Present Status and Future Prospects of Hypernuclear Physics at J-PARC

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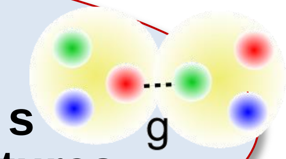
Contents

1. Present status of SNP experiments at J-PARC

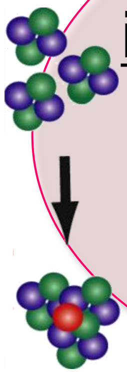
Motivations of strangeness nuclear physics

BB interactions



Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures

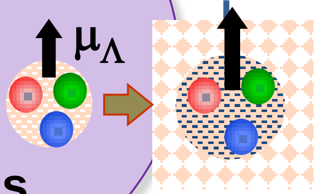
Test lattice QCD calculations



Impurity effect in nuclear structure

Changes of size,
deformation, clustering,
Appearing new symmetry,
…

Properties and behavior of baryons in nuclei

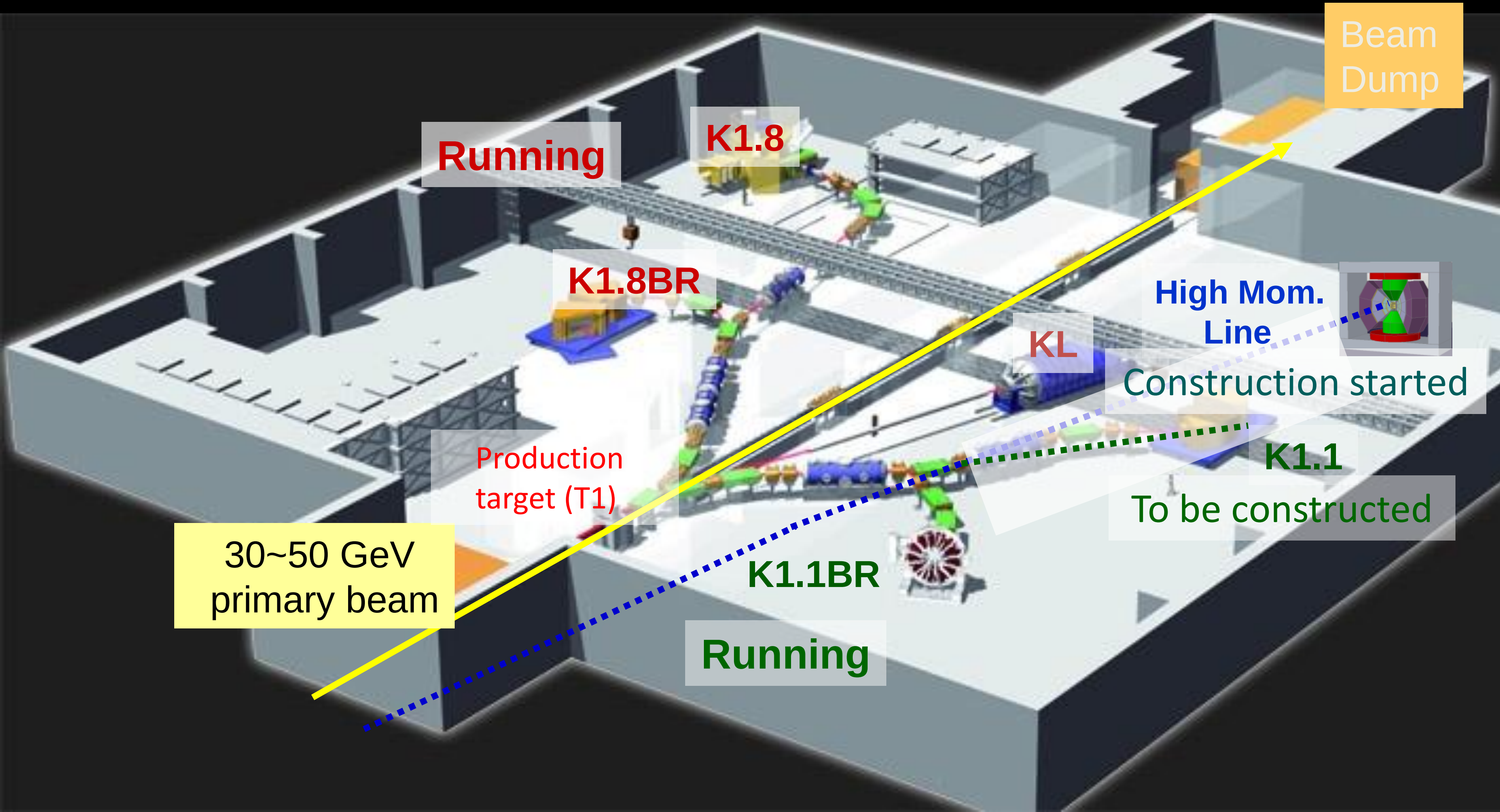


μ_Λ in a nucleus,
Single particle levels
of heavy Λ hypernuclei
...

Clues to understand
hadrons and nuclei
from quarks

Cold and dense
nuclear matter
with strangeness

Present status of J-PARC Hadron Hall and nuclear/hadron physics

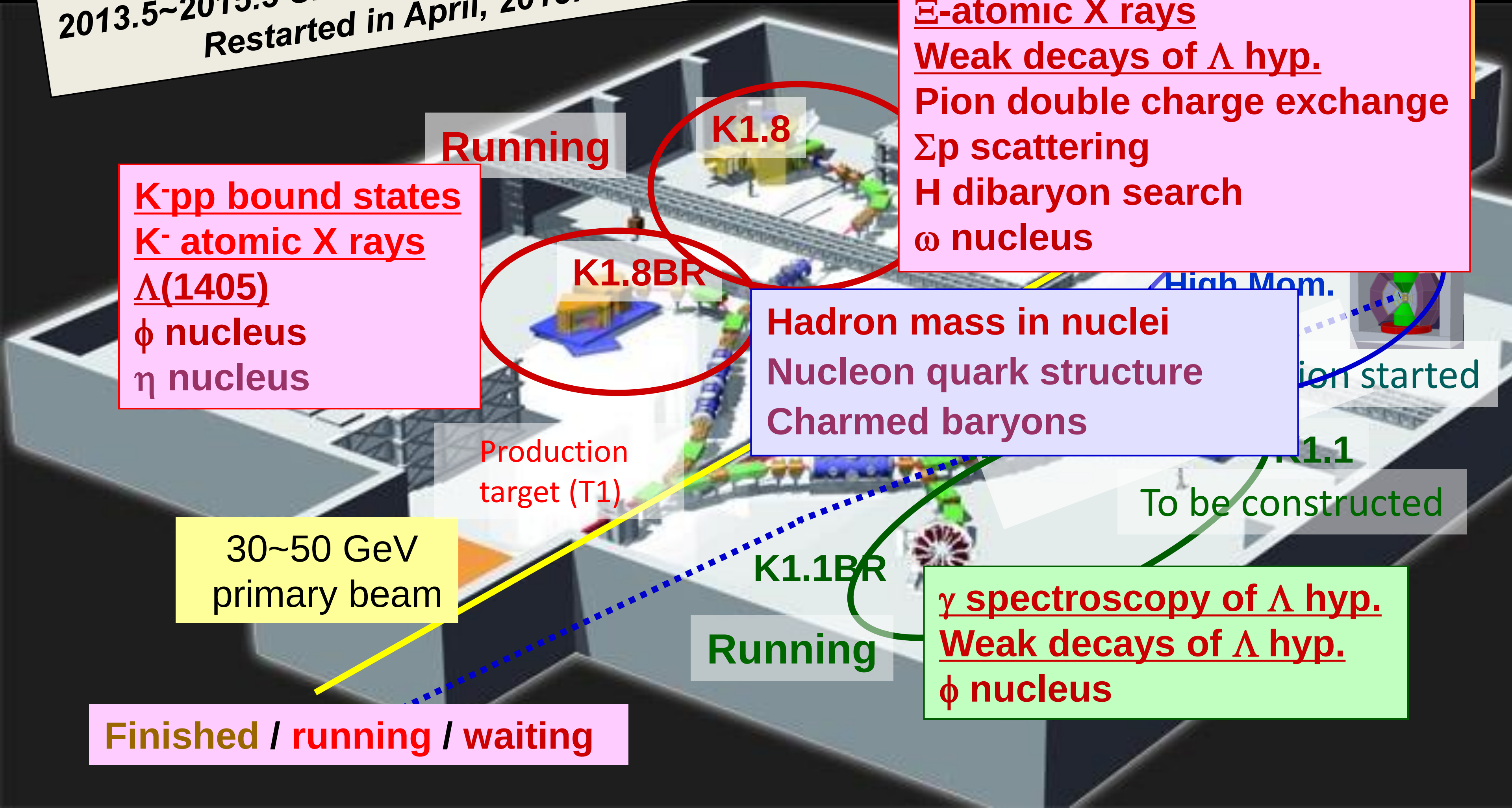


Approved (stage2 / stage1) / Proposed

Present status of J-PARC
and nuclear/h n

2011.3~2012.1 Shutdown due to the earthquake
2013.5~2015.3 Shutdown due to radiation accident
Restarted in April, 2015!

- Θ^+ search
- K^-pp bound states
- n-rich Λ hypernuclei
- γ spectroscopy of Λ hyp.
- Ξ Hypernuclei
- $\Lambda\Lambda$ hypernuclei
- Ξ-atomic X rays
- Weak decays of Λ hyp.
- Pion double charge exchange
- Σp scattering
- H dibaryon search
- ω nucleus



- K^-pp bound states
- K^- atomic X rays
- $\Lambda(1405)$
- ϕ nucleus
- η nucleus

- Hadron mass in nuclei
- Nucleon quark structure
- Charmed baryons

- γ spectroscopy of Λ hyp.
- Weak decays of Λ hyp.
- ϕ nucleus

Finished / running / waiting

Status of Strangeness Nuclear Physics exp. at J-PARC

- ◆ Pentaquark search by (π^-,K-) E19 *Θ^+ not observed*
- ◆ n-rich hypernuclei by (π^-,K^+) E10 *${}^{6}_{\Lambda}$H not observed*
- ◆ K^-pp by ^{3}He(K^-,n) E15
- ◆ K^-pp by d(π^+,K^+) E27 *"K-pp like" structure seen*
- ◆ γ spectroscopy of Λ hypernuclei E13 *${}^{4}_{\Lambda}$He CSB confirmed*
- ◆ Λ(14

S= -1 → -2

- ◆ ΛΛ hypernuclei / Ξ atom X rays E07
- ◆ K- atom X rays with TES E62
- ◆ Ξ atom X rays E03
- ◆ K-d X rays E57
- ◆ Ξ hypernuclear spectroscopy E05
- ◆ Weak decay (ΛNN) E18
- ◆ $\Sigma^{\pm}$p scattering E40
- ◆ Weak decay (ΔI=1/2) E22
- ◆ (Unbound) H dibaryon E42

◆ *Finished*
◆ *Partly took data /Runnning*
◆ *Just started*
◆ *Waiting / Under preparation*

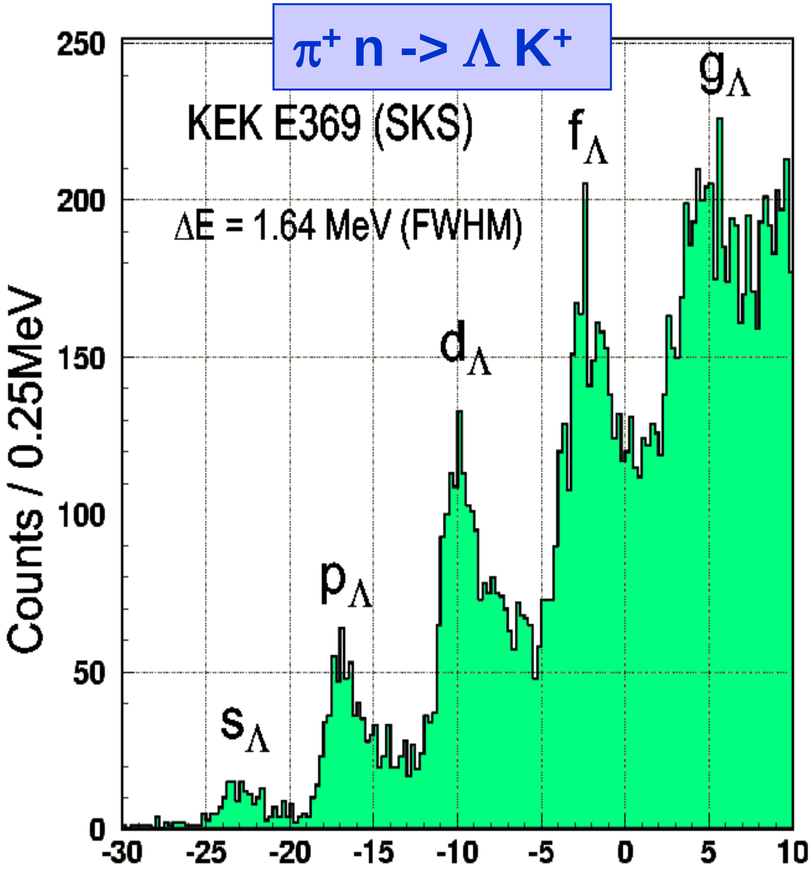
2. Λ Hypernuclear γ-ray Spectroscopy

Previous (π^+,K^+) data and ΛN interaction

SKS at KEK-PS

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

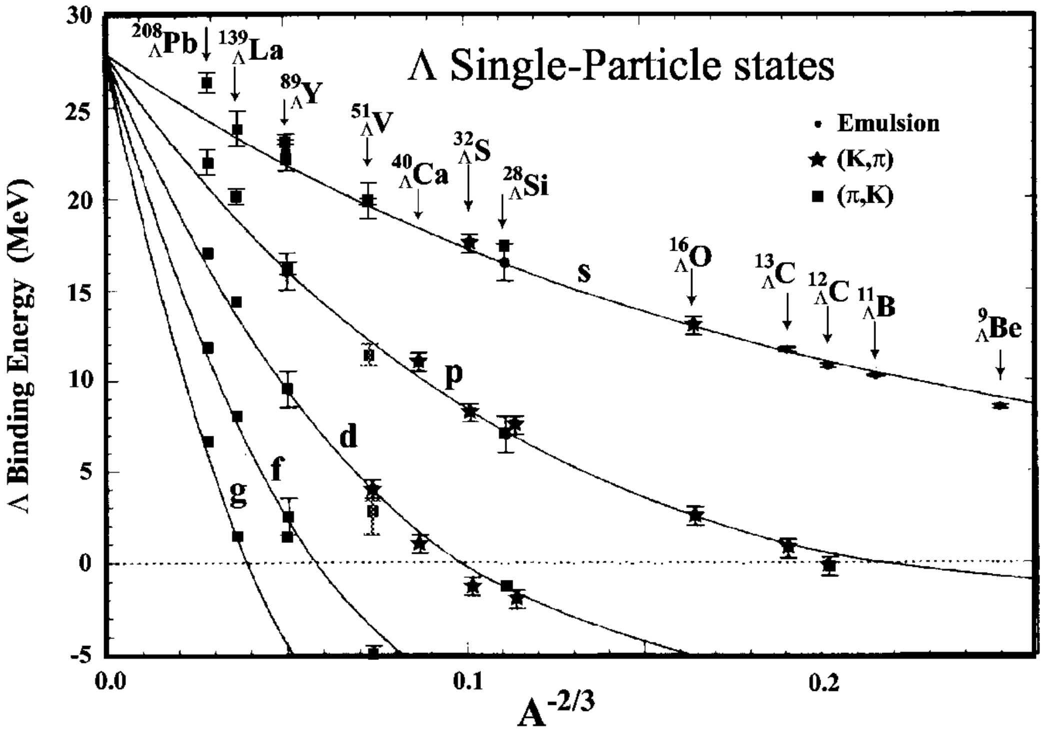
$\pi^+ n \to \Lambda K^+$



Mass of hypernucleus $-B_\Lambda$ (MeV)

Hotchi et al., PRC 64 (2001) 044302

Data as of 1996



U_Λ = - 30 MeV (< U_N = -50 MeV) established

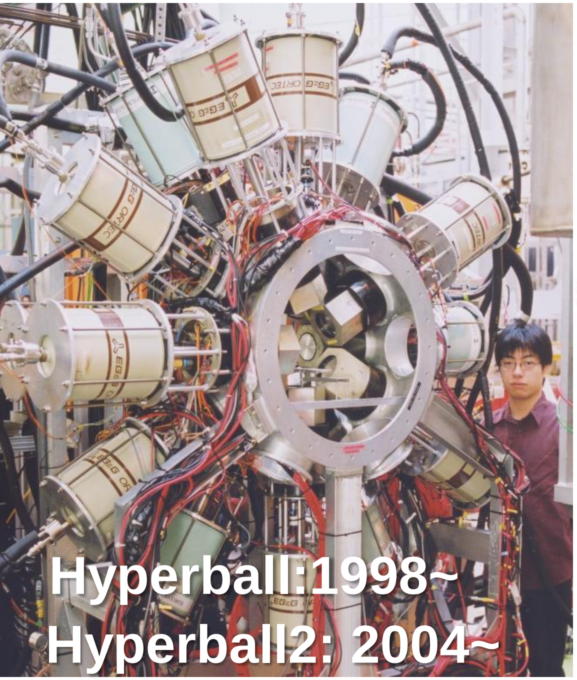
better resolution
n-rich hypernuclei

for further info. on ΛN int.

(e,e'K⁺) at JLab

γ spectroscopy and (π^-,K^+) at J-PARC

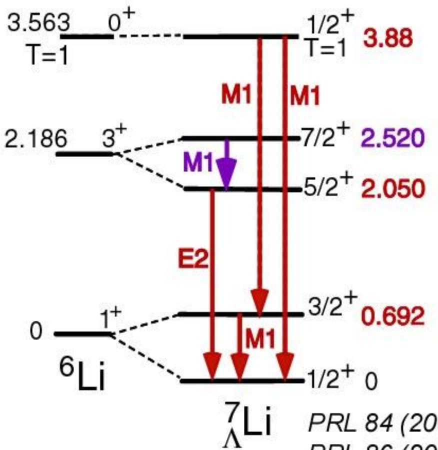
Hypernuclear γ-ray data (2012)



Hyperball:1998~

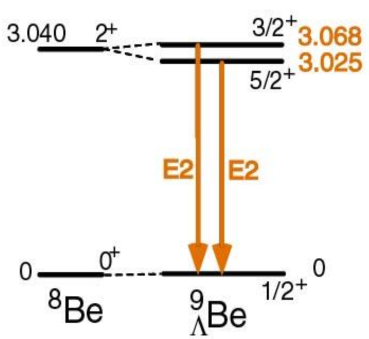
Hyperball2: 2004~

^{7}Li (π^+,K$^+\gamma$) KEK E419



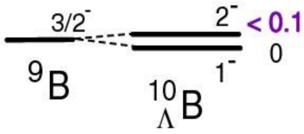
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

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



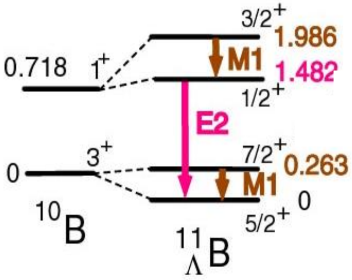
PRL 88 (2002) 082501
NPA 754 (2005) 58c

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



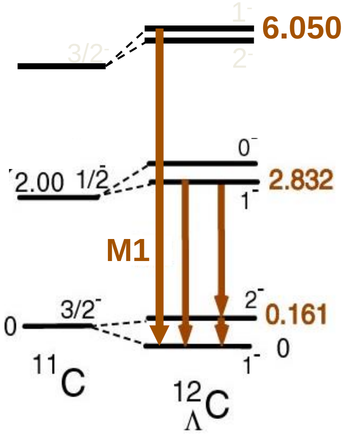
NPA 754 (2005) 58c

^{11}B (π^+,K$^+\gamma$) KEK E518



NPA 754 (2005) 58c

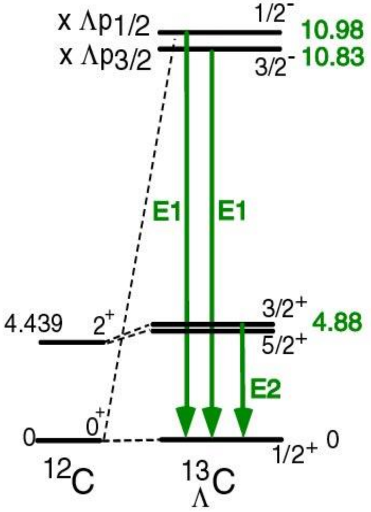
^{12}C (π^+,K$^+\gamma$) KEK E566



EPJ A33 (2007) 243

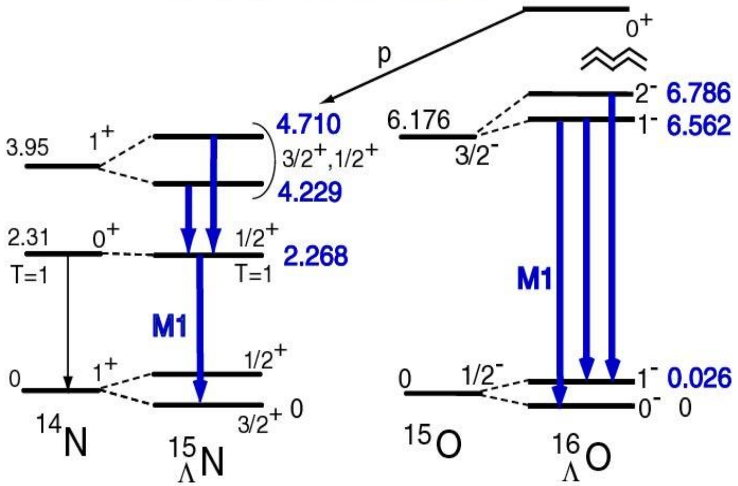
PTEP (2015) 081D01

^{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

ΛN spin-dependent interactions

- **Two-body ΛN effective interaction**

Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

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

$$\bar{V} \qquad \Delta \qquad S_\Lambda \qquad S_N \qquad T$$

Well known from U_Λ = - 30 MeV

p-shell: 5 radial integrals for $s_\Lambda p_N$ w.f.

$$\Delta = \int V_\sigma(r)\,|u(r)|^2\,r^2 dr, \quad \mathbf{r} = \mathbf{r}_{s_\Lambda} - \mathbf{r}_{p_N}$$

γ-ray data => Δ = 0.33 (0.43 for A=7), S_Λ = -0.01, S_N = -0.4, T= 0.03 [MeV]

Small spin-dependent forces have been established.

