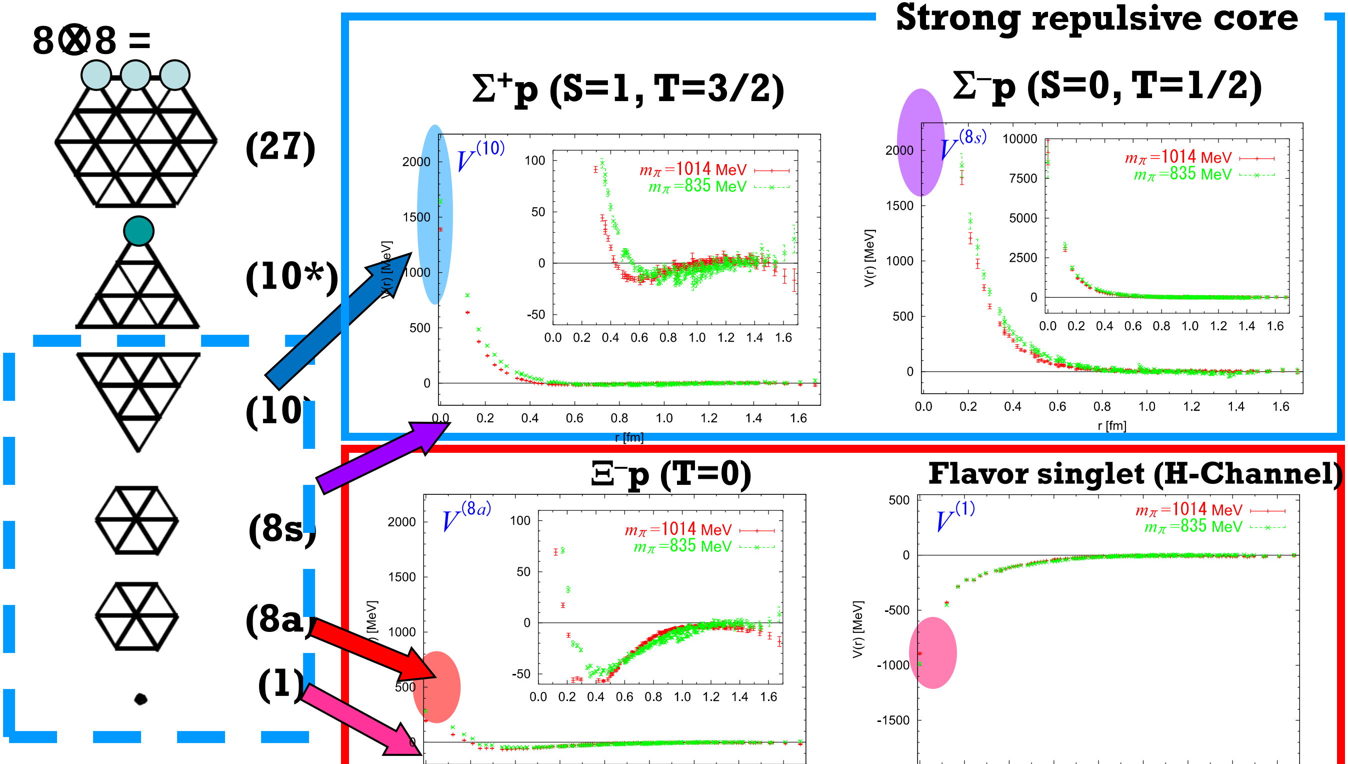
  High resolution (e,e' K^+), (π^+,K^+) spectroscopy

  γ–spectroscopy

Slide by Koji Miwa

Baryon Baryon interaction by Lattice QCD

6 independent forces in flavor SU(3) symmetry

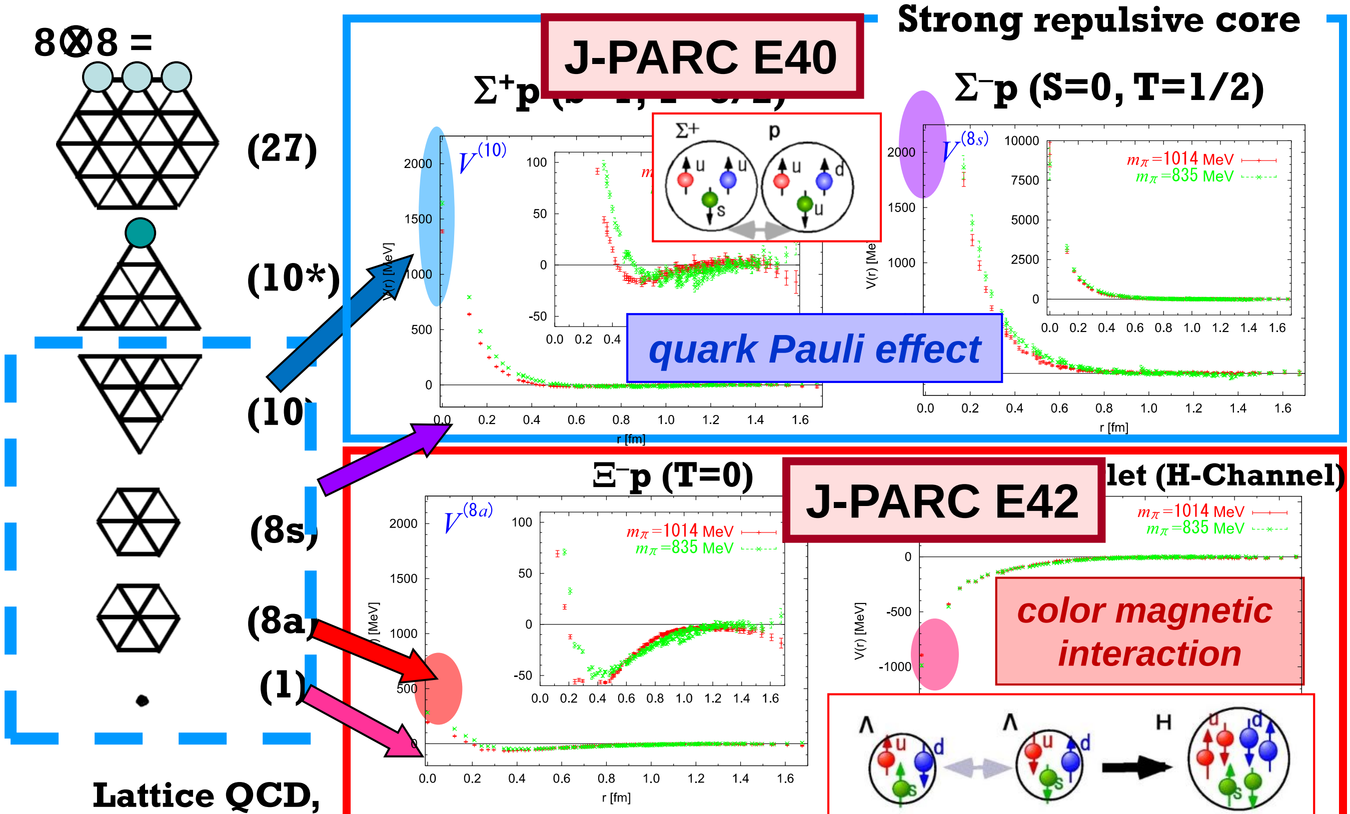


Lattice QCD,
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

Slide by Koji Miwa

Baryon Baryon interaction by Lattice QCD

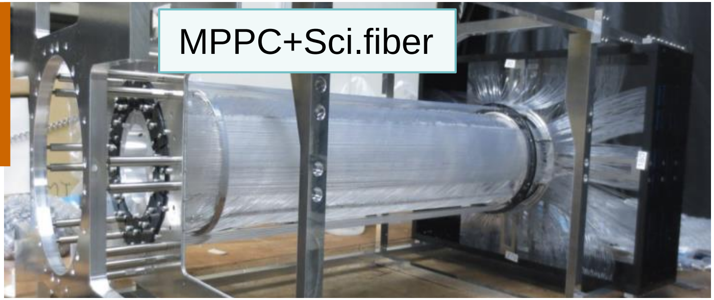
6 independent forces in flavor SU(3) symmetry