- **Feedback to BB interaction models thru G-matrix calc. (Millener)**

	Δ	S_Λ	S_N	T	(MeV)
ND	-0.048	-0.131	-0.264	0.018	
NF	0.072	-0.175	-0.266	0.033	
NSC89	1.052	-0.173	-0.292	0.036	
NSC97f	0.421	-0.149	-0.238	0.055	
ESC04a	0.381	-0.108	-0.236	0.013	
ESC08a	0.146	-0.074	-0.241	0.055	
(“Quark model”		0.0	-0.4)		
Exp.	0.4	-0.01	-0.4	0.03	

Nijmegen models

LS force:

All Nijmegen models fail.

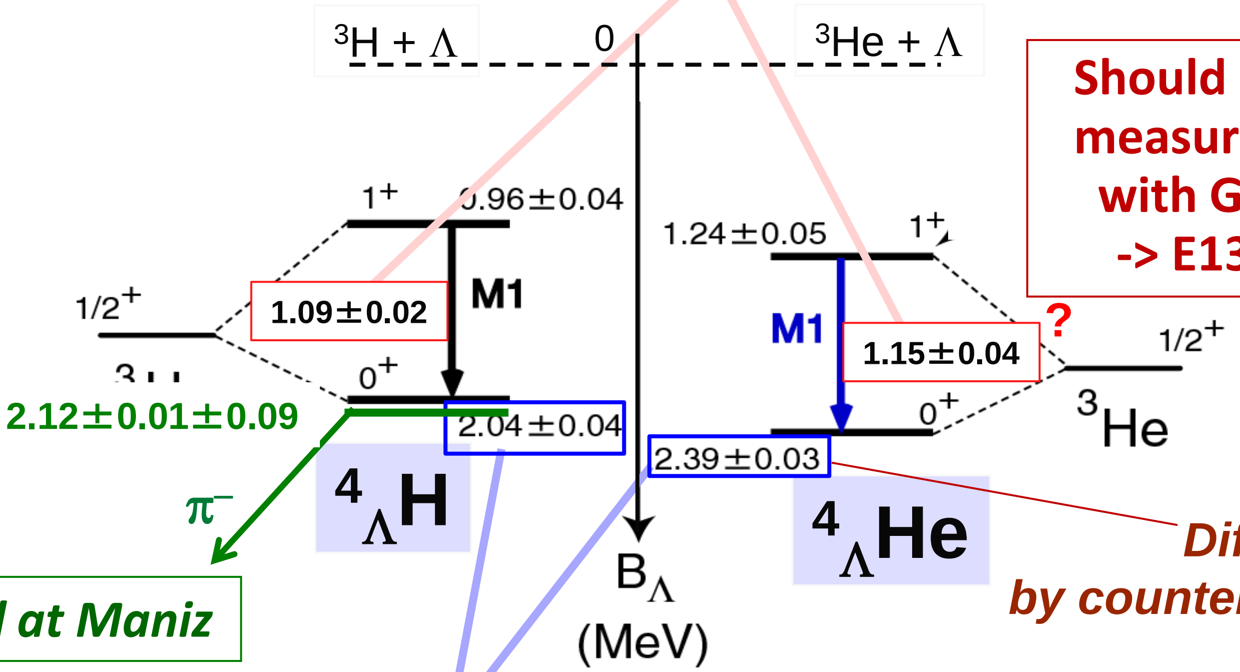
Quark model looks OK.

Charge Symmetry Breaking puzzle in A=4

Origin: Unkown. ΛN-ΣN coupling?
But 4-body calc's with Λ–Σ mixing
using Nijmegen interactions failed
=> Long standing puzzle

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

Old NaI data



Should be measured with Ge -> E13

Difficult by counter experiments

Measured at Maniz

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

Old emulsion data

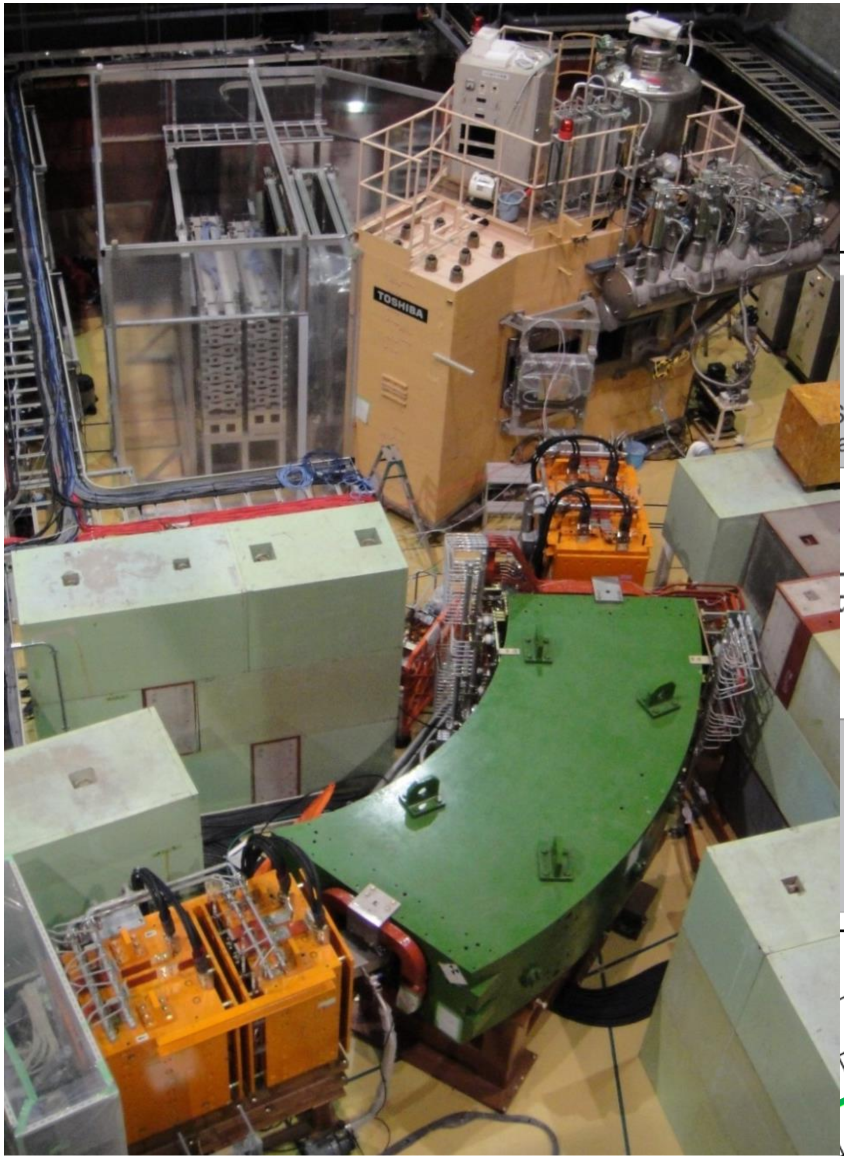
no systematic error

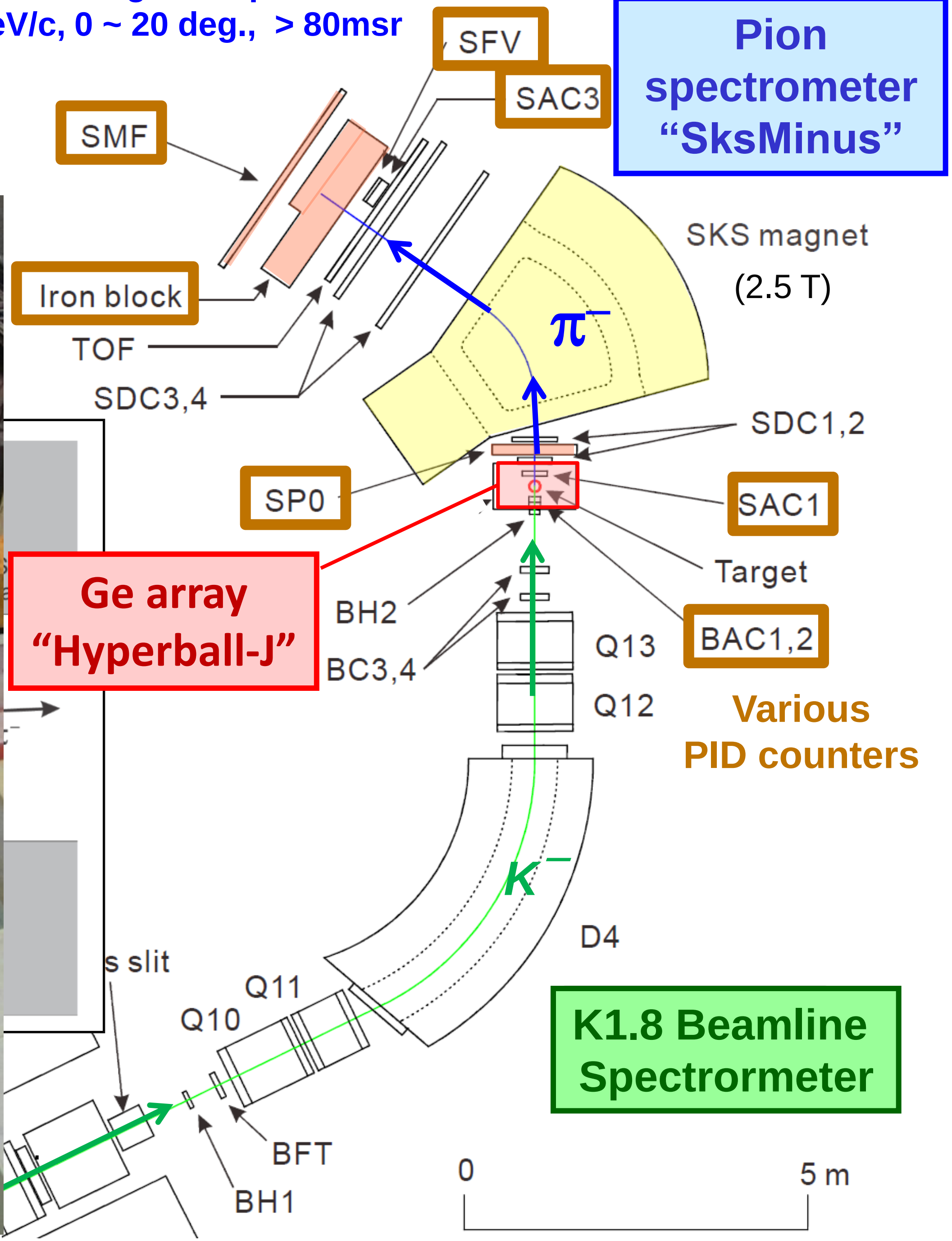
M. Juric et al. NPB 52 (1973) 1

Experimental confirmation of CSB
Is necessary

E13 Setup at K1.8

SksMinus: wide and large acceptance
1.2 ~ 2.0 GeV/c, 0 ~ 20 deg., > 80msr





Pion spectrometer "SksMinus"

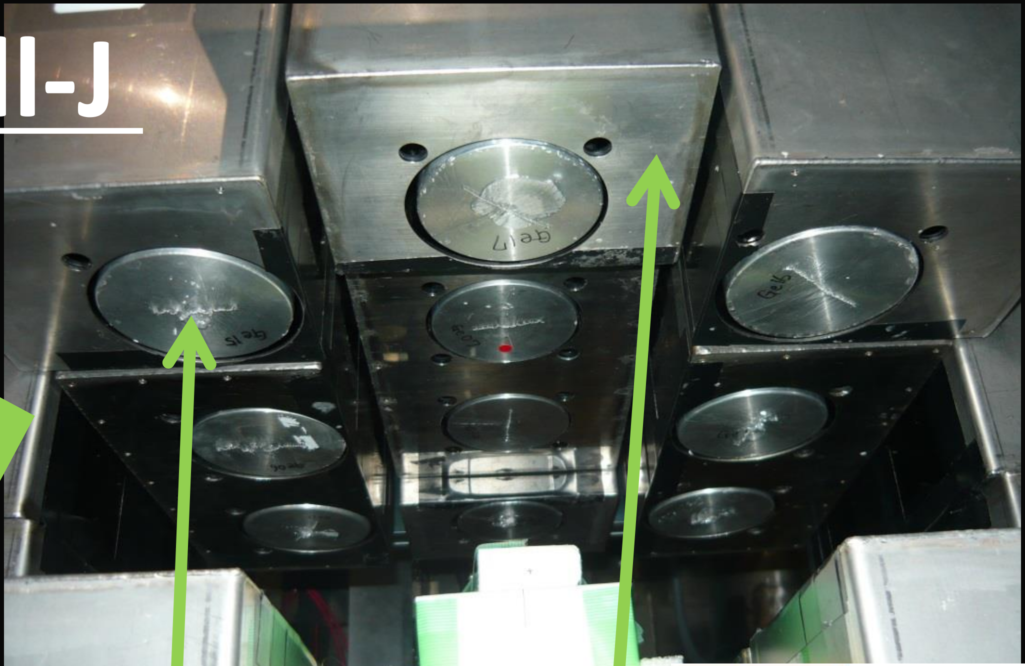
Ge array "Hyperball-J"

Various PID counters

K1.8 Beamline Spectrormeter

Hyperball-J

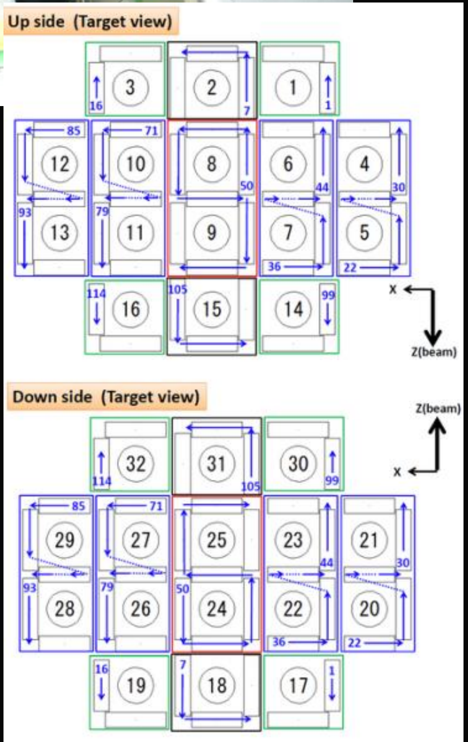
Pulse-tube refrigerator



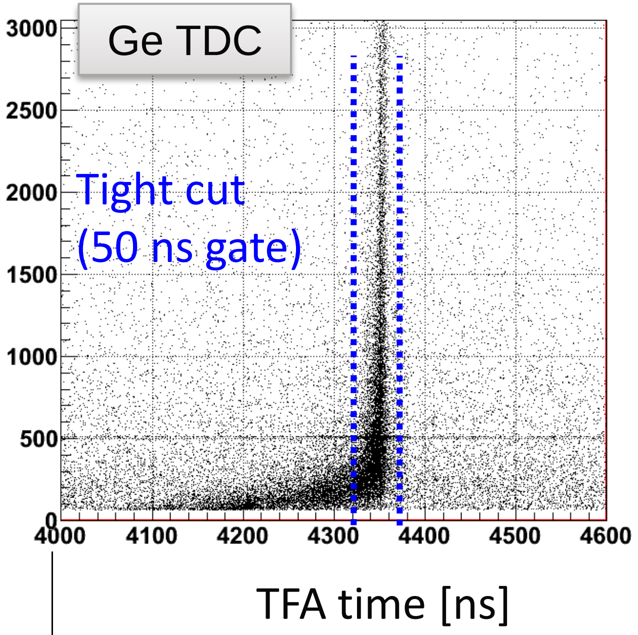
Ge cooled down to ~70K (c.f. 92K w/LN2) to reduce radiation damage

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%)

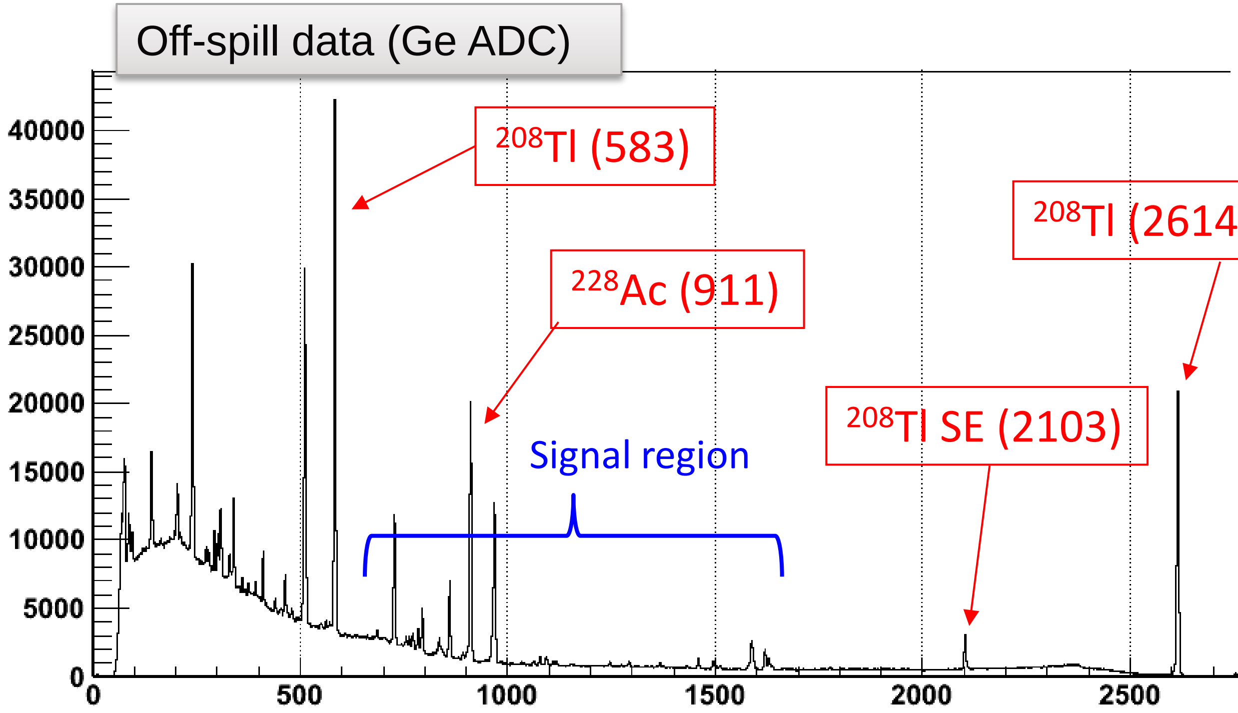


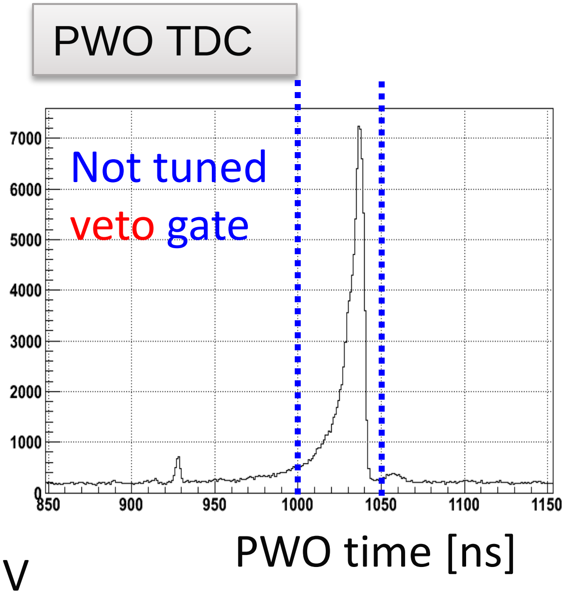
Ge ADC calibration / TDC cut



(1) Calibration (off-spill period)
using Th-W source mounted near each Ge detector

(2) Off-spill -> on-spill : offset < 0.7 keV
using 511 keV peak position





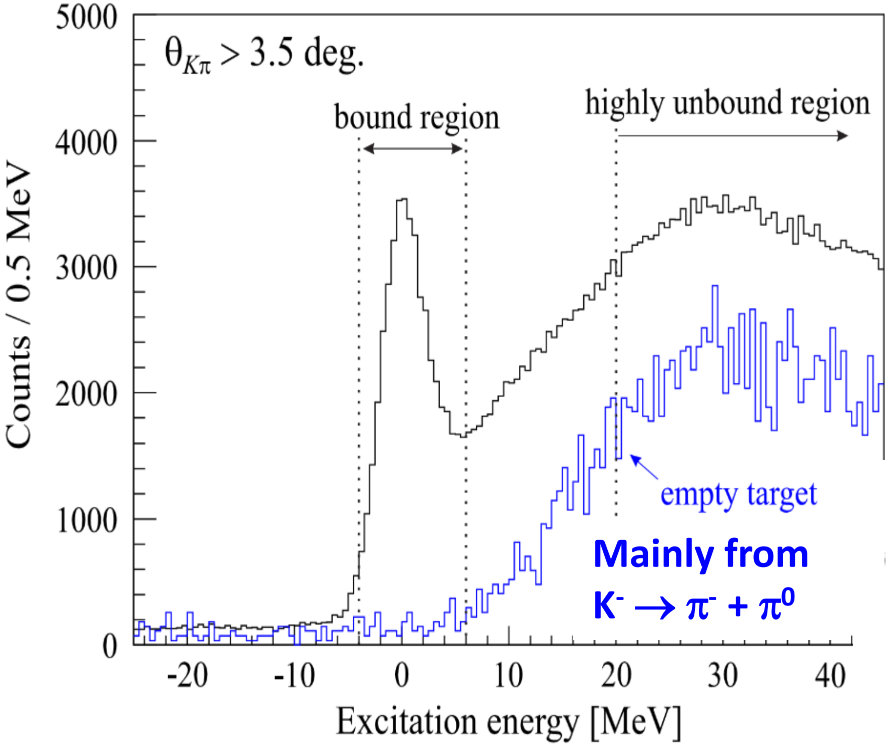
Energy resolution (off- spill) : 4.5 ~ 5.5 keV (FWHM) @ 1~2 MeV
(after summing all detectors)

Gain drift: <0.5 keV @ 1.3 MeV

Missing mass ($^{4}_{\Lambda}$He) ^{4}He(K^{-},π^{-}) at 1.5 GeV/c

Run on 4/18~4/27, 2015

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



Mainly from $K^{-} \rightarrow \pi^{-} + \pi^{0}$

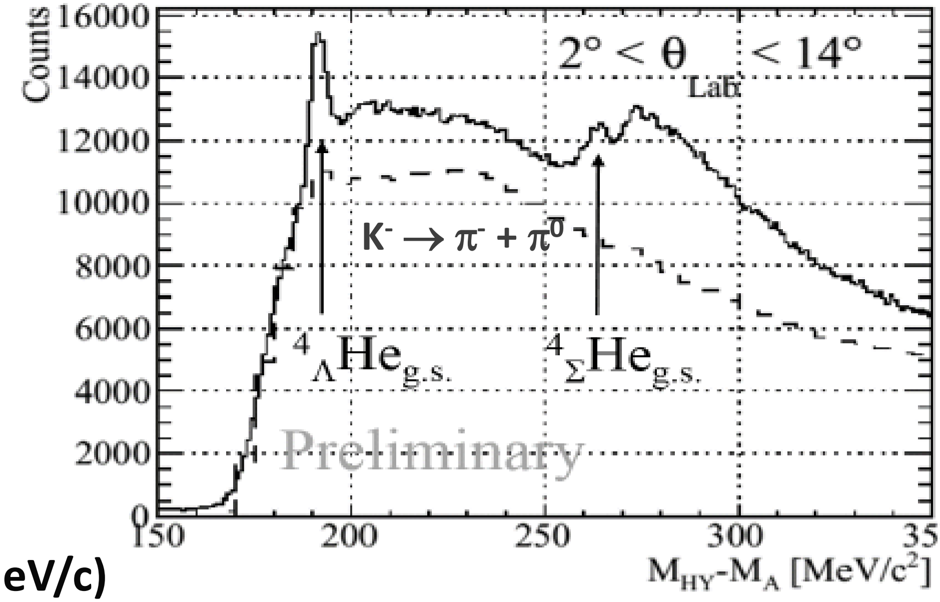
3.5 ~ 12.0 deg.

Black : with liq. He (physics run)

Blue : empty target

(w/o liq. He, w/target cell)

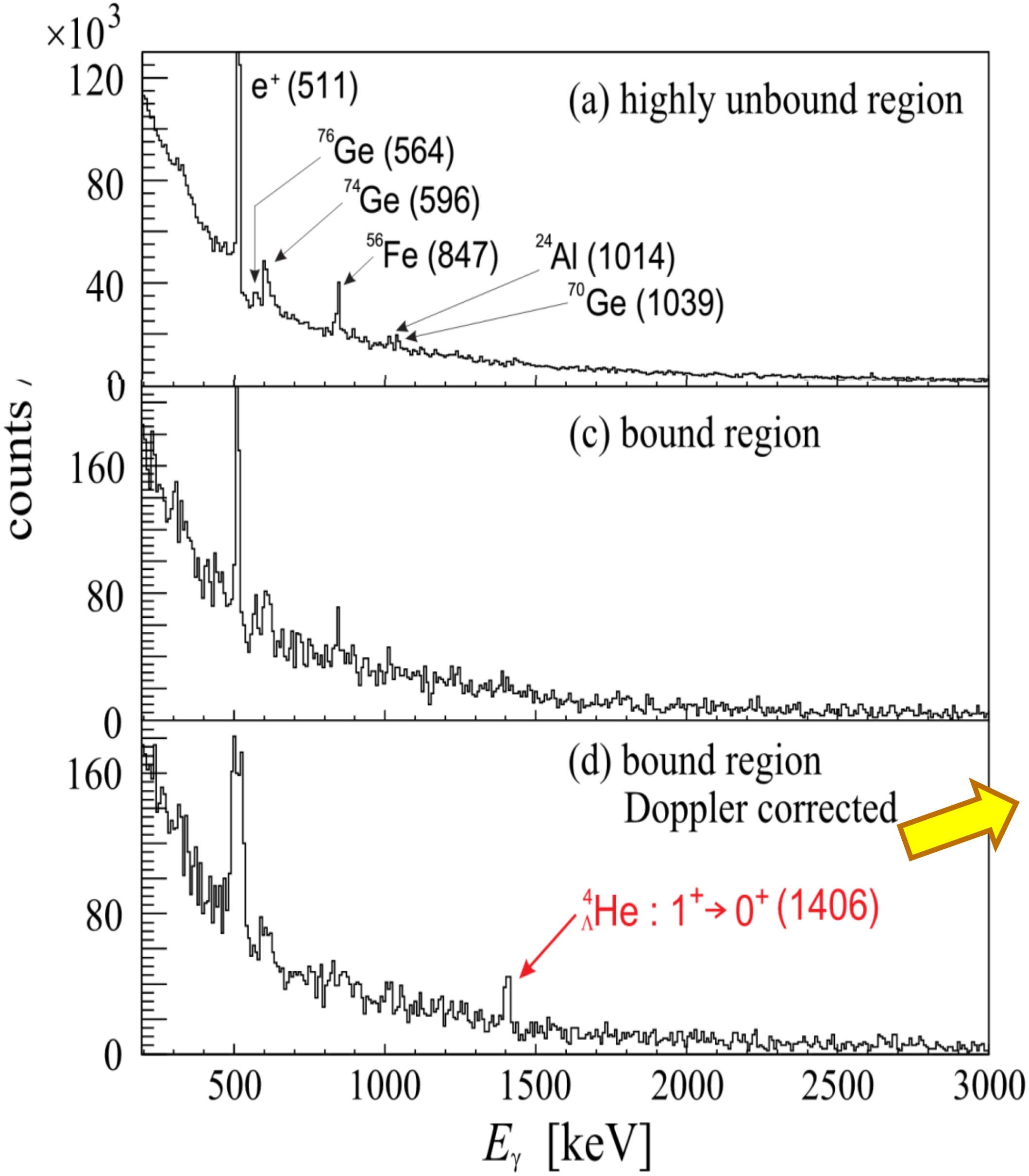
$^{4}_{\Lambda}$He(0^{+}) dominant + $^{4}_{\Lambda}$He(1^{+})
Peak width = resolution ~5.4 MeV (FWHM)



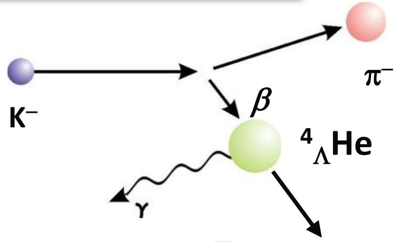
Byproduct: Spectrum for $^{4}_{\Sigma}$He (p_{K}=1.5 GeV/c) was also successfully taken.

Nakagawa et al., HYP2015 proceeding.

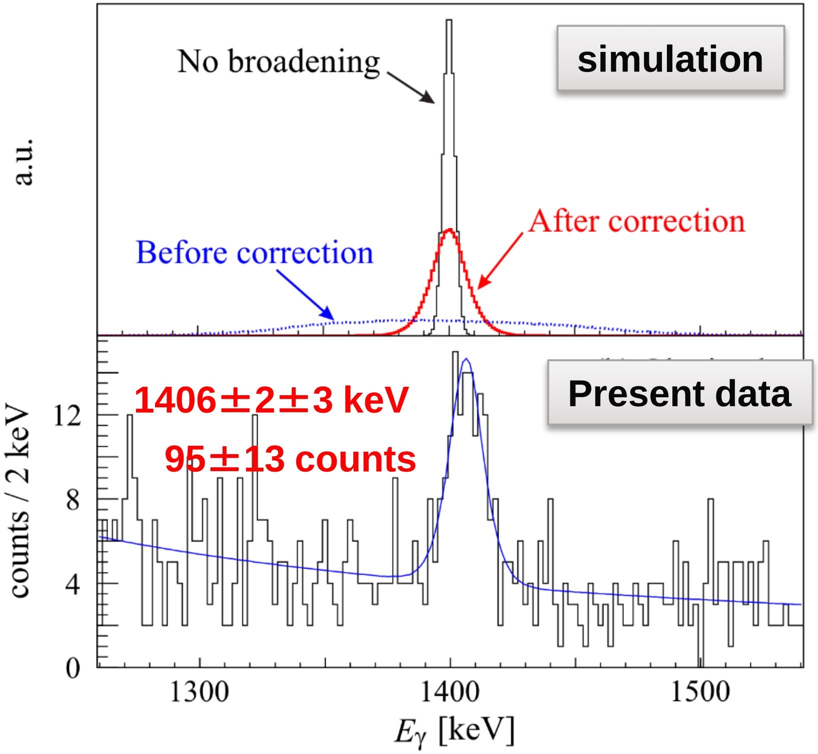
Mass-gated γ spectrum



Doppler shift correction



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

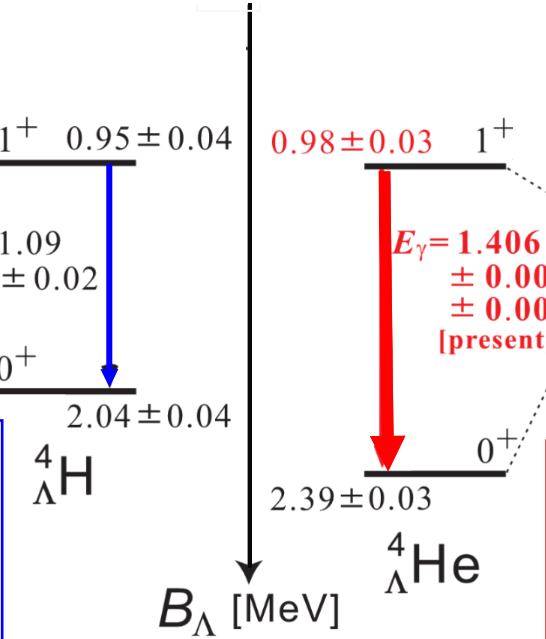


1406±2±3 keV

95±13 counts

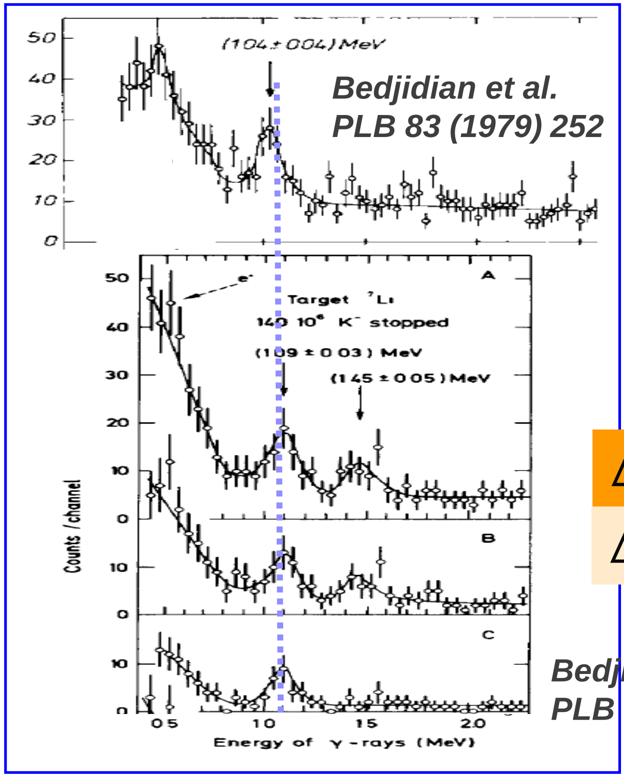
- **Existence of CSB confirmed only by γ-ray data**
- **Large spin dependence in CSB found by combining with emulsion data**

Results



Theoretical studies will elucidate the origin of CSB and the ΛN -ΣN interaction.

Old data (1.15 MeV) was denied.



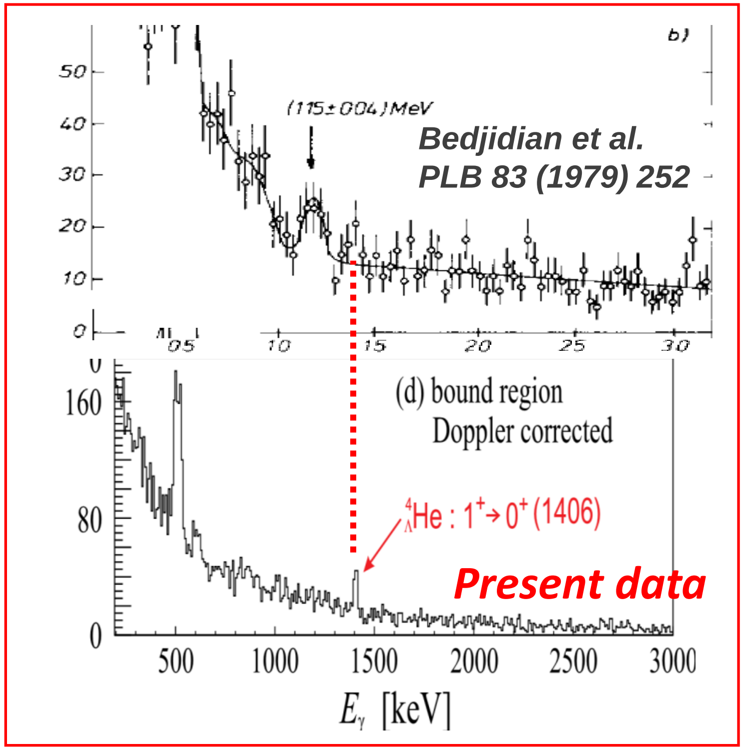
Bedjidian et al. PLB 83 (1979) 252

Bedjidian et al. PLB 62 (1976) 467

Combining with emulsion data,

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

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



Bedjidian et al. PLB 83 (1979) 252

Present data

PRL **115,** 222501 (2015) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2015

Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda$He

T. O. Yamamoto,[1] M. Agnello,[2,3] Y. Akazawa,[1] N. Amano,[4] K. Aoki,[5] E. Botta,[3,6] N. Chiga,[1] H. Ekawa,[7] P. Evtoukhovitch,[8] A. Feliciello,[3] M. Fujita,[1] T. Gogami,[7] S. Hasegawa,[9] S. H. Hayakawa,[10] T. Hayakawa,[10] R. Honda,[10] K. Hosomi,[9] S. H. Hwang,[9] N. Ichige,[1] Y. Ichikawa,[9] M. Ikeda,[1] K. Imai,[9] S. Ishimoto,[5] S. Kanatsuki,[7] M. H. Kim,[11] S. H. Kim,[11] S. Kinbara,[12] T. Koike,[1] J. Y. Lee,[13] S. Marcello,[3,6] K. Miwa,[1] T. Moon,[13] T. Nagae,[7] S. Nagao,[1] Y. Nakada,[10] M. Nakagawa,[10] Y. Ogura,[1] A. Sakaguchi,[10] H. Sako,[9] Y. Sasaki,[1] S. Sato,[9] T. Shiozaki,[1] K. Shirotori,[14] H. Sugimura,[9] S. Suto,[1] S. Suzuki,[5] T. Takahashi,[5] H. Tamura,[1] K. Tanabe,[1] K. Tanida,[9] Z. Tsamalaidze,[8] M. Ukai,[1] Y. Yamamoto,[1] and S. B. Yang[13]