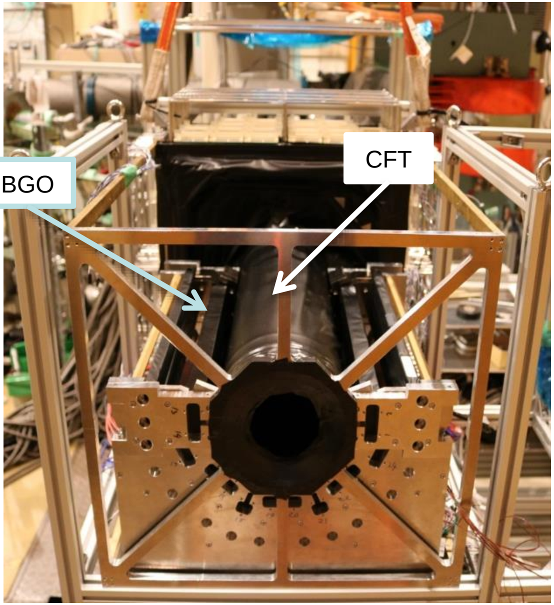
Weakly repulsive or attractive Core

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

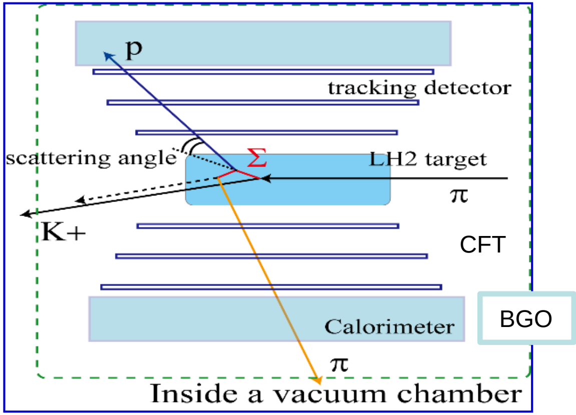
J-PARC E40 (Miwa et al.) Σp Scattering Experiment



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



Under preparation. Run from 2018 Feb.

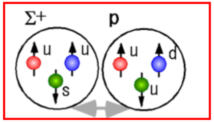


dσ/dΩ for Σ^+p, Σ^-p, Σ^-p->Λn (p_Σ = 400-700 MeV/c)

=> Phase shift from dσ/dΩ (90°)

=> Confirm quark Paul effect

Future: Λp scattering
Asymmetry -> LS force



How to study density dependence of ΛN interaction in matter (ΛNN force) ?

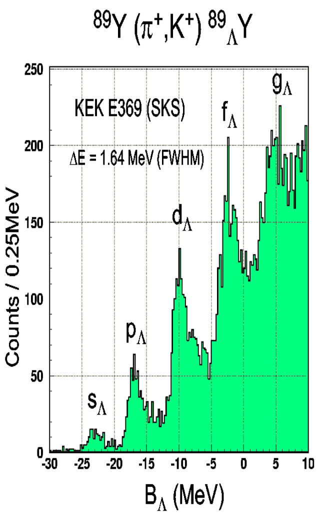
Ab-initio calc. of nuclear binding energies => NNN repulsion necessary
Similar YNN (YYN, YYY) repulsive forces?

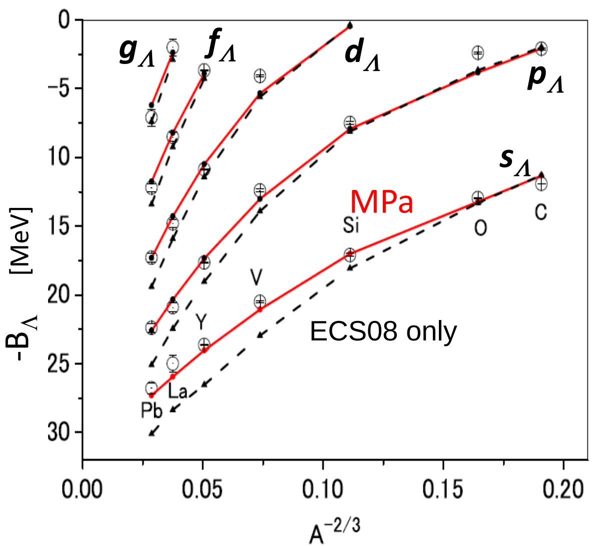
Experimentally approach:

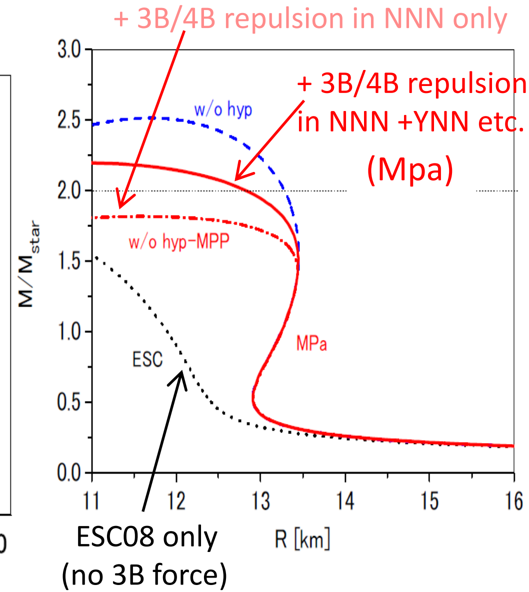
Precise B_{Λ} data for wide A of Λ hypernuclei
0.1 MeV accuracy is necessary

Yamamoto, Furumoto, Rijken et al.
PRC88 (2013) 2, 022801
PRC90 (2014) 045805

determined from HI collision data



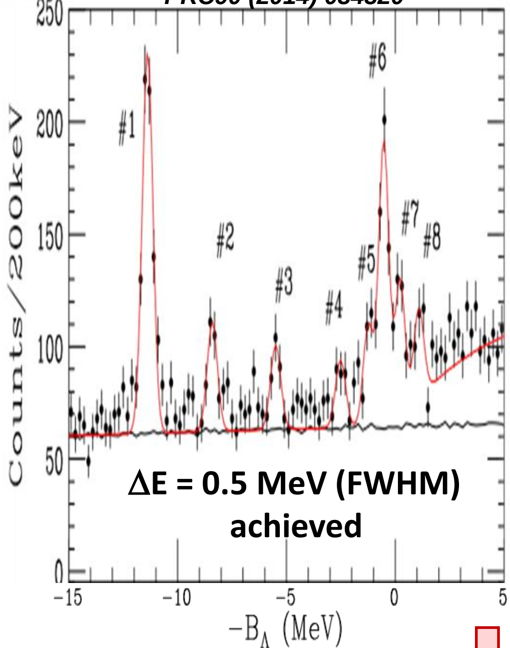


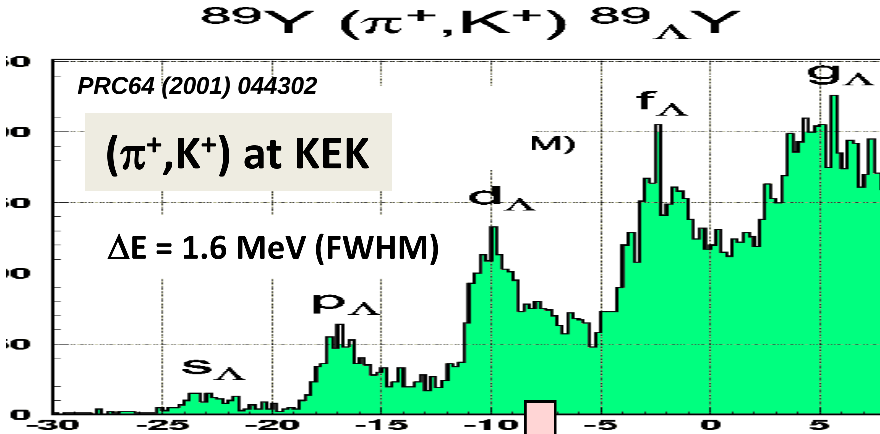


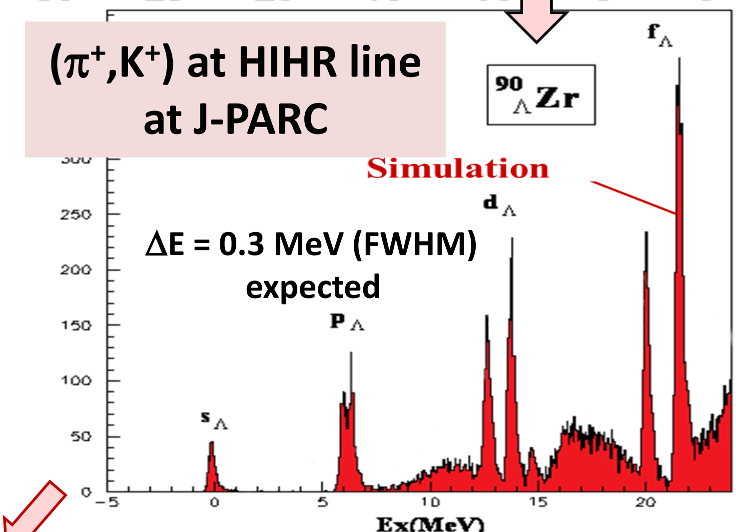
High Resolution HN Spectroscopy

(e,e’K$^+$) at JLab

PRC90 (2014) 034320

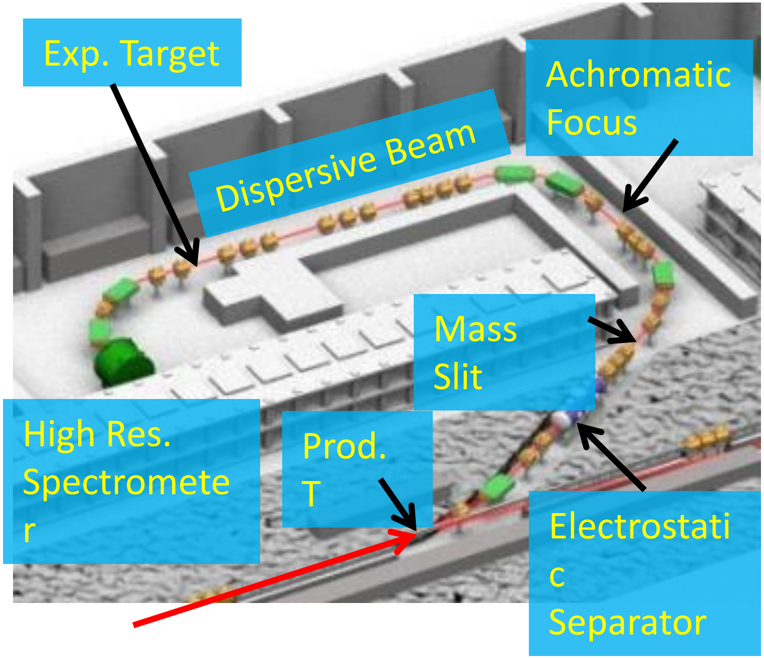


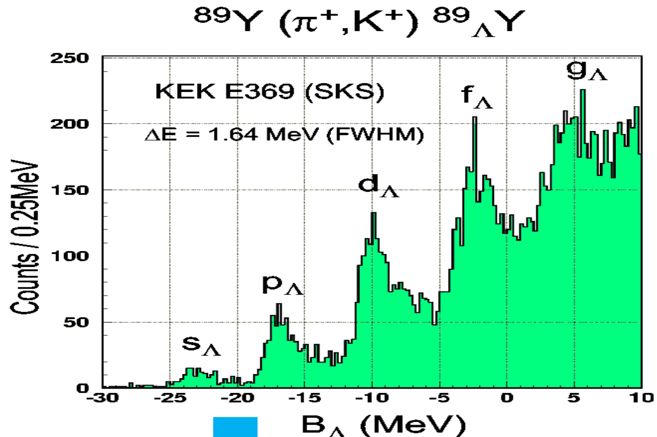


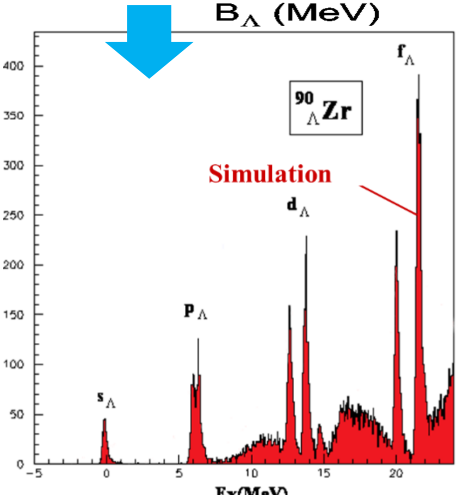


BE accuracy < 0.1 MeV => Density dependence of ΛN int.

High-Intensity High-Resolution line (HIHR)





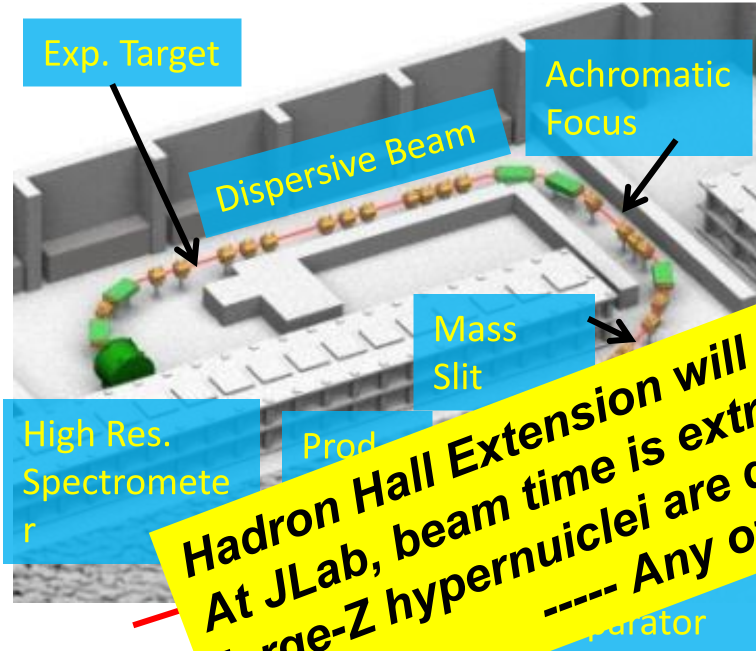


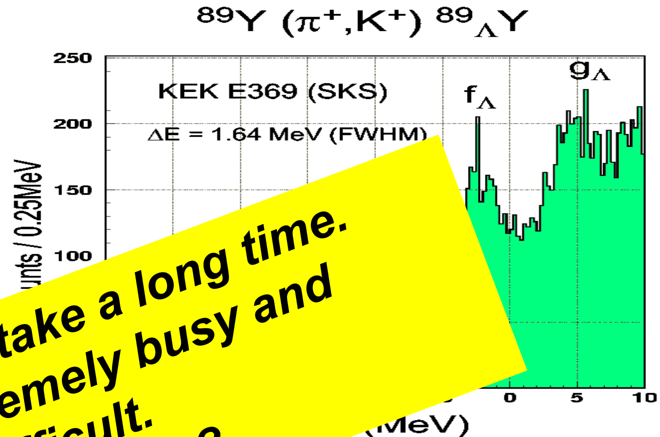
Intensity: ~ 1.8×10^{8} pion/pulse
(1.2 GeV/c, 50 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)

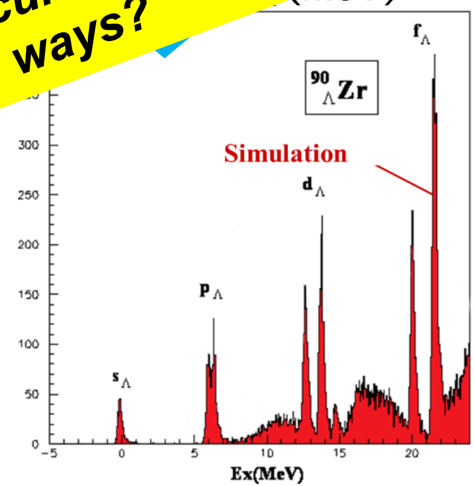
$\Delta p/p \sim 1/10000$ ($\Delta m \sim 200$ keV)

designed by H. Noumi

High-Intensity High-Resolution line (HIHR)







Hadron Hall Extension will take a long time.
At JLab, beam time is extremely busy and
large-Z hypernuiclei are difficult.
----- Any other ways?