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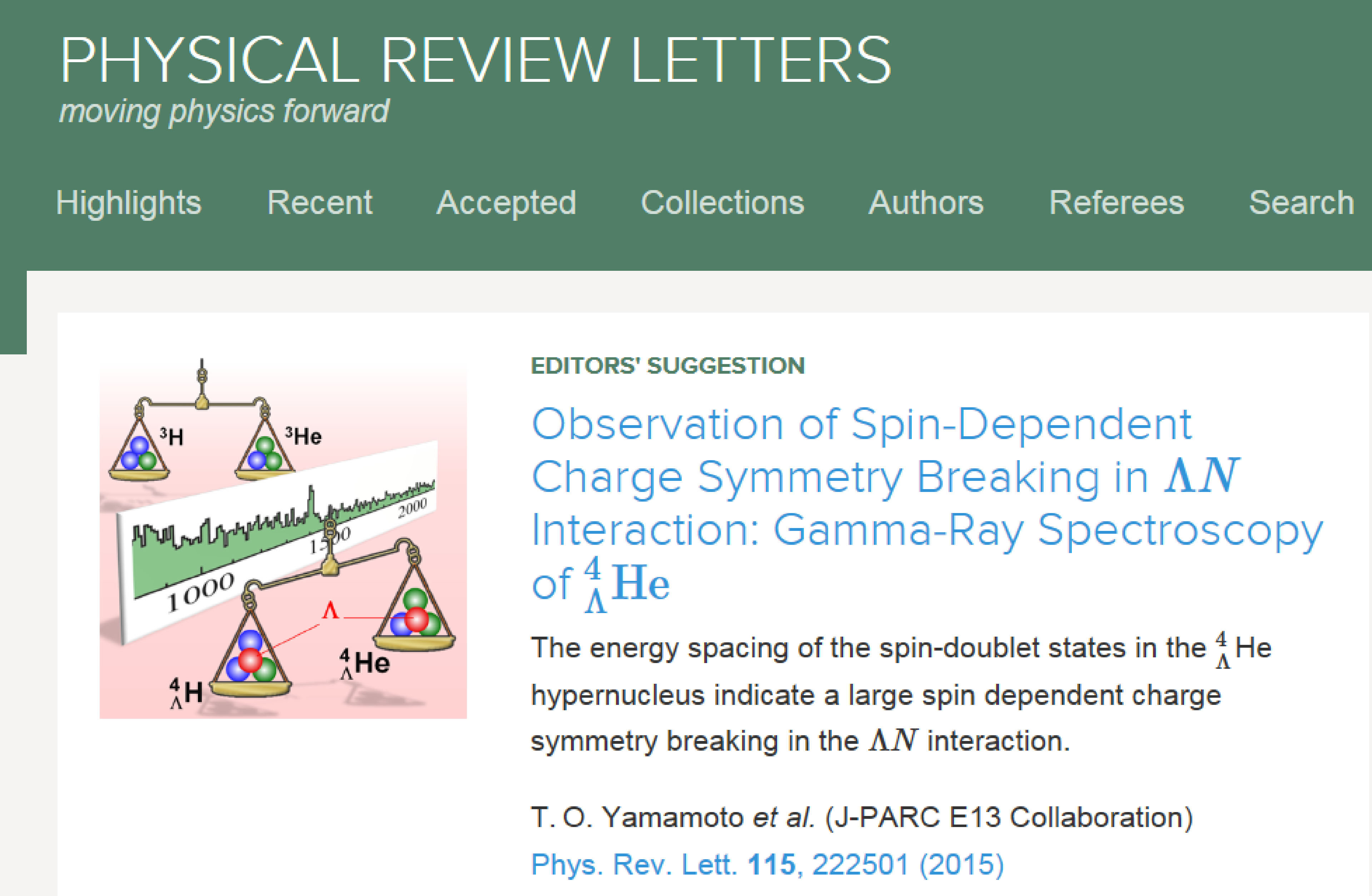
(Received 12 August 2015; published 24 November 2015)

The energy spacing between the spin-doublet bound state of $^4_\Lambda\mathrm{He}(1^+, 0^+)$ was determined to be $1406 \pm 2 \pm 2$ keV, by measuring γ rays for the $1^+ \to 0^+$ transition with a high efficiency germanium detector array in coincidence with the $^4\mathrm{He}(K^-, \pi^-)^4_\Lambda\mathrm{He}$ reaction at J-PARC. In comparison to the corresponding energy spacing in the mirror hypernucleus $^4_\Lambda$H, the present result clearly indicates the existence of charge symmetry breaking (CSB) in ΛN interaction. By combining the energy spacings with the known ground-state binding energies, it is also found that the CSB effect is large in the 0^+ ground state but is vanishingly small in the 1^+ excited state, demonstrating that the ΛN CSB interaction has spin dependence.

DOI: 10.1103/PhysRevLett.115.222501 PACS numbers: 21.80.+a, 13.75.Ev, 23.20.Lv, 25.80.Nv



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EDITORS' SUGGESTION

Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda\mathrm{He}$

The energy spacing of the spin-doublet states in the $^4_\Lambda$He hypernucleus indicate a large spin dependent charge symmetry breaking in the ΛN interaction.

T. O. Yamamoto *et al.* (J-PARC E13 Collaboration)

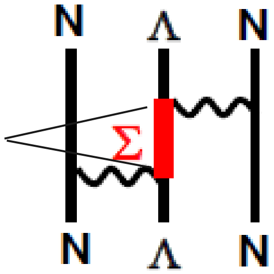
Phys. Rev. Lett. **115**, 222501 (2015)

Press-released from Tohoku U., KEK, JAEA, J-PARC

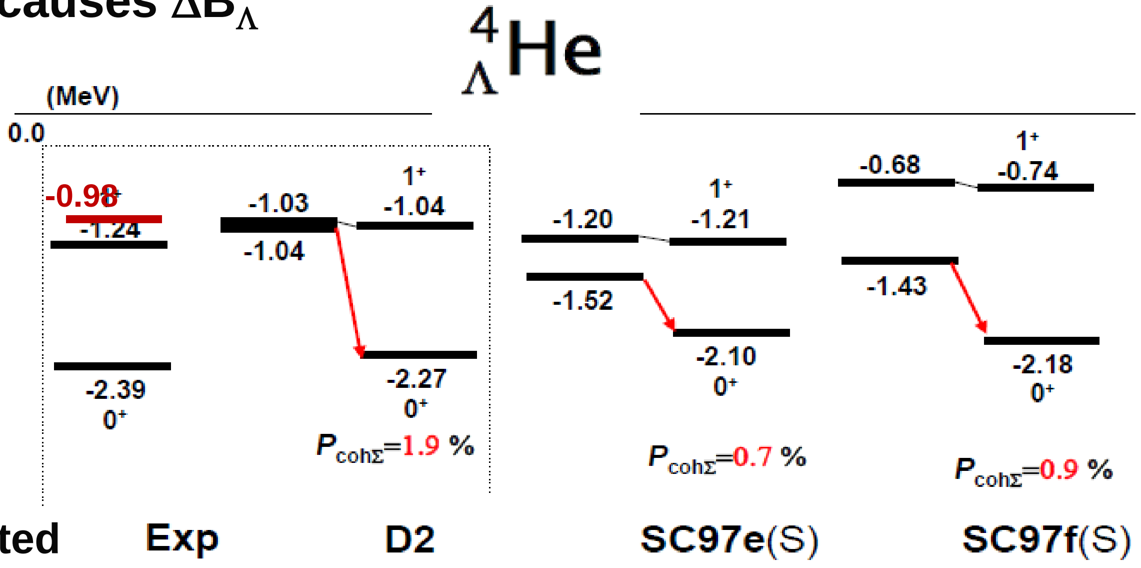
What is the origin of the large CSB effect?

- Σ mixing through ΛNN 3-body force is large for 0^+ but very small for 1^+, suggesting ΛN-ΣN coupling causes ΔB_Λ

ΛN-ΣN coupling force



Akaishi et al., PRL 84 (2000) 3539



D2: central only

SC: tensor dominated

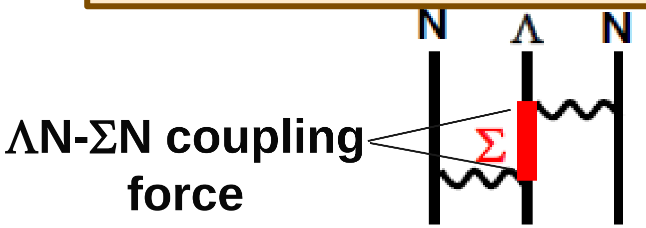
- Exact calc. including $\Sigma^+\Sigma^-$ mass difference as well as CSB in BB force (Nijmegen SC97e) gives only $\Delta B_\Lambda(0^+)$ ~70 keV. *Nogga et al., PRL 88 (2002) 172501*
- p-shell hypernuclear levels are very well reproduced by Λ–Σ coupling from D2 interaction. *Millener (2005)*
- Shell model calc. using D2 gives $\Delta B_\Lambda(0^+)$ ~200 keV. *A. Gal, PLB 744 (2015) 352*
- Ab-initio calc. using Bonn-Juelich EFT force (LO) reproduces $\Delta(B_\Lambda(0^+)$- $\Delta B_\Lambda(1^+))$ ~0.3 MeV. = Large central force *D. Gazda and A. Gal*

What is the origin of the large CSB effect?

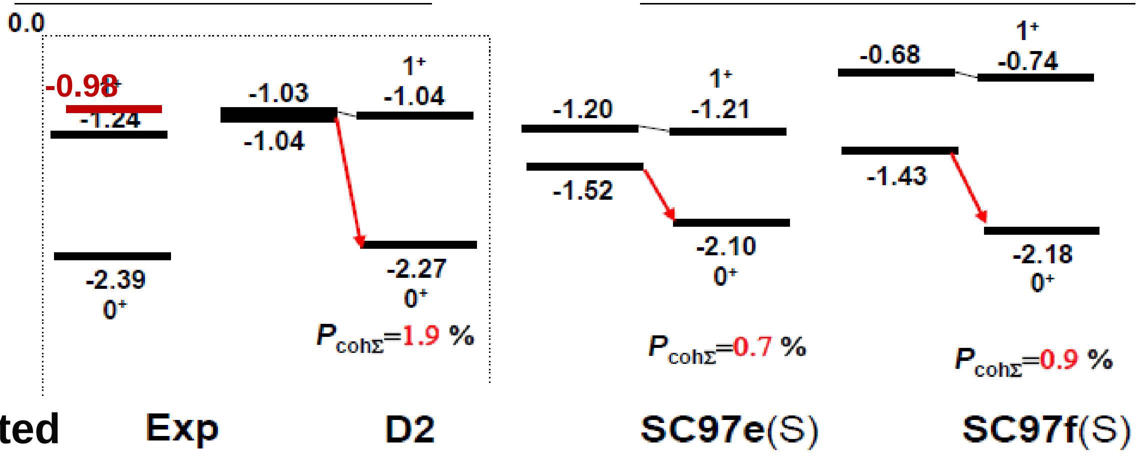
∗ Σ

su

The observed CSB effect is sensitive to the ΛN-ΣN coupling force.



Akaishi et al., PRL 84 (2000) 3539



D2: central only
SC: tensor dominated

∗ Exact calc. including $\Sigma^+\Sigma^-$ mass difference as well as CSB in BB force (Nijmegen SC97e) gives only $\Delta B_\Lambda(0^+)$ ~70 keV. *Nogga et al., PRL 88 (2002) 172501*

∗ p-shell hypernuclear levels are very well reproduced by Λ–Σ coupling from D2 interaction. *Millener (2005)*

∗ Shell model calc. using D2 gives $\Delta B_\Lambda(0^+)$ ~200 keV. *A. Gal, PLB 744 (2015) 352*

∗ Ab-initio calc. using Bonn-Juelich EFT force (LO) reproduces $\Delta(B_\Lambda(0^+)$- $\Delta B_\Lambda(1^+))$ ~0.3 MeV. = Large central force *D. Gazda and A. Gal*

Reproduction of level energies

D.J. Millener, J.Phys.Conf.Ser.
312 (2011) 022005

Millener's parameter set

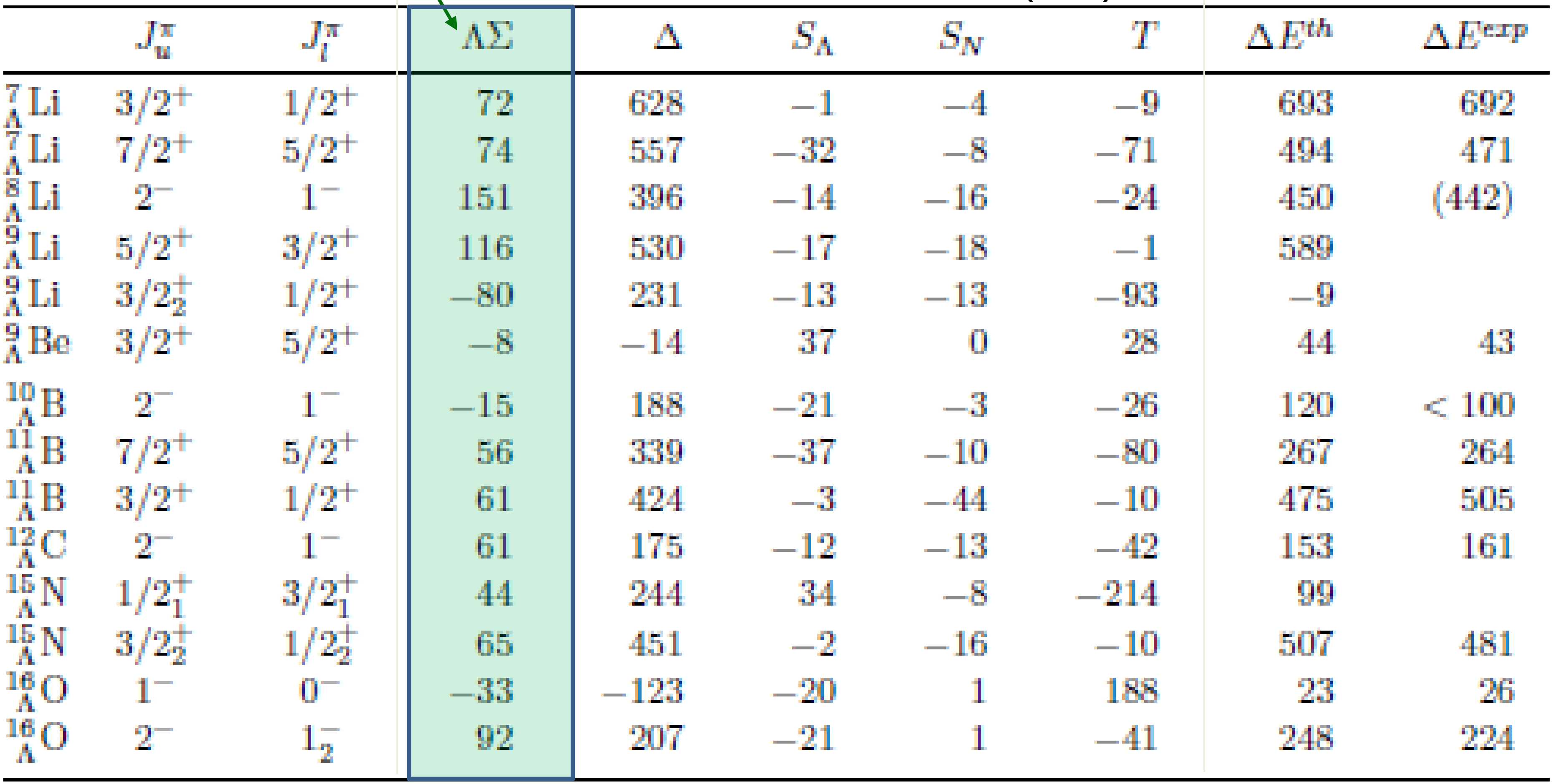
Δ = 0.33 (0.43 for A=7), S_Λ = -0.015, S_N = -0.35, T= 0.024 [MeV]

doublet spacing

Calculated from G-matrix using ΛN–ΣN force in NSC97f

contribution of each term (keV)

keV



	J^π_u	J^π_l	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
${}^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
${}^{7}_{\Lambda}$Li	$7/2^+$	$5/2^+$	74	557	−32	−8	−71	494	471
${}^{8}_{\Lambda}$Li	2^-	1^-	151	396	−14	−16	−24	450	(442)
${}^{9}_{\Lambda}$Li	$5/2^+$	$3/2^+$	116	530	−17	−18	−1	589	
${}^{9}_{\Lambda}$Li	$3/2^+_2$	$1/2^+$	−80	231	−13	−13	−93	−9	
${}^{9}_{\Lambda}$Be	$3/2^+$	$5/2^+$	−8	−14	37	0	28	44	43
${}^{10}_{\Lambda}$B	2^-	1^-	−15	188	−21	−3	−26	120	< 100
${}^{11}_{\Lambda}$B	$7/2^+$	$5/2^+$	56	339	−37	−10	−80	267	264
${}^{11}_{\Lambda}$B	$3/2^+$	$1/2^+$	61	424	−3	−44	−10	475	505
${}^{12}_{\Lambda}$C	2^-	1^-	61	175	−12	−13	−42	153	161
${}^{15}_{\Lambda}$N	$1/2^+_1$	$3/2^+_1$	44	244	34	−8	−214	99	
${}^{15}_{\Lambda}$N	$3/2^+_2$	$1/2^+_2$	65	451	−2	−16	−10	507	481
${}^{16}_{\Lambda}$O	1^-	0^-	−33	−123	−20	1	188	23	26
${}^{16}_{\Lambda}$O	2^-	1^-_2	92	207	−21	1	−41	248	224

er.

Millener's calc. for $\Sigma\Lambda$ coupling effect makes almost perfect agreement.

He uses a simplified $\Sigma\Lambda$ interaction (only central)

(Akaishi's D2) <-> NSC: tenor dominated

Why?

d

	J_u^π	J_l^π	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
${}^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
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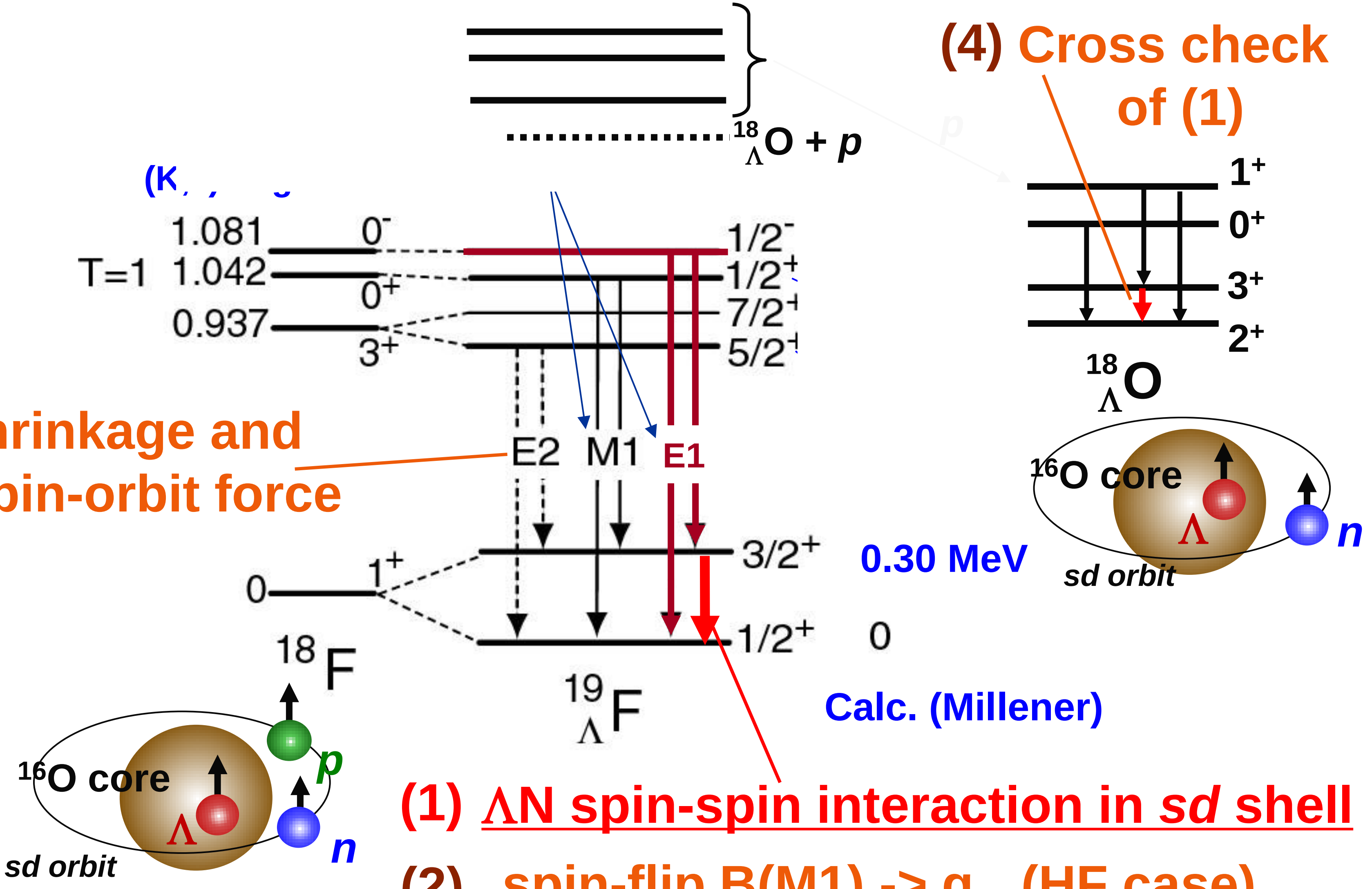
${}^{16}_{\Lambda}$O	2^-	1_2^-	92	207	−21	1	−41	248	224