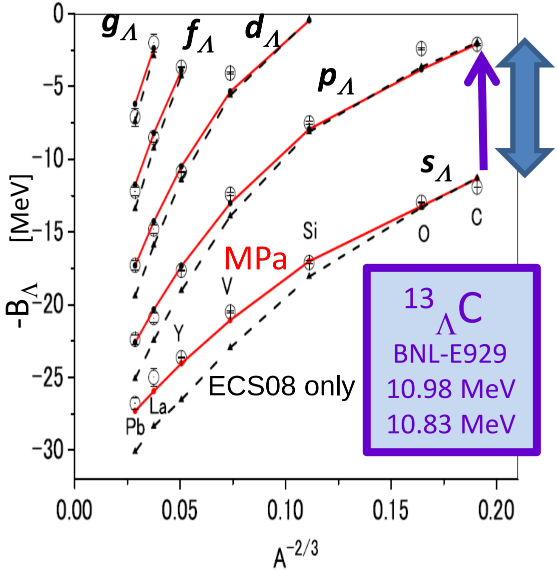
Intensity ... ion/pulse
(1 ... /c, 50 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)
Δp/p ~ 1/10000 (Δm~200 keV)

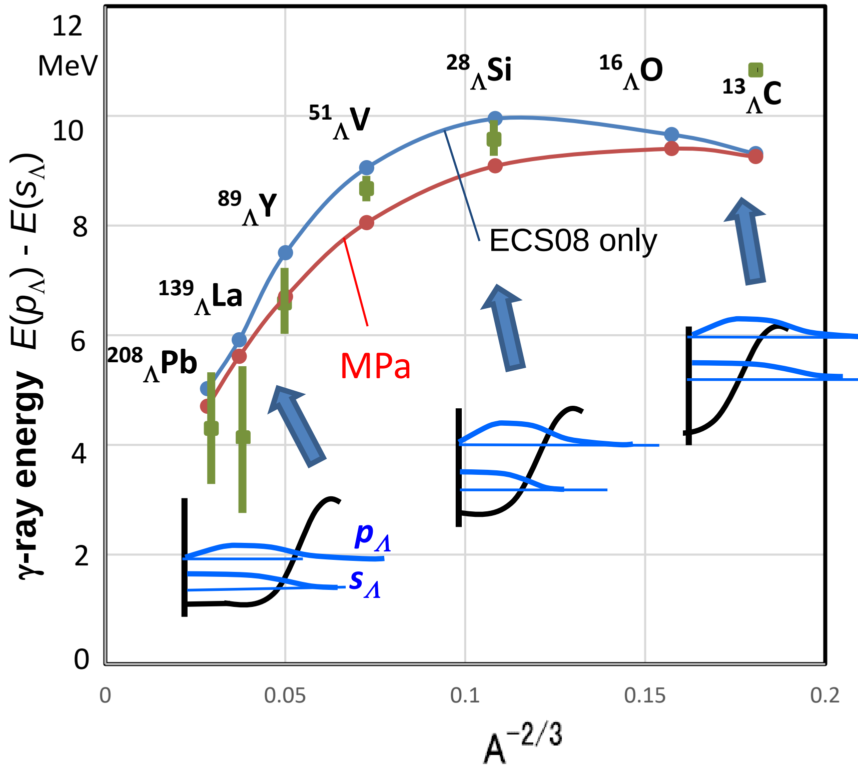
designed by H. Noumi

Another approach using γ-rays

p_Λ-s_Λ spacing is affected by density dep. of ΛN interaction

It can be precisely (~keV) measured with E1 γ-transitions.





E1 (p_Λ->s_Λ) measurement for a wide A range

$^{29}{}_{\Lambda}$Si, $^{52}{}_{\Lambda}$Cr, $^{89}{}_{\Lambda}$Y, $^{135}{}_{\Lambda}$La, $^{208}{}_{\Lambda}$Pb

(K^-,π^-) 1.1 GeV/c @K1.1 line
>100 kW, Total ~ 7 weeks

- **Density dependence of ΛN interaction**

  => Solve hyperon puzzle

- **Origin of nuclear LS splitting**

- 2-body LS force

  --- Very small due to cancellation between large symmetric LS and large antisymmetric LS forces

- Tensor force

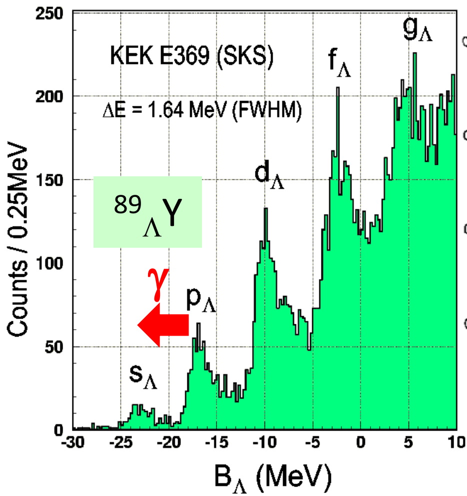
  ----No one pion exchange -> small, no isospin dependence.

- Many-body correlation

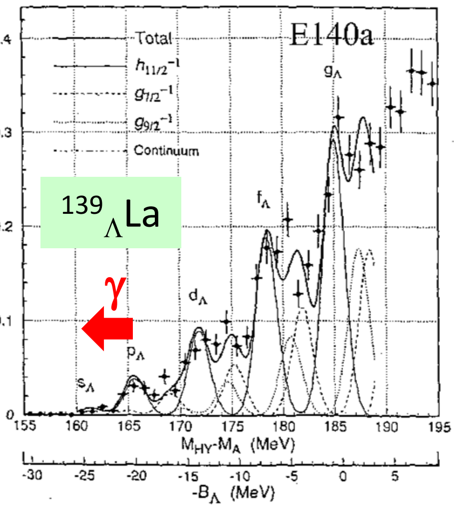
  ----No one pion exchange ->Small ?

Heavy hypernuclei

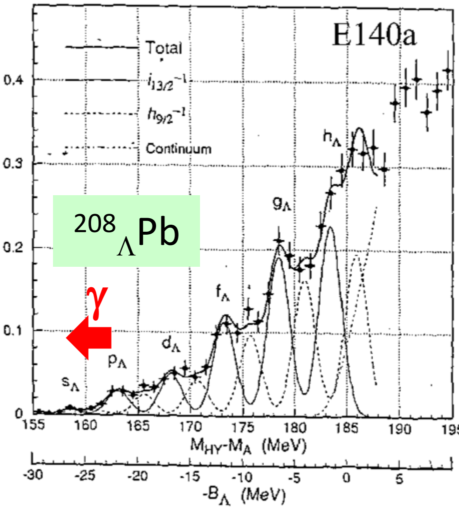
$^{89}Y\ (\pi^+,K^+)\ ^{89}{}_{\Lambda}Y$



$^{139}La(\pi^+,K^+)^{139}_{\Lambda}La,\ p_\pi = 1.06\ GeV/c$



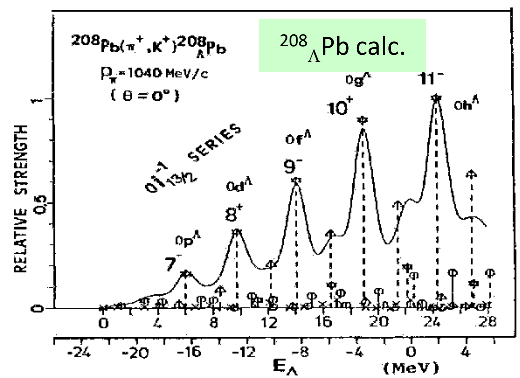
$^{208}Pb(\pi^+,K^+)^{208}_{\Lambda}Pb,\ p_\pi = 1.06\ GeV/c$



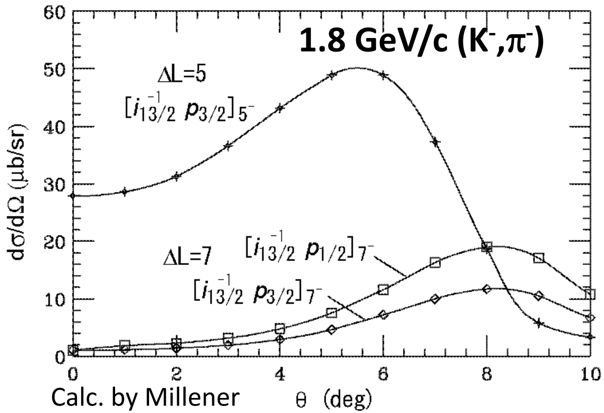
(π^+,K^+) reaction

KEK E140a, K6+SKS

Hasegawa et al., PRC 53 (1996) 1210



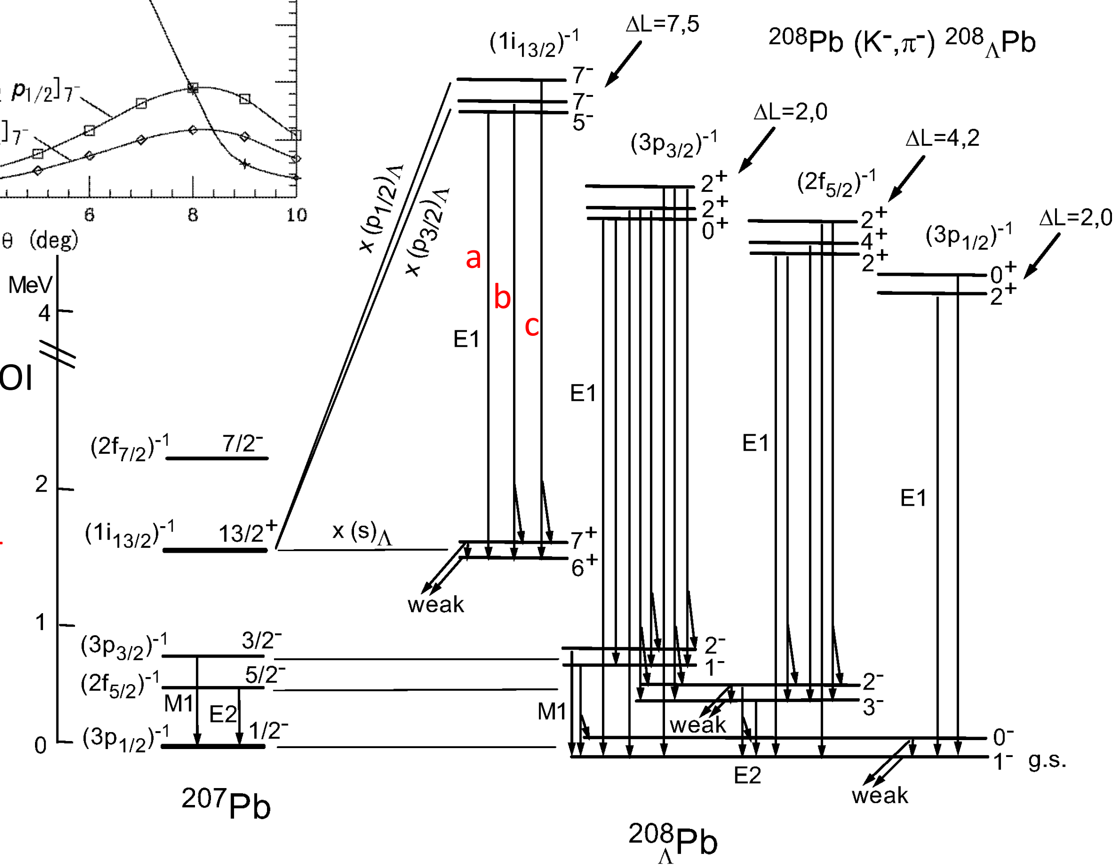
γ-spectroscopy of $^{208}_{\Lambda}Pb$



Calc. by Millener

from J-PARC LOI

15 days at K1.1
@120 kW
a: ~300 ev
b: ~200 ev
c: ~700 ev



3. Future prospect

3.2 Modification of baryons in nuclear matter

“Modifications” of baryons in nuclear matter

- **EMC effect (Change of structure function in DIS)**
- **Change of form factors ? “Swelling”?**
- **Change of magnetic moment ??**

....

Why?

- **Structure change in nuclear medium?**
- **Effects of baryon mixing, meson exchange current,...**
- **Partial restoration of chiral symmetry??**

Hyperons are free from Pauli blocking – suitable probe

⇨ **Λ’s magnetic moment in a hypernucleus**

Λ’s beta-decay rate (g_A) in a hypernucleus

E63: Measure μ_Λ in a nucleus for the first time

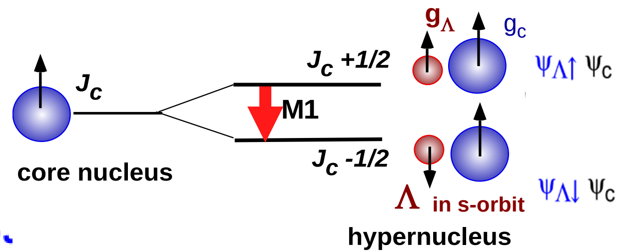
Measurement of μ_Λ in a hypernucleus is extremely difficult =>J-PARC-HI

Λ-spin-flip M1 transition: B(M1) -> g_Λ

$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$
$$= (2J_{up}+1)^{-1} |\langle \psi_{\Lambda\downarrow} \psi_c \| \mu \| \psi_{\Lambda\uparrow} \psi_c \rangle|^2$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c)\cdot$$

$$= \frac{3}{8\pi} \frac{2J_{low}+1}{2J_c+1} (g_\Lambda - g_c)^2 \quad [\mu_N^2]$$



: assuming "weak coupling" between a Λ and the core.

R.H. Dalitz and A. Gal, Annals of Phys. 116 (1978) 167.

$^7_\Lambda$Li ~100%

Doppler Shift Attenuation Method: eg) B(E2): Tanida et al. *PRL 86 (2001) 1982*

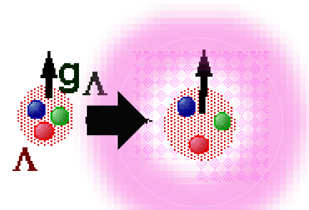
$$\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 B(M1)$$

g_Λ may be modified in a nucleus ~ +2--5 % for $^4_\Lambda$He

due to Λ–Σ mixing ? (Dover-Gal) -7% for $^7_\Lambda$Li

K exchange current ? (Oka et al.)

Possible effects of structure change??