2. Results and analysis status of E13-1

2.2 $^{19}_{\Lambda}$F

$^{19}_{\Lambda}$F spectroscopy

The first study of sd-shell hypernuclei



(4) Cross check of (1)

(3) Shrinkage and N-spin-orbit force

(1) ΛN spin-spin interaction in *sd* shell

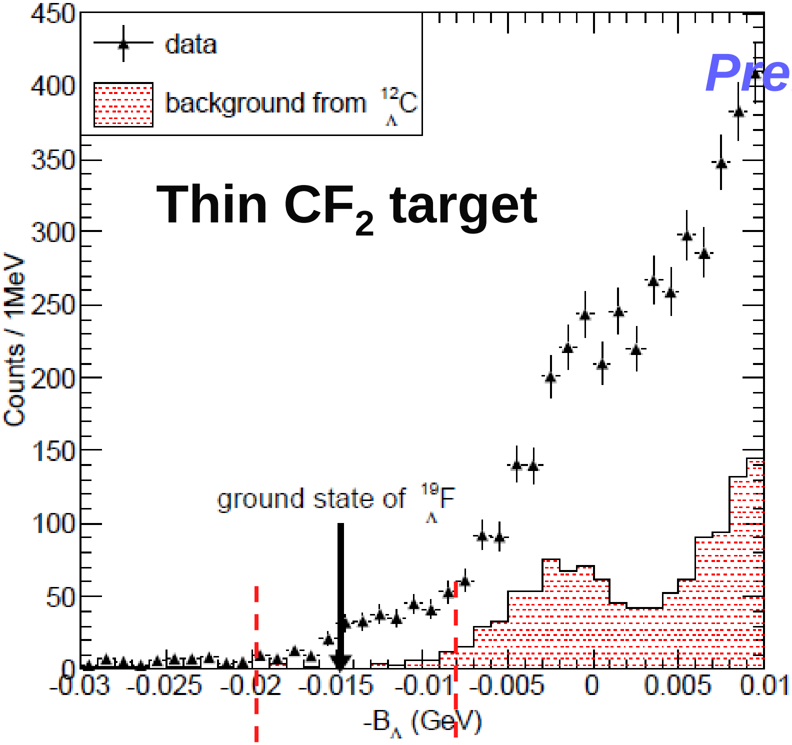
(2) spin-flip B(M1) -> g_{Λ} (HF case)

Missing mass for ${}^{19}_{\Lambda}F$

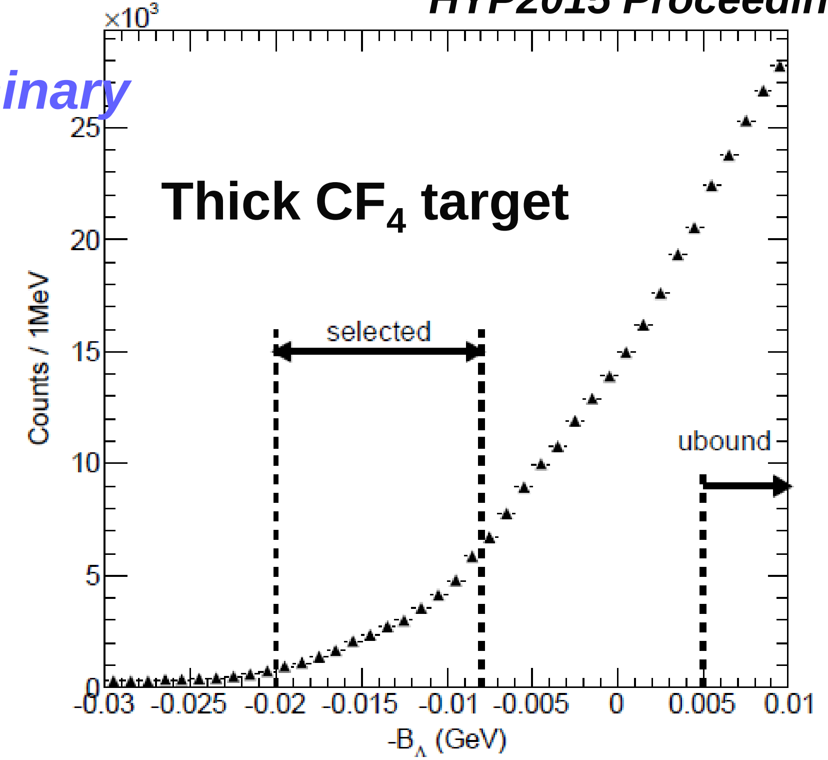
${}^{19}F(K^-,\pi^-)$ at 1.8 GeV/c

S. Yang et al.

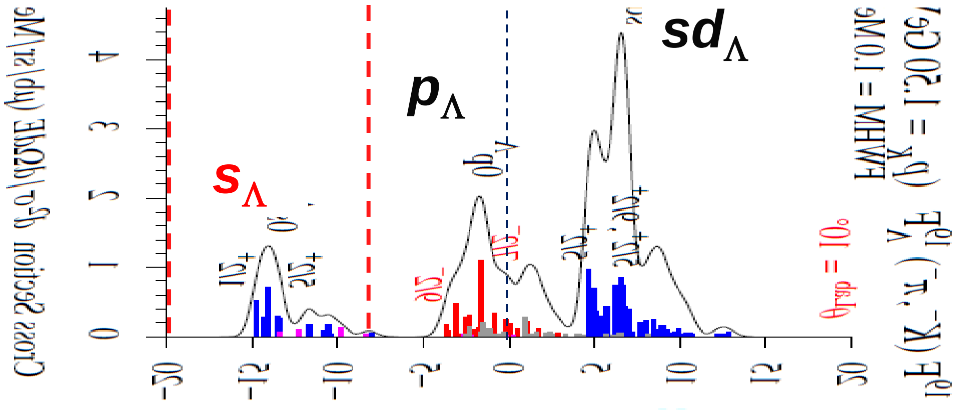
HYP2015 Proceedings



Preliminary



$- B_{\Lambda}$ (GeV)

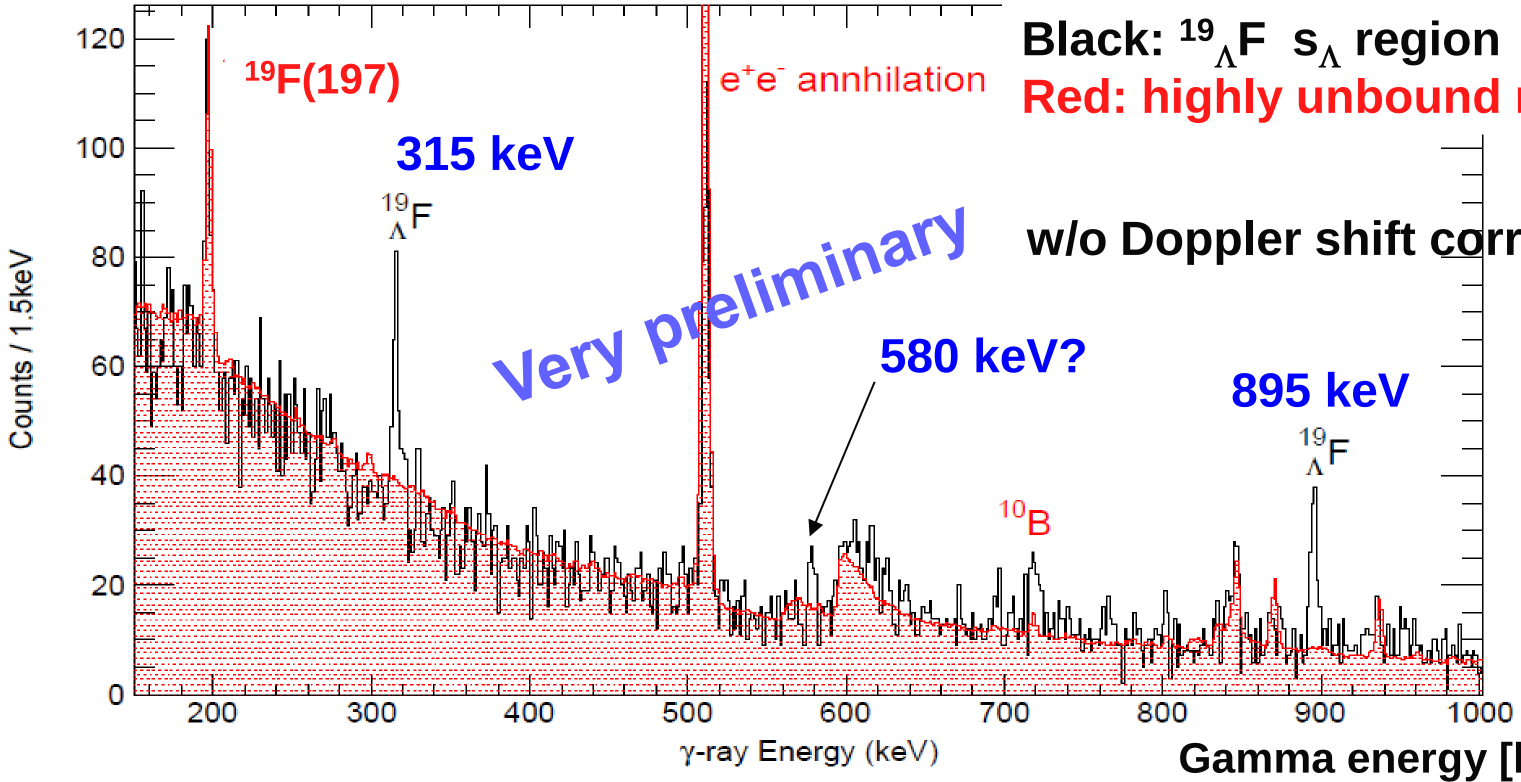


${}^{19}_{\Lambda}F$ shell model calc.
by Umeya and Motoba

Mass-gated γ-ray spectrum

S. Yang et al.
HYP2015 Proceedings

Run on 6/6~6/26, 2015



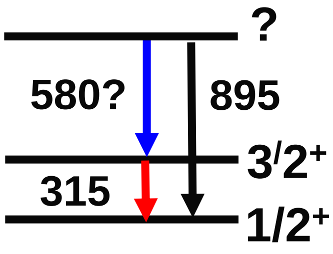
Black: $^{19}{}_{\Lambda}$F s$_{\Lambda}$ region

Red: highly unbound region

w/o Doppler shift correction

Gamma energy [keV]

- Most likely, the 315 keV peak is assigned as the g.s. doublet M1 transition, $^{19}{}_{\Lambda}$F(3/2$^+$ ->1/2$^+$)
- If the 580 keV is confimed to be a peak, this level scheme is reconstructed. The initial state may be able to be assigned.
- Analysis going on for assignments, search for more γ-rays and cross sections.

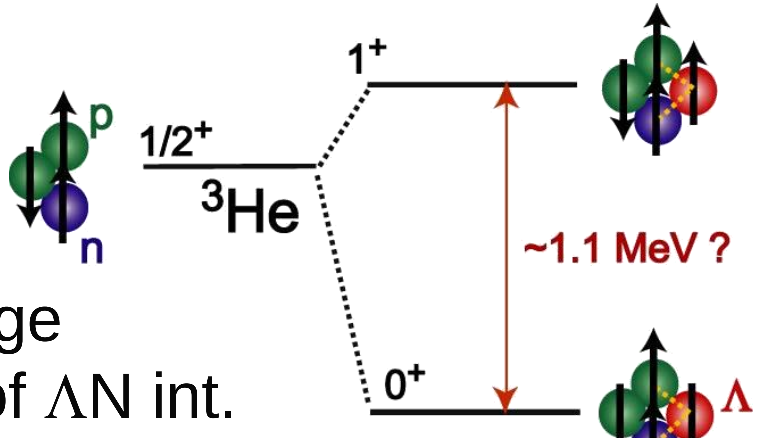


A-dependence of ΛN interaction strength

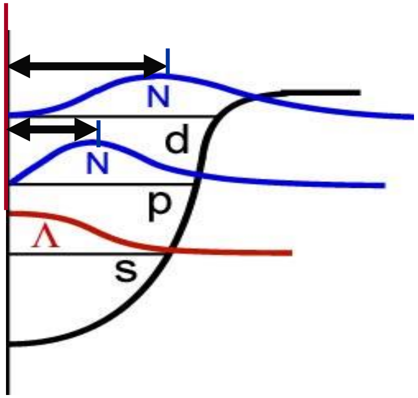
=> Information on

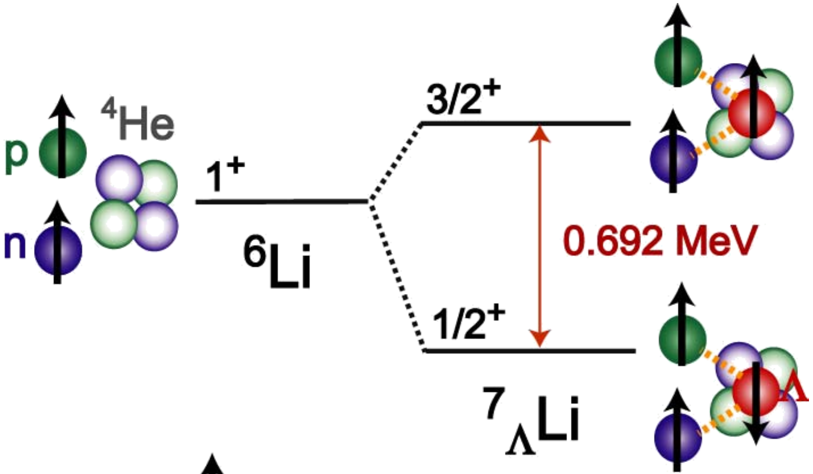
wave functions and interaction range

=> confirm short-range nature of ΛN int.

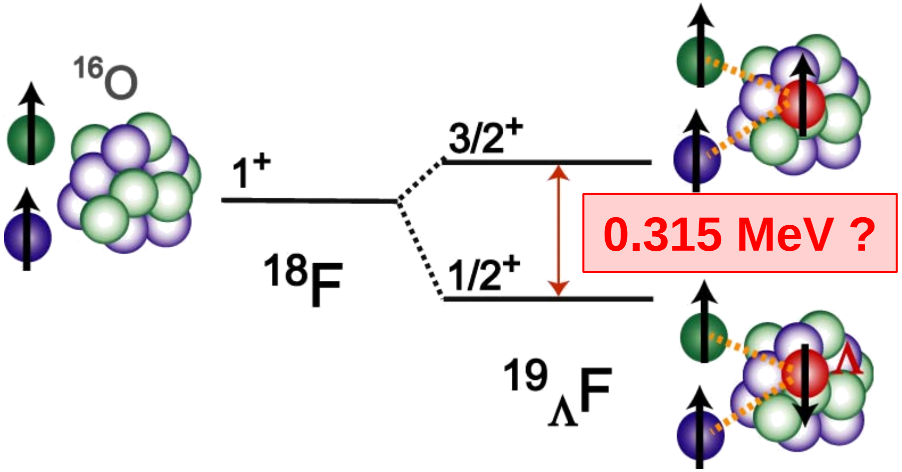


$s_\Lambda s_N$





$s_\Lambda p_N$



$\bar{r}\,(s_\Lambda\text{-}d_N) > \bar{r}\,(s_\Lambda\text{-}p_N) > \bar{r}\,(s_\Lambda\text{-}s_N)$

$s_\Lambda d_N$

Next step: g_Λ in a nucleus

Λ's magnetic moment in a nucleus may be changed in a nucleus. Λ, free from Pauli effect, is a good probe.

$$\mu_q = \frac{e\hbar}{2m_q c}$$

m_q : Constituent quark mass

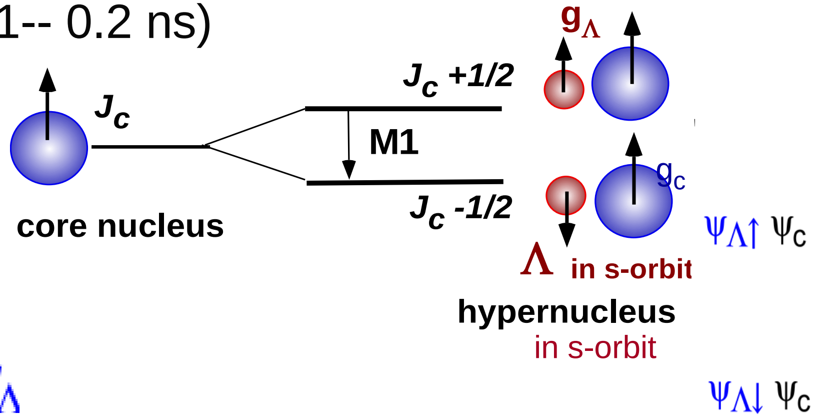
m_q *decrease* -> μ_q *increase* ?

Λ–Σ mixing (Dover-Gal), K exchange current (Oka)

~ +2--5 % for $^4_\Lambda$He -7% for $^7_\Lambda$Li

Direct measurement of g_Λ is very difficult (τ ~0.1-- 0.2 ns)

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



$$B(M1) = (2J_{up}+1)^{-1}\,|\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

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

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

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

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

But "core polarization" effect by a Λ ?
It should be very small
due to spin-dependent ΛN forces
which are much smaller than NN case.

$^7_\Lambda$Li ~100%

Doppler Shift Attenuation Method

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

For the free g_Λ value, B(M1) = 0.326 μ_N^2 from weak coupling,
B(M1) = 0.322 μ_N^2 from a cluster model calc.
Ab-initio calc. is awaited.