No Pauli effect

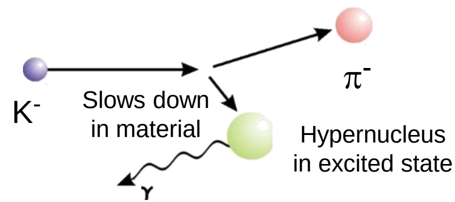
Accuracy of lifetime measurement

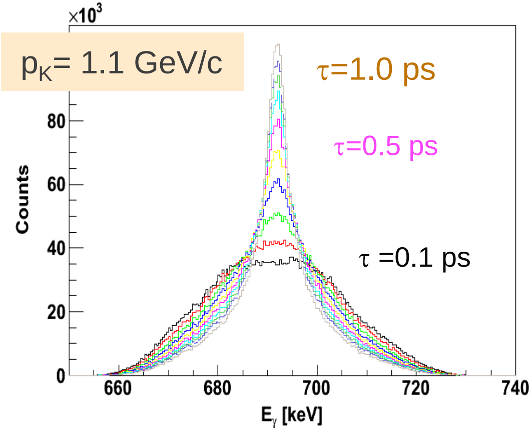
Doppler shift attenuation method

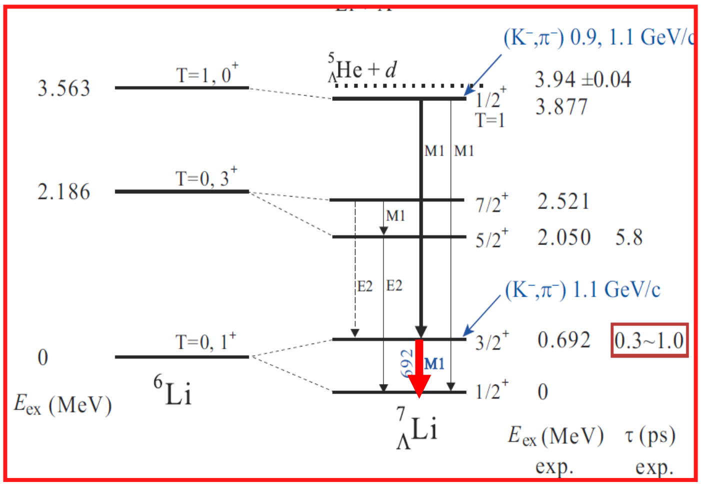
τ ~ 0.5 ps

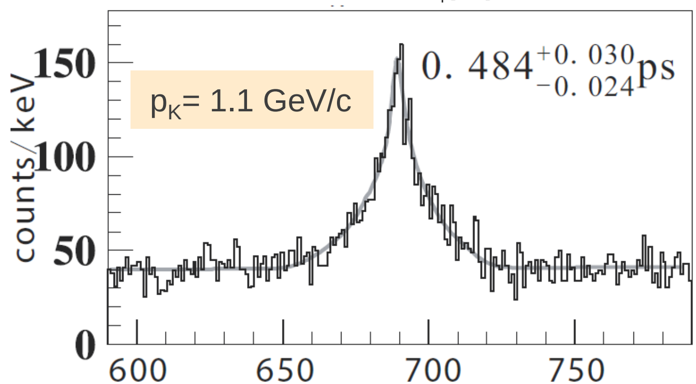
t_{stop} ~ 2 ps

in Li_2O (2.01 g/cm^3)









H. Tamura et al., Nucl.Phys. A881 (2012) 310

For 35 days for 50kW

Assuming 56k K^-/spill for 0.9 GeV/c

176k K^-/spill for 1.1 GeV/c

Stat. error

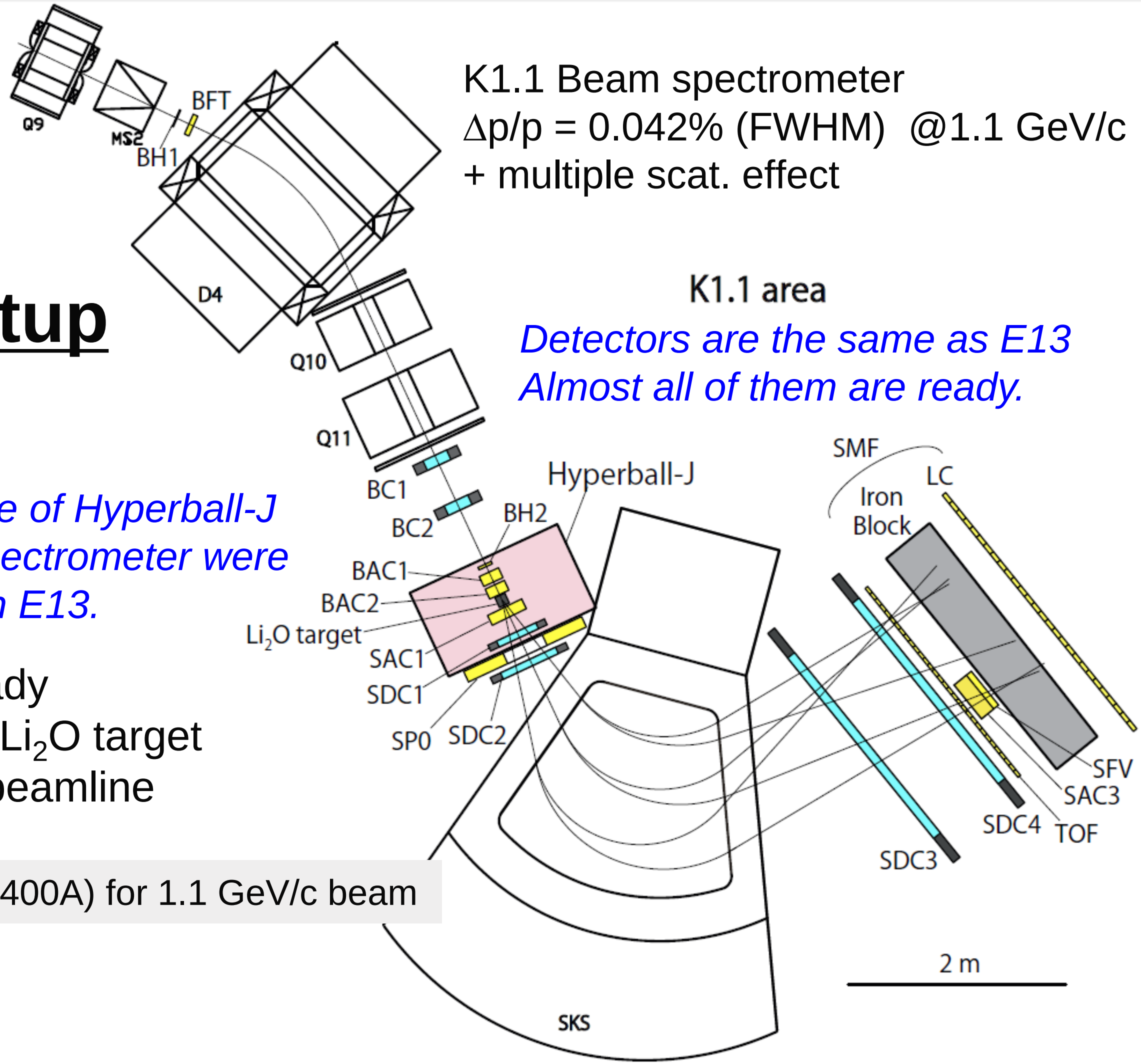
$\Delta\tau/\tau = 6\%$

$$=> \frac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|} \sim 3\%$$

E63 setup

K1.1

K1.1 Beam spectrometer
Δp/p = 0.042% (FWHM) @1.1 GeV/c
+ multiple scat. effect



Detectors are the same as E13
Almost all of them are ready.

Performance of Hyperball-J and SKS spectrometer were confirmed in E13.