Hopefully run at K1.1 beam line n 2017

Next step: g_Λ in a nucleus

Λ's magnetic moment in a nucleus

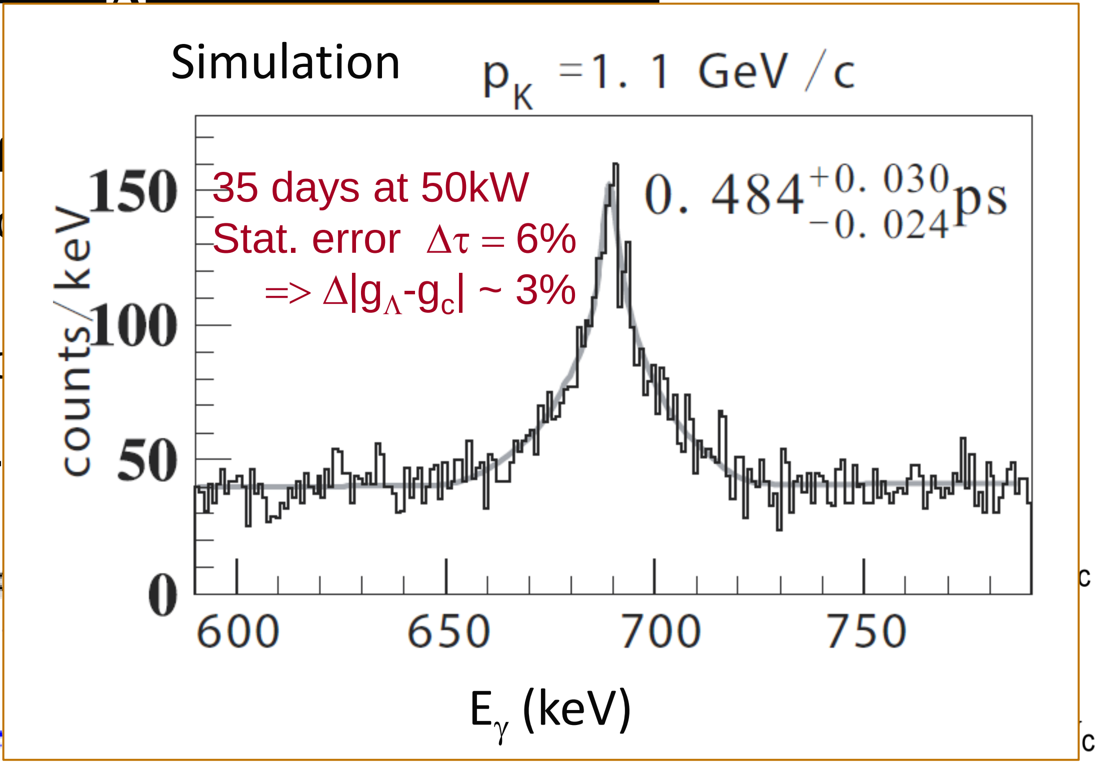
in a nucleus. Λ, free from Pauli eff

Λ–Σ mixing (Dover-Gal), K exc

~ +2--5 % for ${}^{4}_{\Lambda}$He

Direct measurement of g_Λ is very d

Λ-spin-flip M1 transition: B(M1) ->



$$B(M1) = (2J_{up}+1)^{-1}\,|\langle\, \Psi_{low} \,\|\, \mu \,\|\, \Psi_{u}$$

$$= (2J_{up}+1)^{-1}\,|\langle\, \psi_{\Lambda\downarrow}\, \psi_c \,\|\, \mu \,\|$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c$$

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

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

But "core polarization" effect by a Λ ?
It should be very small
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B(M1) = 0.322 $\mu_N{}^2$ from a cluster model calc.
Ab-initio calc. is awaited.

Hopefully run at K1.1 beam line n 2017

3. Σ-N systems

What we know about Σ-N force

$^4_\Sigma$He bound state

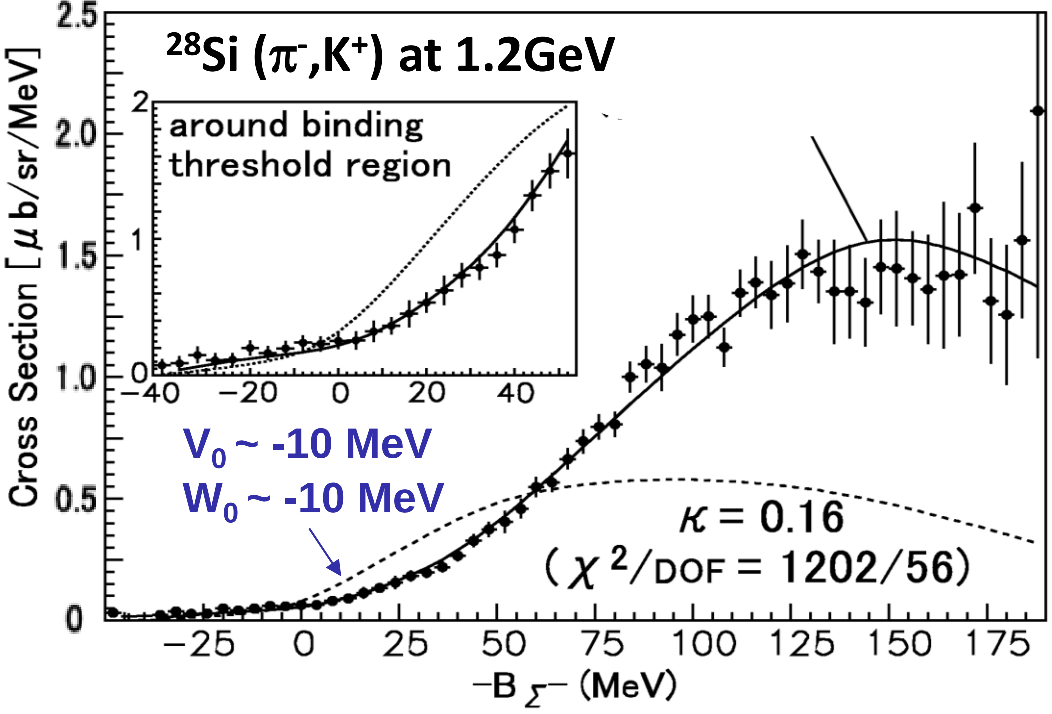
suggests **large spin-isospin dependence**

(I,S) = (3/2,0), (1/2,1) attractive

(3/2,1), (1/2,0) repulsive

-- Consistent with meson exchange models

Σ^--^{28}Si Nuclear potential (KEK E438)

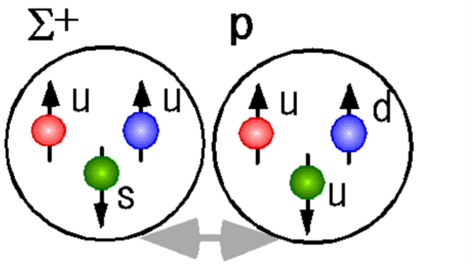


PRL 87(2002) 072301

- Strong repulsion comes from Pauli effect between quarks?

  Quark Cluster Model

  Lattice QCD



ΣN (I,S) = (3/2,1)

- Σ's never appear in n-stars?

High statistics

Σ^+p/ Σ^-p scattering experiment

J-PARC E40

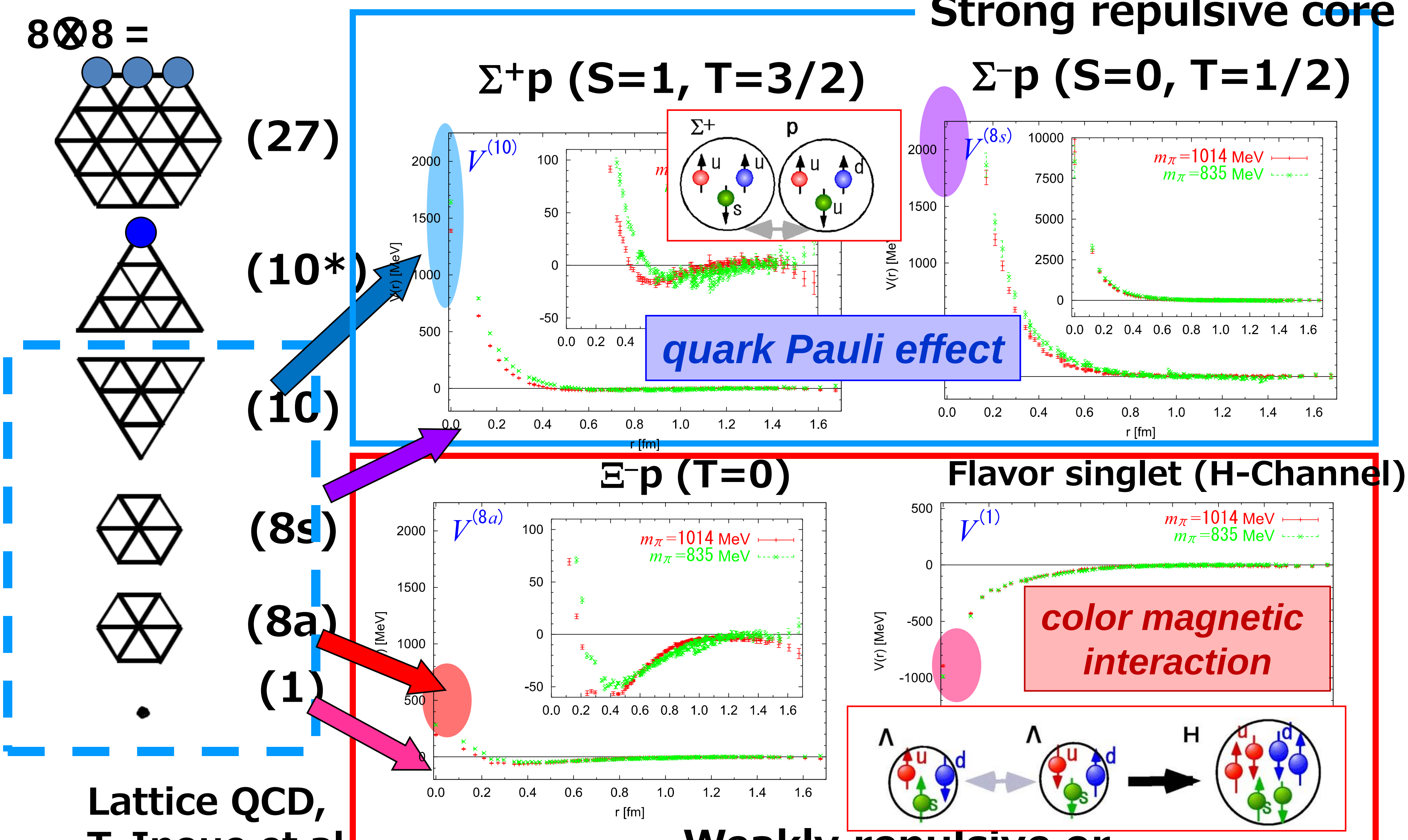
-> **Strongly repulsive** potential (U~ +30 MeV)

How repulsive are (I,S) = (3/2,1), (1/2,0) channels?

Slide by Koji Miwa

Baryon Baryon interaction by Lattice QCD

6 independent forces in flavor SU(3) symmetry



$8 \otimes 8 =$

(27)

(10*)

(10)

(8s)

(8a)

(1)

Strong repulsive core

Σ^+p (S=1, T=3/2)

Σ^-p (S=0, T=1/2)

quark Pauli effect

Ξ^-p (T=0)

Flavor singlet (H-Channel)

color magnetic interaction

Weakly repulsive or attractive Core

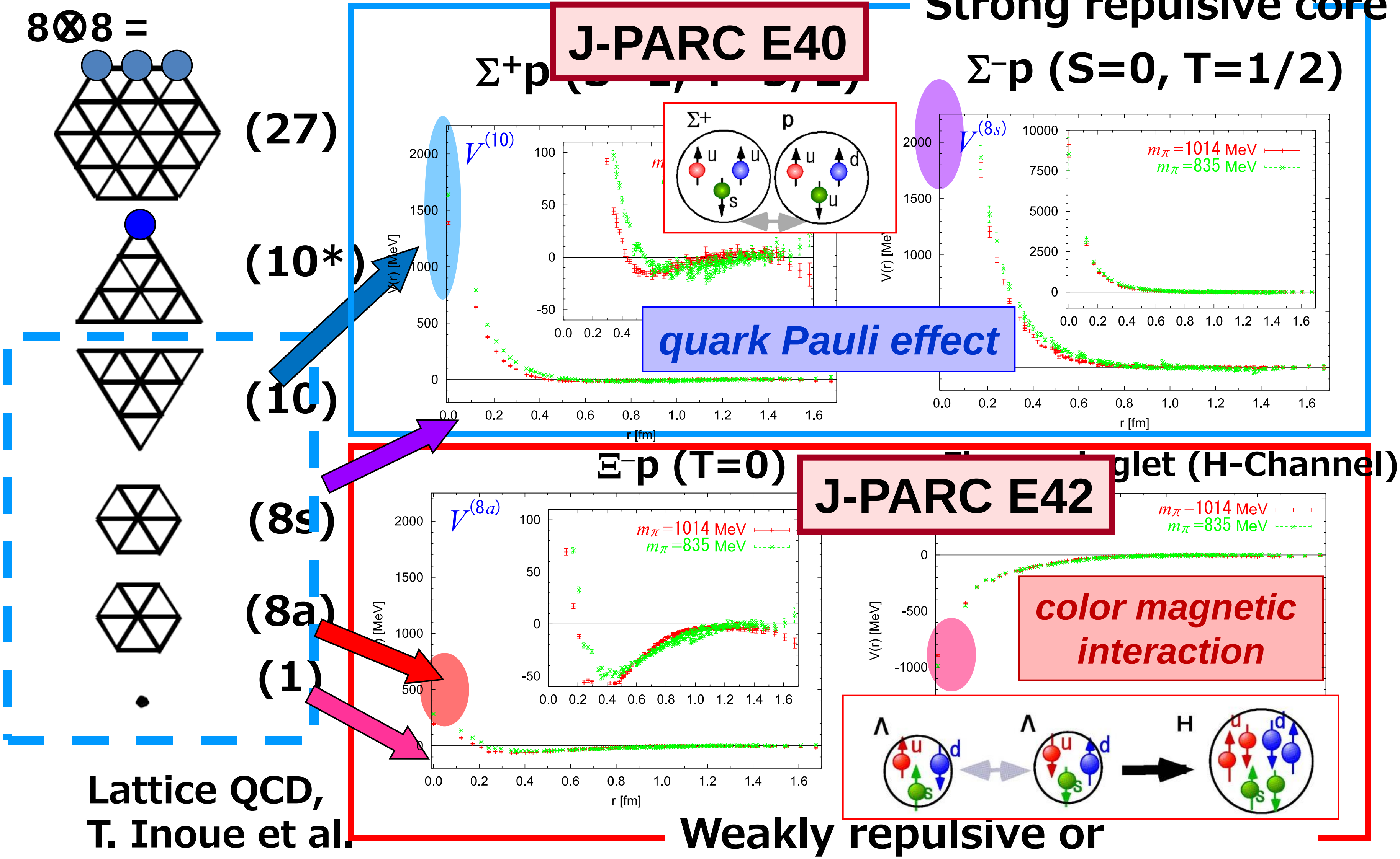
Lattice QCD,
T. Inoue et al.
Prog. Theor. Phys. 124 (2010)

Slide by Koji Miwa

Ba CD

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

6 independent forces in flavor SU(3) symmetry



$8 \otimes 8 =$

(27)

(10*)

(10)

(8s)

(8a)

(1)

Strong repulsive core

J-PARC E40

Σ^+p (S=1, T=3/2)

Σ^-p (S=0, T=1/2)

quark Pauli effect

Ξ^-p (T=0)

Flavor singlet (H-Channel)

J-PARC E42

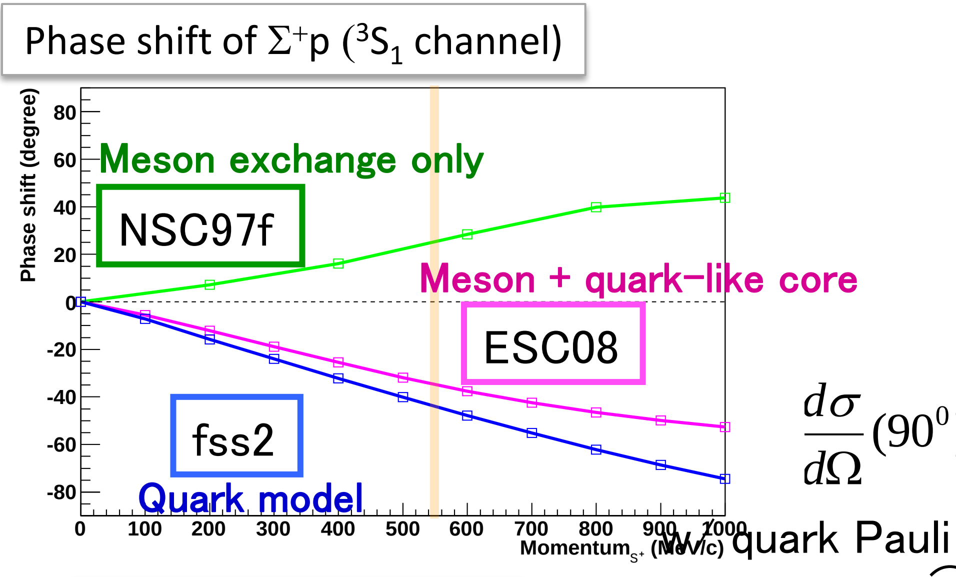
color magnetic interaction

Weakly repulsive or attractive Core

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

Slide by Koji Miwa

E40: Phase shift of $^3S_1$ channel

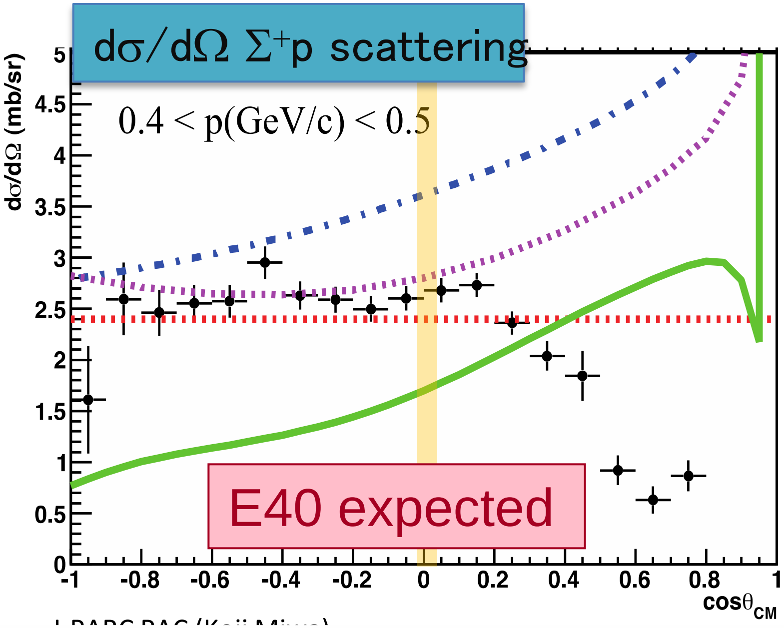


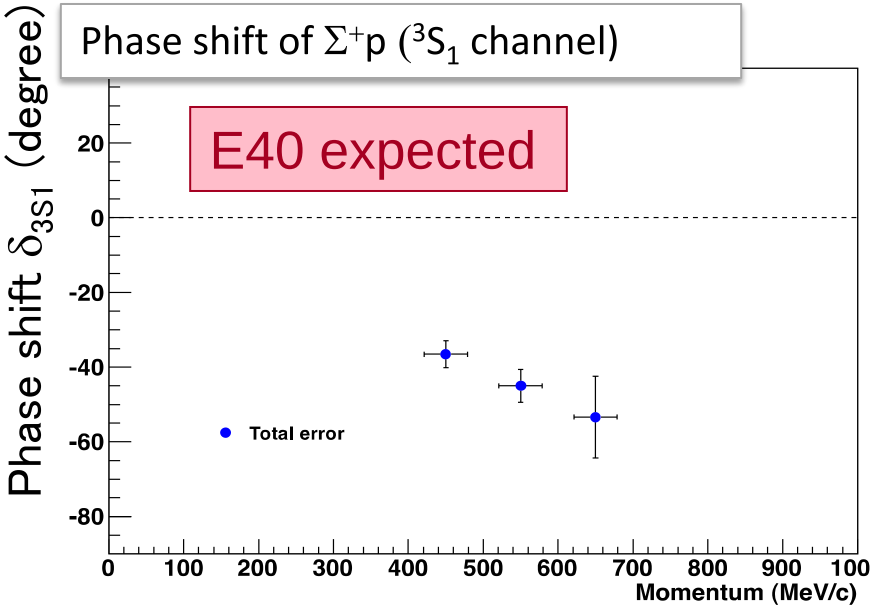
- Energy dependence of δ_{3S1} from $d\sigma/d\Omega(90^o)$

Negligibly small

Almost model-independent

$$\frac{d\sigma}{d\Omega}(90^0)=\boxed{\frac{1}{4}\frac{1}{k^2}\sin^2\delta_{1S0}}+\boxed{\frac{3}{4}\frac{1}{k^2}\sin^2\delta_{3S1}}+\boxed{(\text{higher waves})}$$





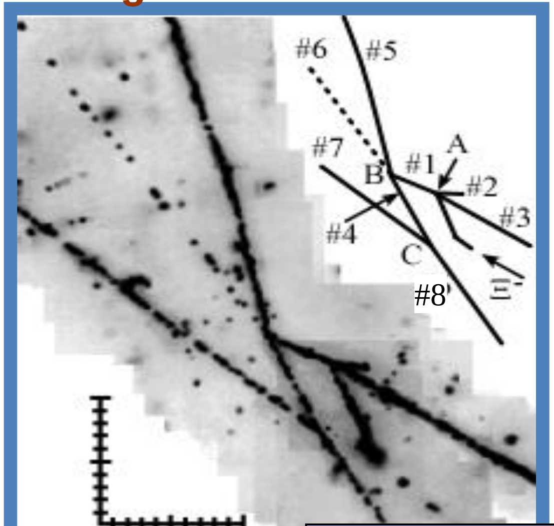
Σ^+ beam momentum (MeV/c)

4. Double Strange Systems

$\Lambda\Lambda$ hypernuclei via emulsion+counter hybrid method (KEK E373)

Nakazawa (Hyp-X conf.)