Almost ready
except for Li_2O target
and K1.1 beamline

2.5T (400A) for 1.1 GeV/c beam

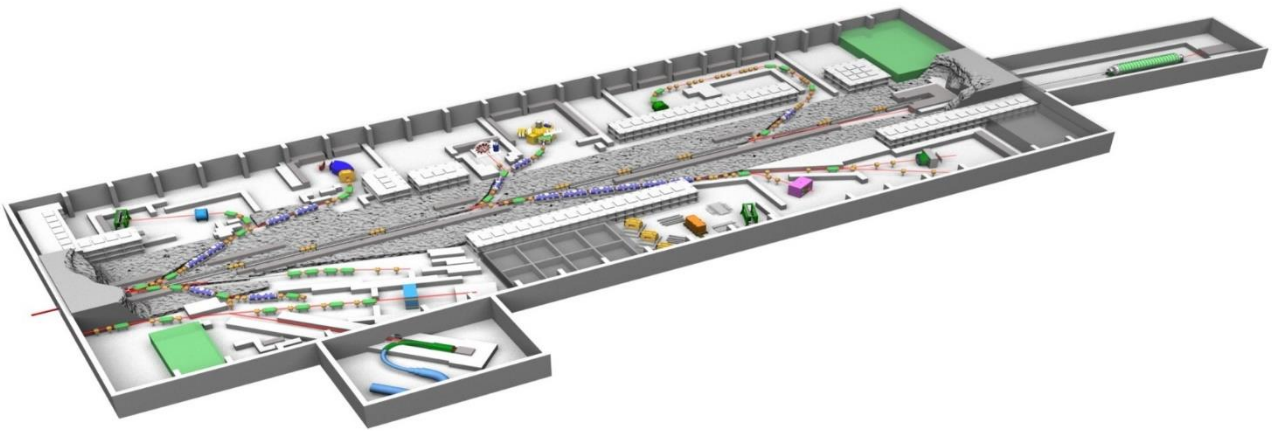
Experimental Plans at K1.1 (personal)

- E63: γ-ray spectroscopy of $^{4}_{\Lambda}$H (CSB), $^{7}_{\Lambda}$Li (g_{Λ}) via (K^-,π^-) *HT*
- Establish (π^-,K^0) reaction method w/SKS *A. Feliciello, E. Botta*

  - Lifetime of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H via (π^-,K^0)
- Weak decay experiments
  - E22: $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He NMWD via (π^+,K^+) *Sakaguchi / Ajimura*

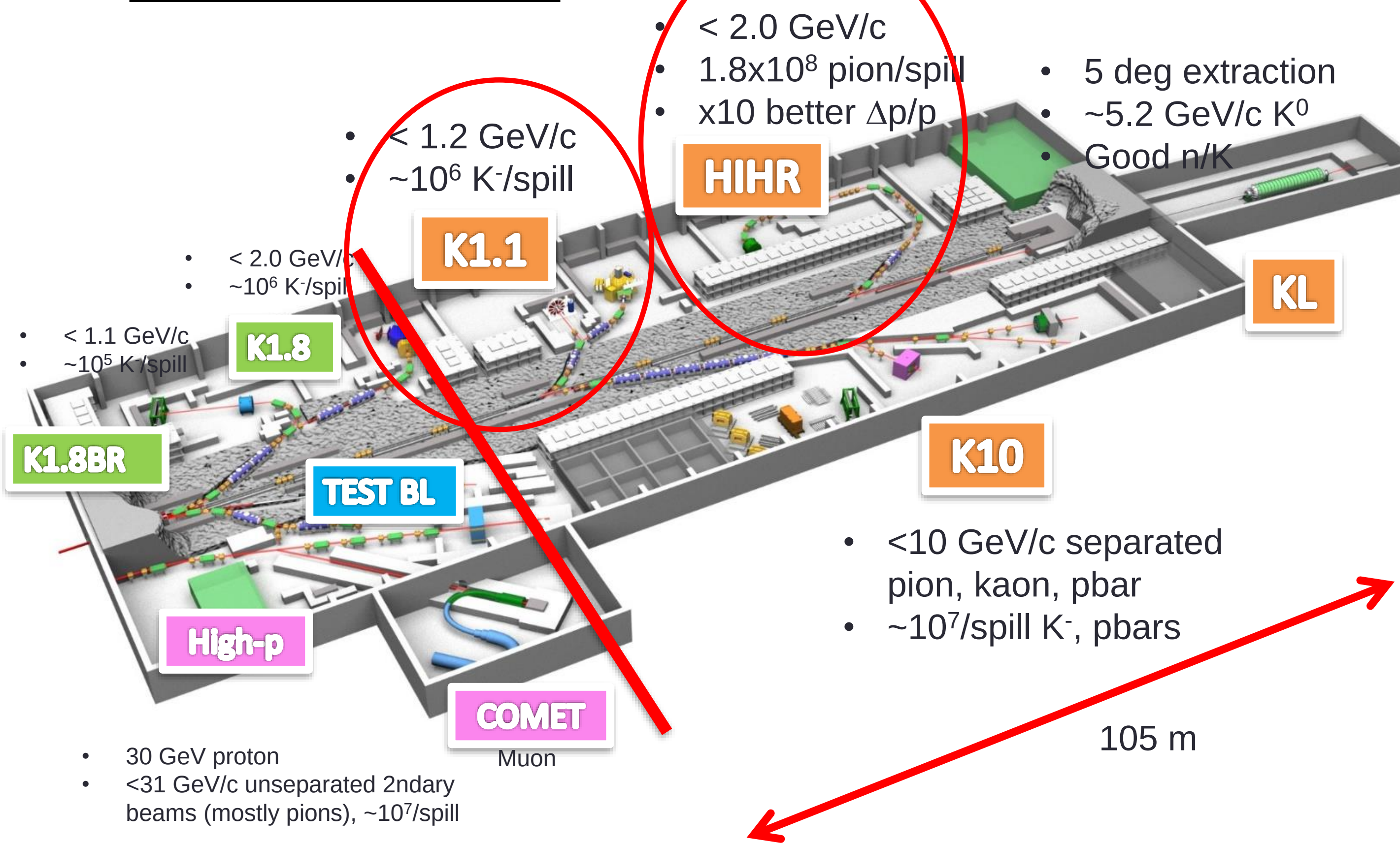
    $^{4}_{\Lambda}$H NMWD via (π^-,K^0) => Test ΔI =1/2 rule
  - E18: $^{12}_{\Lambda}$C $\Lambda NN \rightarrow NNN$ via (π^+,K^+) *Bhang / Outa*
  - Beta decay rate: $^{5}_{\Lambda}$He -> ^{4}He p e^- ν^{bar} , ... *HT*
- E1 γ-rays for $^{29}_{\Lambda}$Si, $^{52}_{\Lambda}$Cr, $^{89}_{\Lambda}$Y, $^{135}_{\Lambda}$La, $^{208}_{\Lambda}$Pb via (K^-,π^-) *HT*
- γ-rays for $^{12}_{\Lambda}$B, $^{16}_{\Lambda}$N via (π^-,K^0) => CSB of p-shell hypernuclei *HT*
- Σ^0-> $\Lambda\gamma$ decay in nucleus ($^{4}_{\Sigma}$He) via (K^-,π^-) *HT*
- Λp scattering experiments *Miwa*