Nagara event



${}^{6}_{\Lambda\Lambda}$He

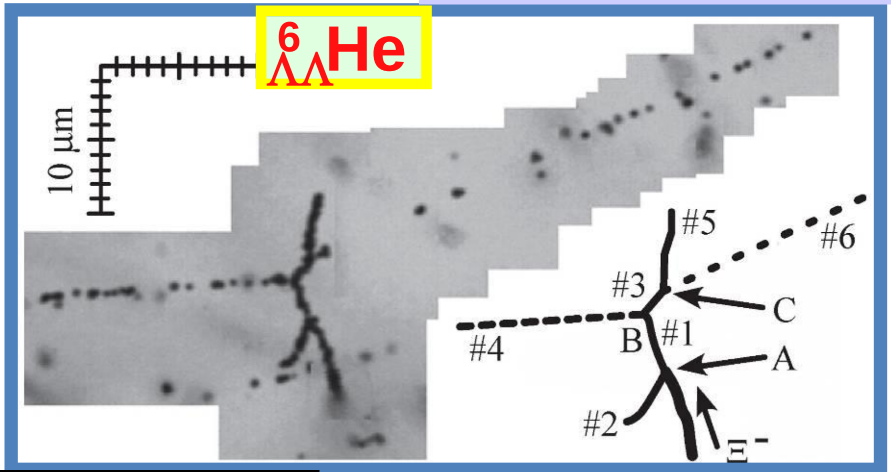
(unique and accurate)

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

PRL 87 (2001) 212502

Mikage event

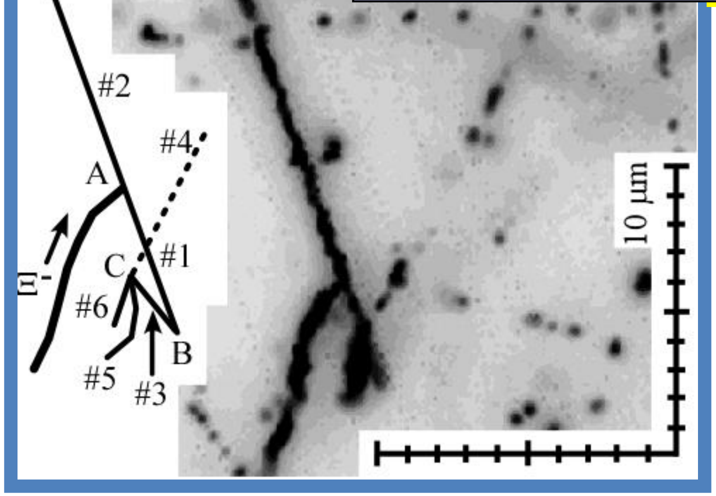
$\Delta B_{\Lambda\Lambda}$= 3.82 ±1.72 MeV



${}^{6}_{\Lambda\Lambda}$He

=> $\Lambda\Lambda$ interaction is found to be weakly attractive

Demachi-yan



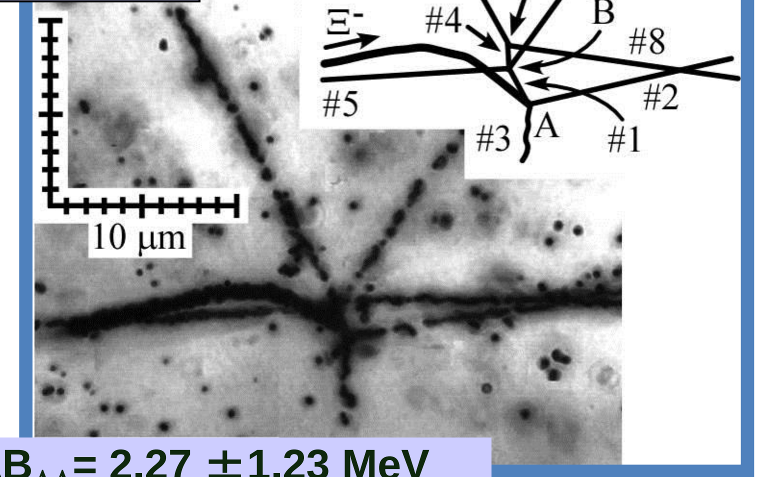
(w/ theoretical help)

$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0

cf. Ex = 3.0

ent

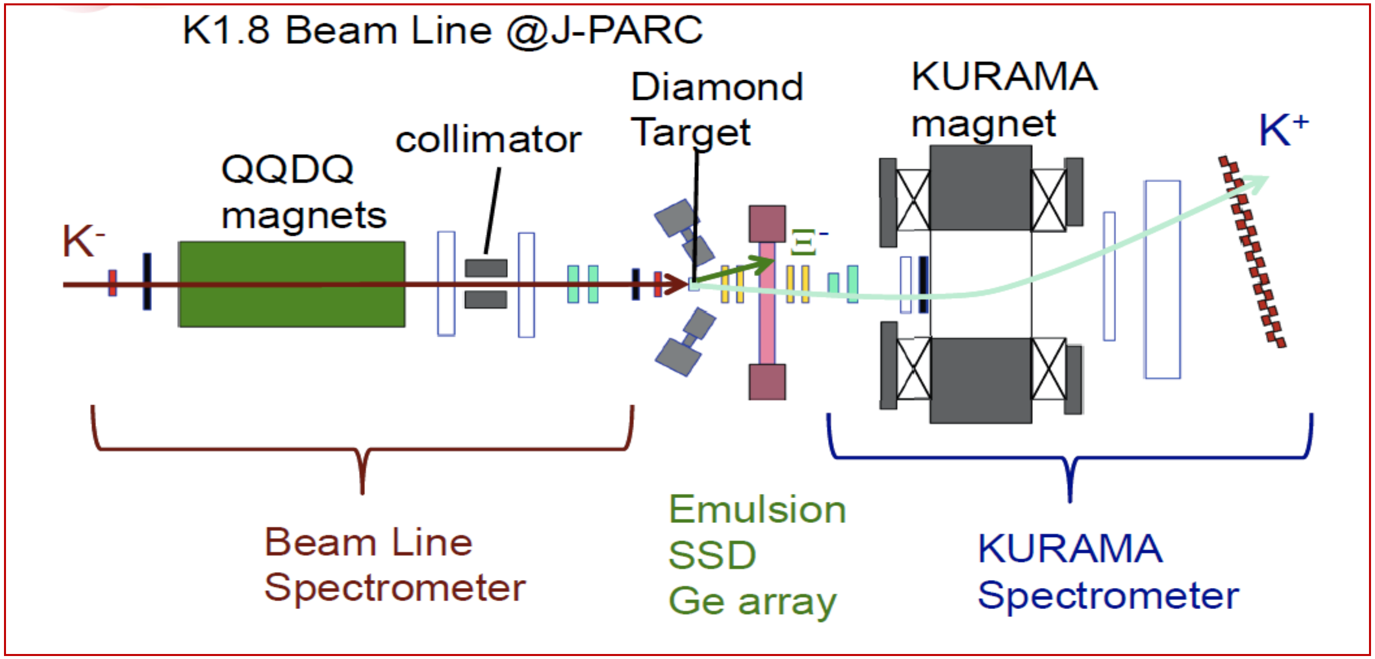
${}^{11}_{\Lambda\Lambda}$Be

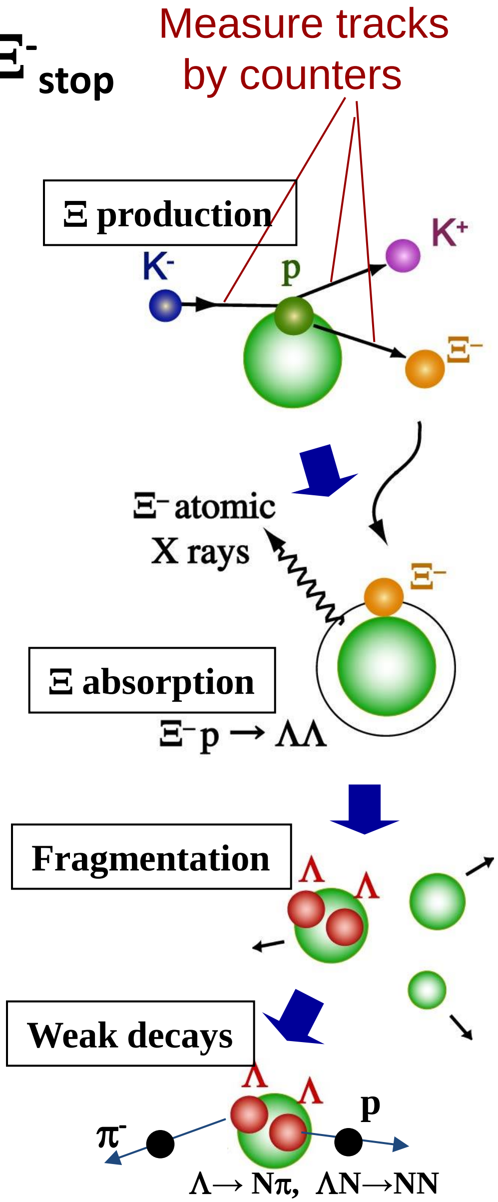


$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

J-PARC E07 (Nakazawa, Imai, Tamura et al.)
S=-2 Systems with Emulsion-Counter Hybrid Method

- Collect $\sim 10^2$ ΛΛ hypernuclear events from $\sim 10^4$ Ξ^-_{stop}
  - Confirm ΛΛ interaction strength
  - Λ–Λ correlation in nucleus from "ΛΛ" -> $\Sigma^- p$ decay
- Measure Ξ^- -atomic X-rays with Ge detectors
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Stopped Ξ^- events identified from emulsion image –> almost no background

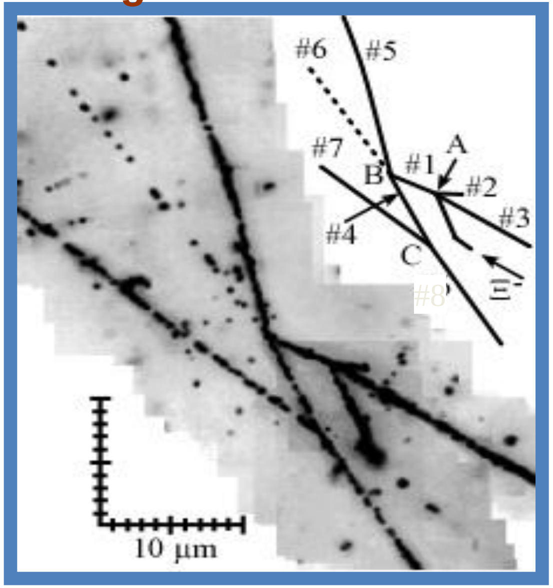




Slide by Nakazawa

ΛΛ hypernuclei (KEK E373)

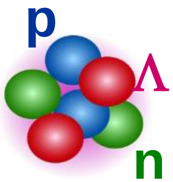
Nagara event



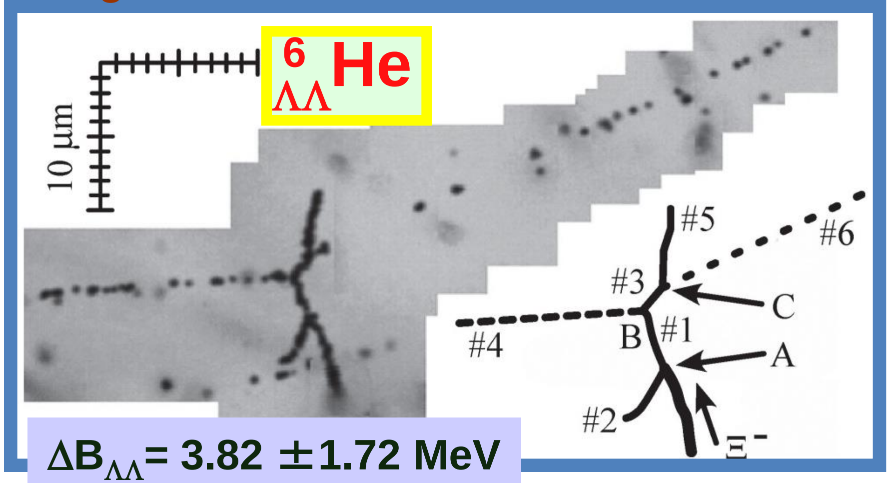
$^{6}_{\Lambda\Lambda}$He

(unique and accurate)

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



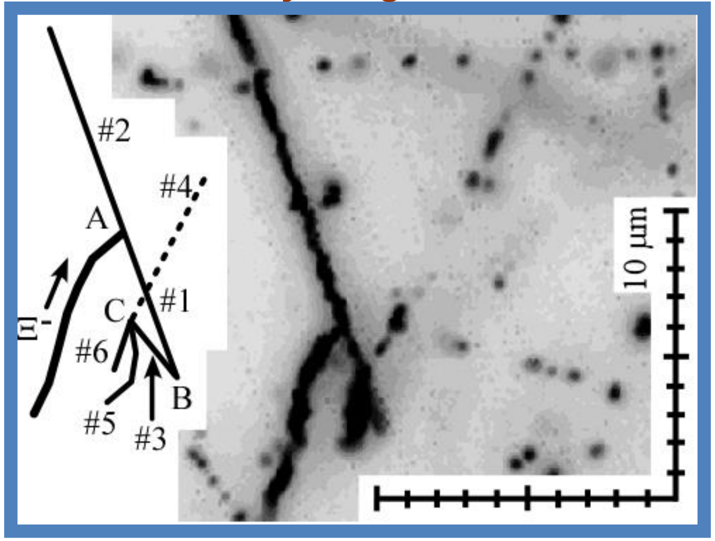
Mikage event



$^{6}_{\Lambda\Lambda}$He

$\Delta B_{\Lambda\Lambda}$= 3.82 ±1.72 MeV

Demachi-yanagi event

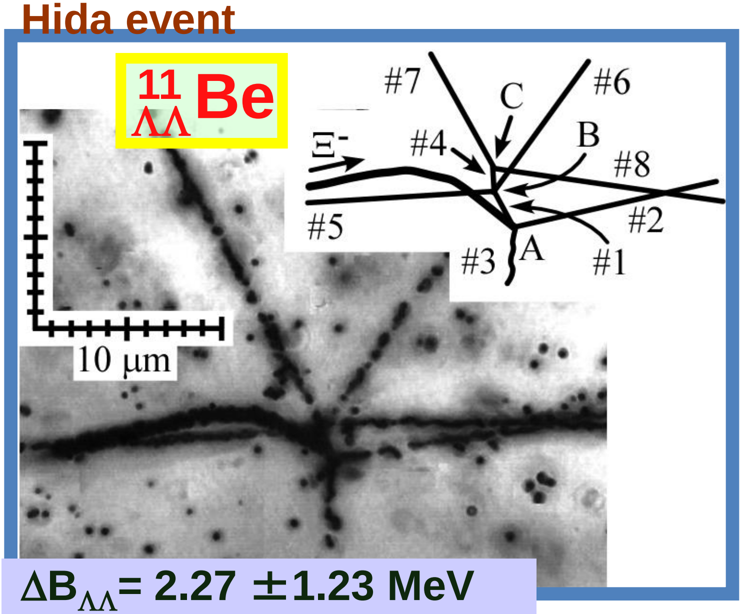


$^{10}_{\Lambda\Lambda}$Be*

(w/ theoretical help)

$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0(*Ex*)

Hida event



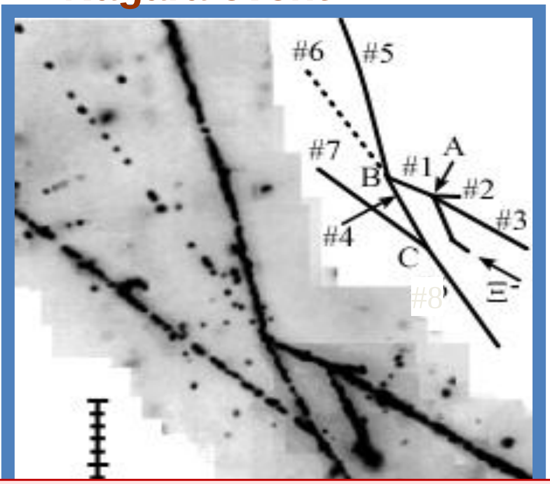
$^{11}_{\Lambda\Lambda}$Be

$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

Slide by Nakazawa

ΛΛ hypernuclei (KEK E373)

Nagara event



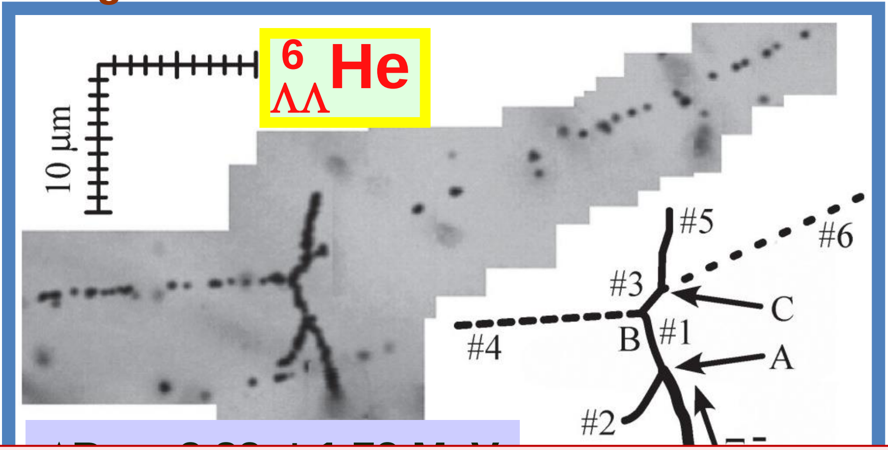
$^{6}_{\Lambda\Lambda}\mathrm{He}$

(unique and accurate)

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

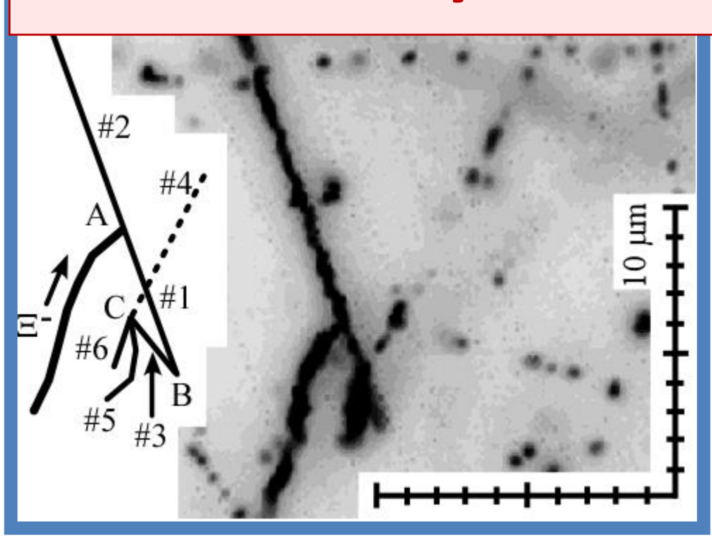
p

Mikage event



$^{6}_{\Lambda\Lambda}\mathrm{He}$

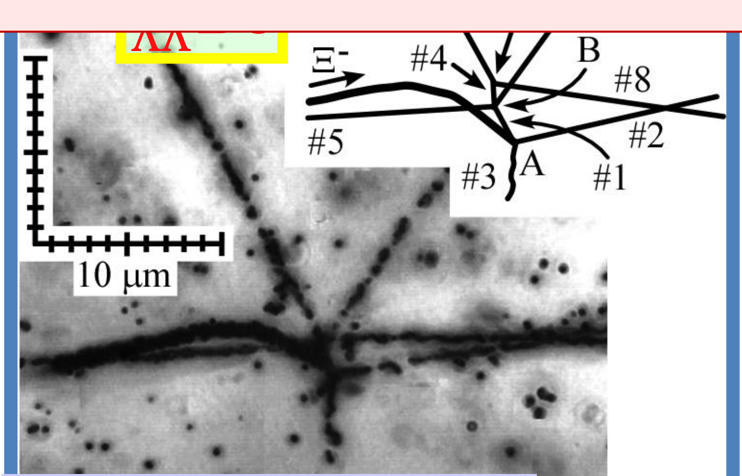
Overall scanning method has been successfully developed.
Reanalysis of E373 data – new events coming!