4. Hadron Hall Extension and Heavy Ion Acceleration at J-PARC

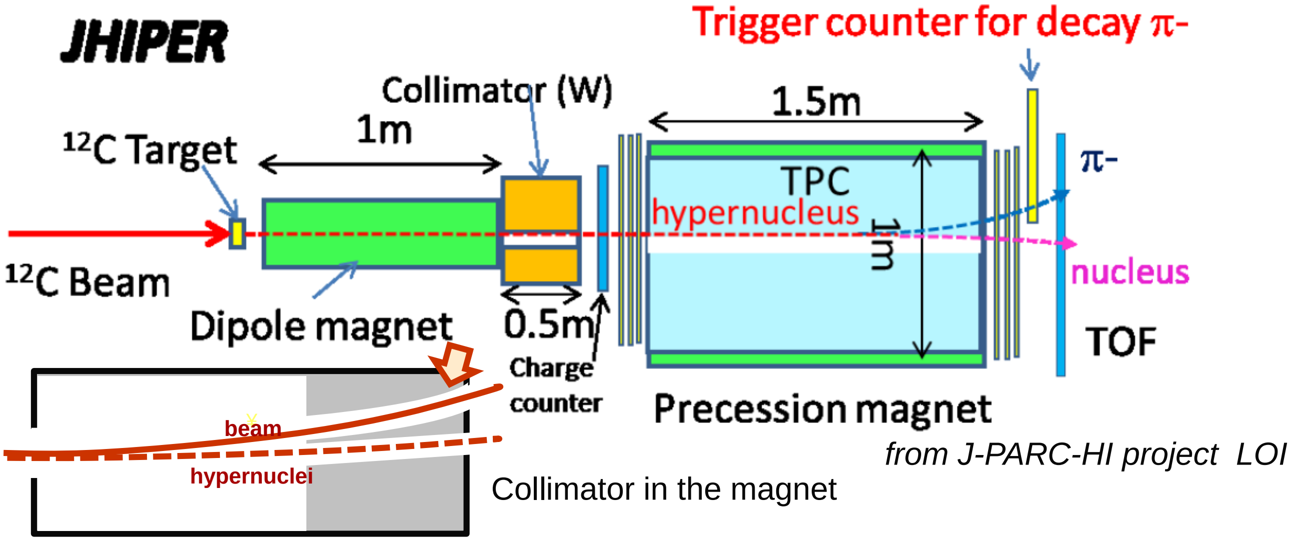


J-PARC Hadron Hall Extension Plan

K1.1 and HIHR are essential for hypernuclear physics in future



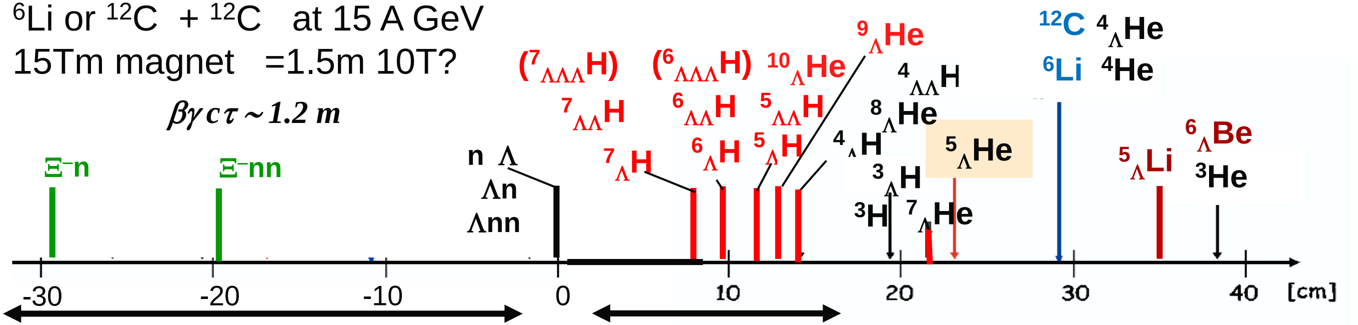
J-PARC HI: Closed-geometry detector



^{6}Li or ^{12}C + ^{12}C at 15 A GeV

15Tm magnet =1.5m 10T?

$\beta\gamma c\tau \sim 1.2\ m$



No contamination from non-strange nuclei

Figure 9: Separation of hypernuclei at the exit of the superconducting magnet, which are by the ^{6}Li projectiles at 20 A GeV.

Hypernuclear physics program at J-PARC HI

- **Neutron(proton)-rich hypernuclei, Multi-strange hypernuclei**

=> BB/BBB interactions, ΛN-ΣN / ΛΛ-ΞN mixing

New Element??

  - Λnn, ${}^{5}_{\Lambda}$H, ${}^{6}_{\Lambda}$H, ${}^{9}_{\Lambda}$He, ${}^{10}_{\Lambda}$He, ${}^{11}_{\Lambda}$Li, ${}^{12}_{\Lambda}$Li; ${}^{3}_{\Lambda\Lambda}$H, ${}^{4}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$H, …
  - Ξ^-n, Ξ^-nn, Ω^-n, $\Xi^-\Xi^-$nn, .. "Weakly-decaying negatively-charged nuclei"
  - Other metastable objects (MEMO) ? Strangelet?
  - ${}^{5}_{\Lambda}$Li, ${}^{6}_{\Lambda}$Be, ${}^{8}_{\Lambda}$B,…
- **Magnetic moments, B(M1) by Coulomb excitation**

=> Baryon properties in a nucleus =ΛN-ΣN mixing, Baryon structure change?

  - Magnetic moment of ${}^{5}_{\Lambda}$He, ${}^{7}_{\Lambda}$He, …
  - Λ-spin-flip B(M1) of ${}^{4}_{\Lambda}$H/${}^{4}_{\Lambda}$He… by Coulomb excitation
- **Lifetimes, weak decay branching ratios** => Baryonic weak interaction
  - ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, (${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He,), …, Ξ^-n -> Σ^-n
- **Interaction cross section in matter** => Nuclear radius, Neutron halo
  - Size of ${}^{3}_{\Lambda}$H, ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$He,..
- **Gamma decays, B(E2) by Coulomb excitation** => Impurity effect
  - ${}^{7}_{\Lambda}$He, ${}^{9}_{\Lambda}$Be, ${}^{13}_{\Lambda}$C,..

Negatively-charged nuclei

Generally, Ξ hypernuclei decay strongly via $\Xi^- p \to \Lambda\Lambda$, giving no 2nd vertex.

=> Identification extremely difficult

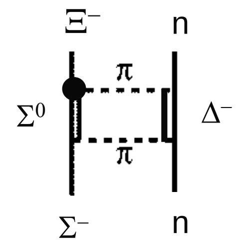
Ξn (S=1, I=1) is predicted to be bound, deuteron analog in {10*}, BE= 3.6 MeV from ESC08a

Kiso event and recent E05 pilot data suggest a rather deep Ξ-nulcear attractive potential

=> Weakly-decaying Ξ hypernuclei? Ξ^-n, Ξ^0p, Ξ^-nn(?),

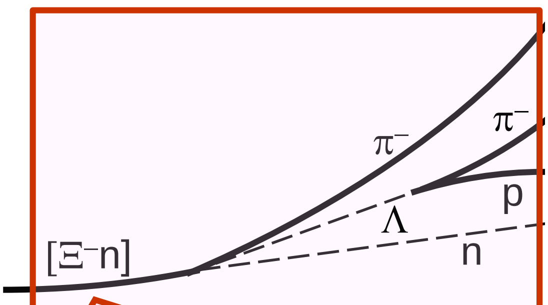
$\Xi^- n \to \Lambda \pi^- n$ (Ξn (S=0, I=1) is predicted to be strongly repulsive)

Weakly-decaying negatively-charged nuclei can be easily separated and identified. Ξ^-n, Ξ^-nn, (Σ^-n), Ω^-n, $\Xi^-\Xi^-nn$



d (K^-,K^+) [Ξ^-n] => Accurate binding energy

HI => Lifetime and Decay mode ($\Xi^-n \to \Sigma^-n$: suppressed?).



Distinguish between Ξ^- and Ξ^-n from rigidity

σ ~1 μb (central)

(Sano, Wakai)

Probably, no problem in the yield

5. Summary

Recent results in hypernuclear physics at J-PARC

- Large CSB effect in A=4 Λ hypernuclei confirmed from precise $^{4}_{\Lambda}He(1^{+}\text{->}0^{+})$ γ-ray measurement
- Ξ–nucleus bound systems observed in emulsion ($\Xi^{-}\,^{14}N$) and in $^{12}C(K\text{-},K\text{+})$ $^{12}_{\Xi}Be$ spectrum.

Future

- **Solve hyperon puzzle**
  - ΣN, ΛN scattering experiments (E40 and beyond)
  - Nuclear density dependence of ΛN interaction

    Precise B_{Λ} via high resolution $(\pi^{+},K^{+})/(e,e'K^{+})$ / E1 γ-ray spectroscopy
- **Modification of baryons in nuclear matter**

  g_{Λ} in hypernucleus to see baryon modification in a nucleus (E63)
- **J-PARC upgrades**

  Hadron Hall extension (K1.1 and HIHR lines) and HI acceleration strongly desired.