$^{10}_{\Lambda\Lambda}\mathrm{Be}^*$

(w/ theoretical help)

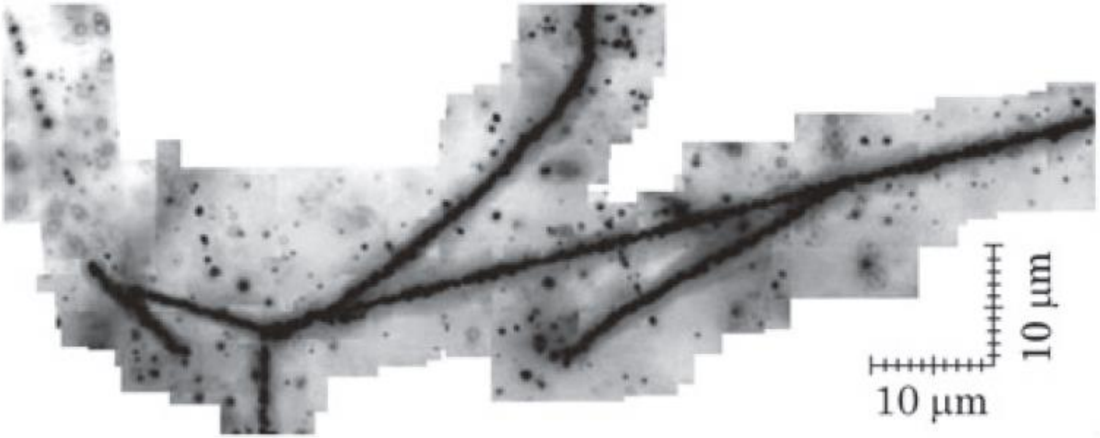
$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0(*Ex*)

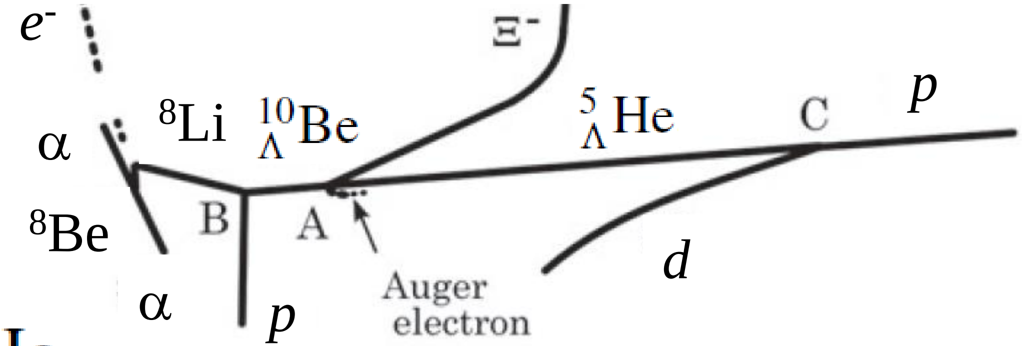


$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

“Kiso event” found by overall scanning method

K. Nakazawa et al.
PTEP 2015, 033D02





uniquely identified as

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

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

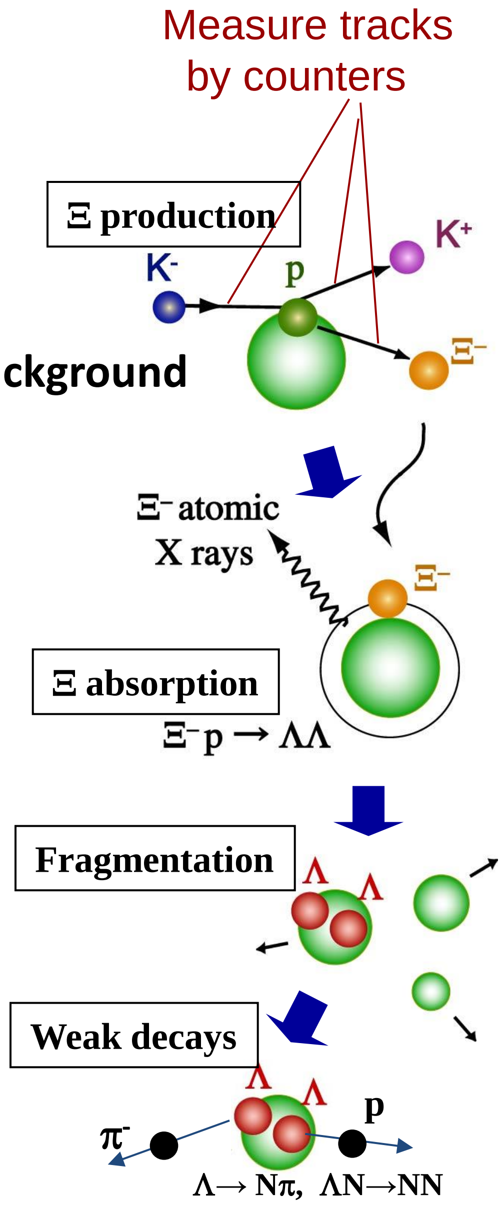
$^{10}_{\Lambda}$Be production: in the ground state in the highest excited state

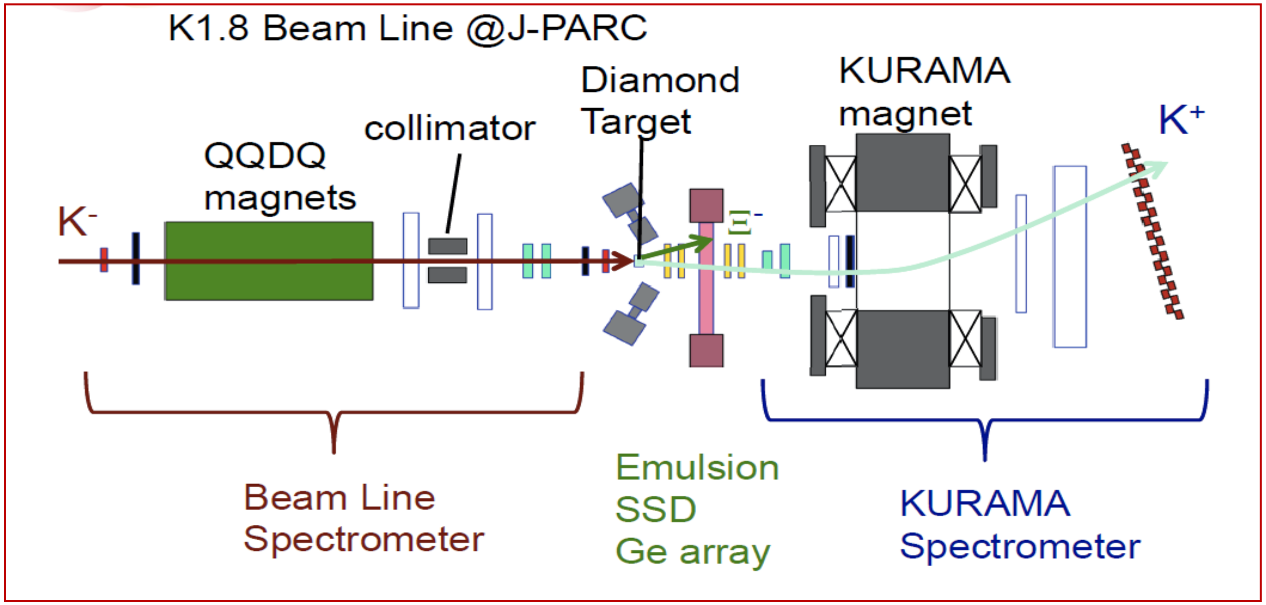
>> 3*D* atomic state of the Ξ^-–^{14}N system (0.17 MeV)

First evidence of a deeply bound Ξ state

J-PARC E07: S=-2 Systems by emulsion

- Collect ~10^2 ΛΛ hypernuclear events from ~10^4 Ξ^-_{stop}
  - ΛΛ interaction strength (nuclear dependence)
  - Λ–Λ correlation in nucleus from "ΛΛ" -> Σ^-p decay
- Measure Ξ^- -atomic X-rays with Ge detectors
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Stopped Ξ^- events identified from emulsion image –> no background



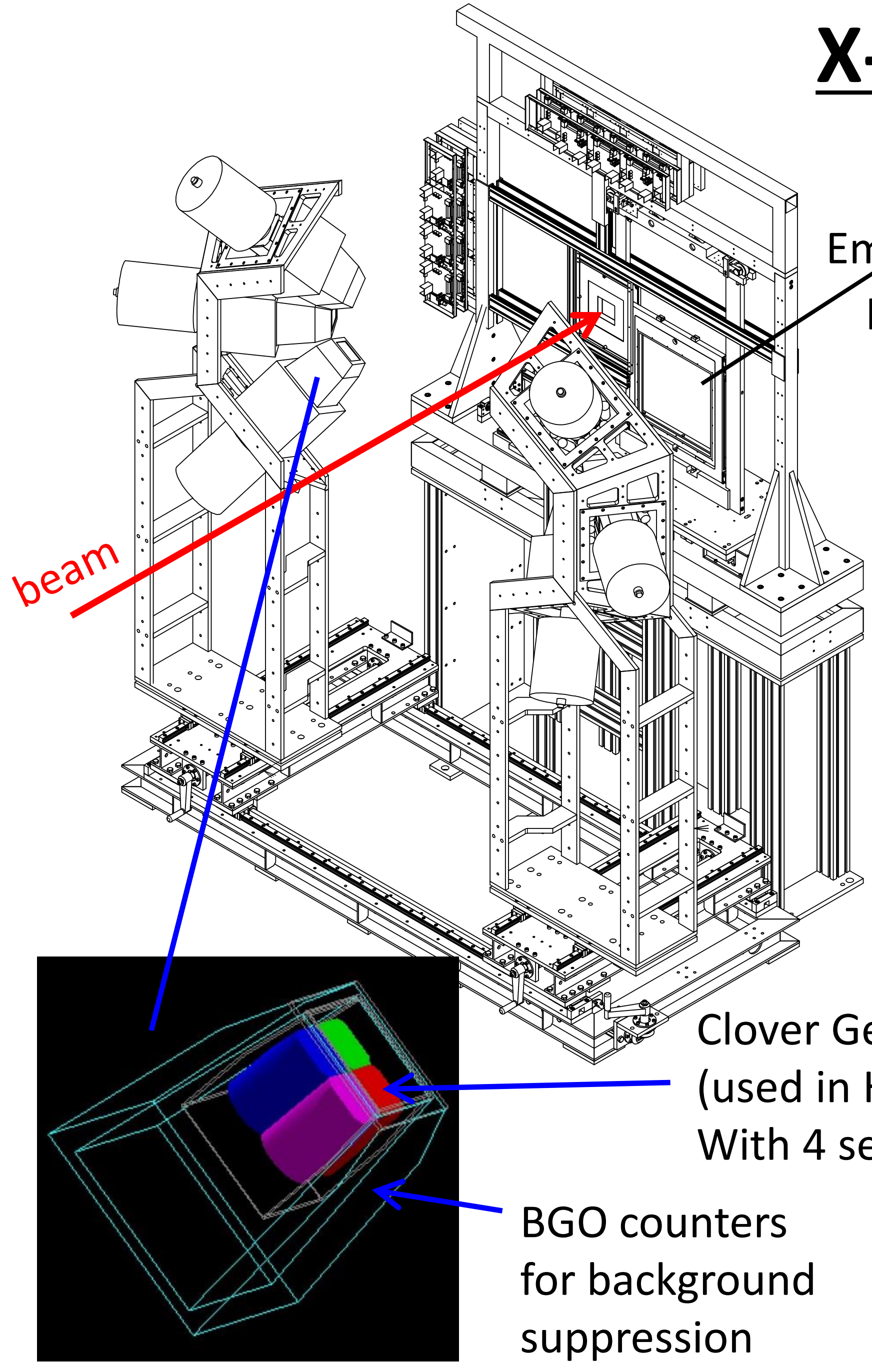


Emulsion and all the counters are ready.
Emulsion beam test experiment is running now.
Switchover SKS -> KURAMA in November 2015

X-ray detector "Hyperball-X"

(Tohoku U./JAEA)

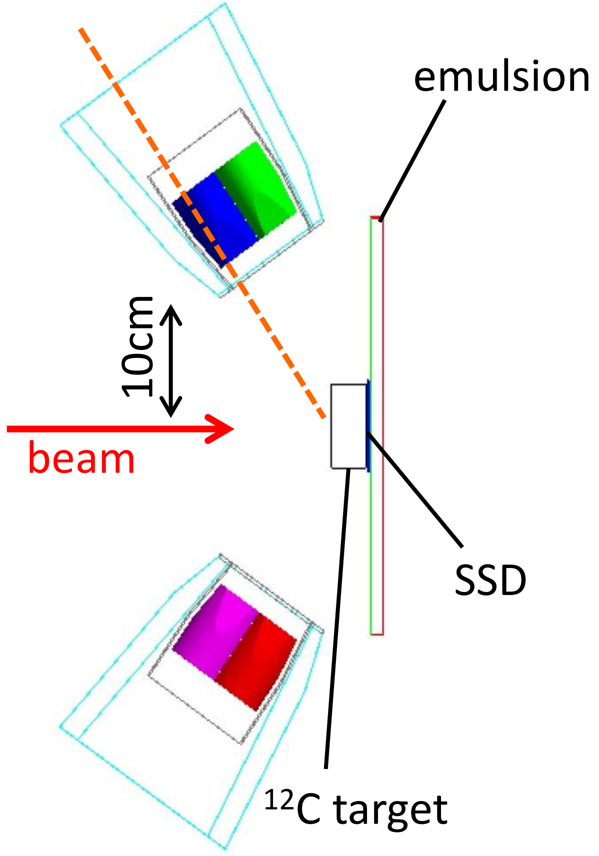
designed by K. Hosomi



Emulsion plate

Clover Ge
(used in Hyperball2)
With 4 segments

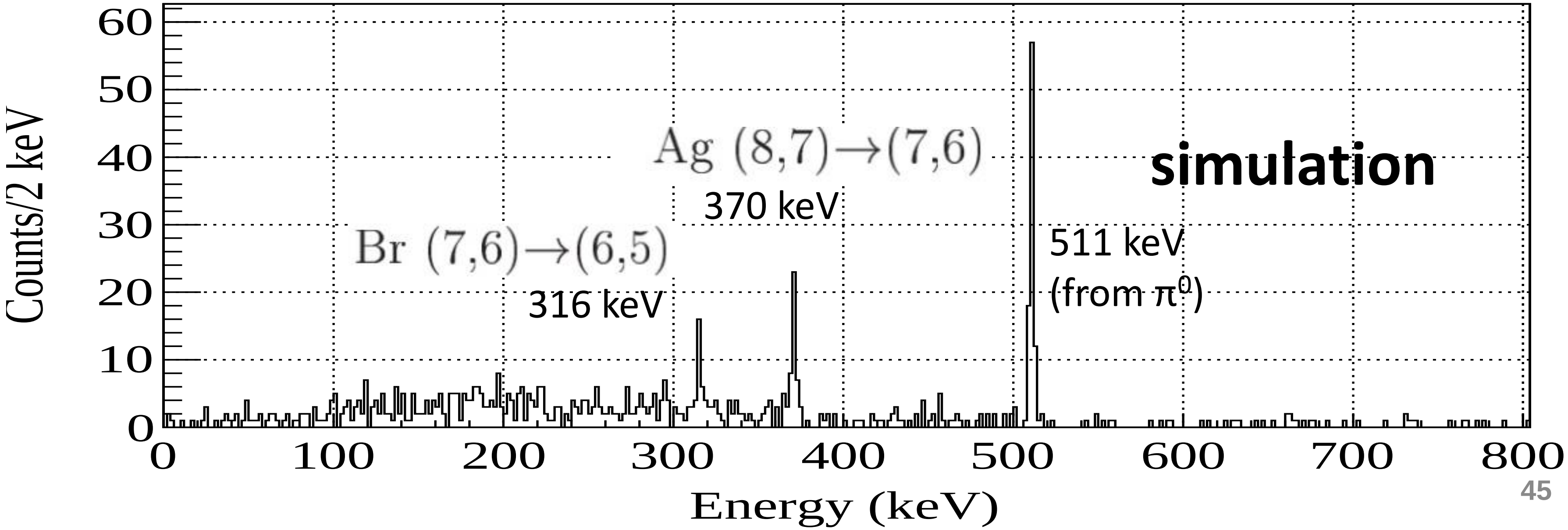
BGO counters
for background
suppression



ε_{photo} = 2.3% @ 350 keV
including absorption
at emulsion and 12C (diamond) target

Expected Spectrum (by Hosomi)

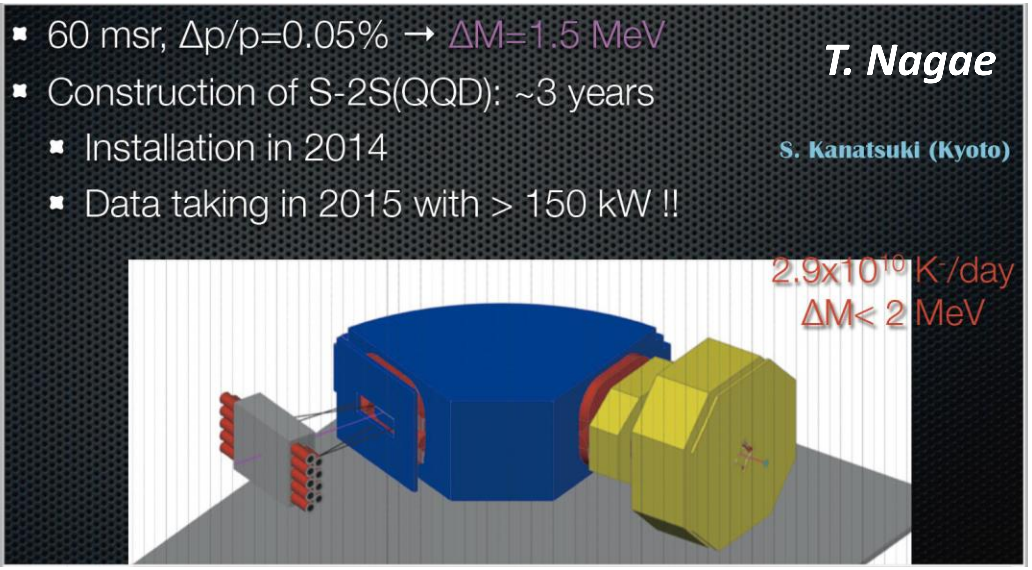
- 10000Ξ stop events tagged in emulsion
- X-ray yield
  - Y_{stop} x Eff_X x Eff_{Ge} = Br(316 keV) 18 counts, Ag(370 keV) 33 counts
- background
  - ΞN->ΛΛ Λ->nπ^0: 580 events
  - Accidental: 150 events (Ge single rate: ~20kHz)
- Ge resolution: 2keV FWHM
  - Statistical errors Br(316 keV): ±400 eV, Ag(370 keV): ± 200 eV



J-PARC E05 (Nagae et al.) $K^- p \rightarrow \Xi^- K^+$
Ξ-hypernuclear spectroscopy by (K^-,K^+)

Properties of ΞN interaction

- Attractive or repulsive? How large?
  Ξ appears in neutron stars?
- Isospin dependence from different targets
- ΞN-ΛΛ coupling force from
  - Ξp→ΛΛ conversion width
  - Ξ /ΛΛ mixing states



- 60 msr, $\Delta p/p$=0.05% → ΔM=1.5 MeV
- Construction of S-2S(QQD): ~3 years
  - Installation in 2014
  - Data taking in 2015 with > 150 kW !!

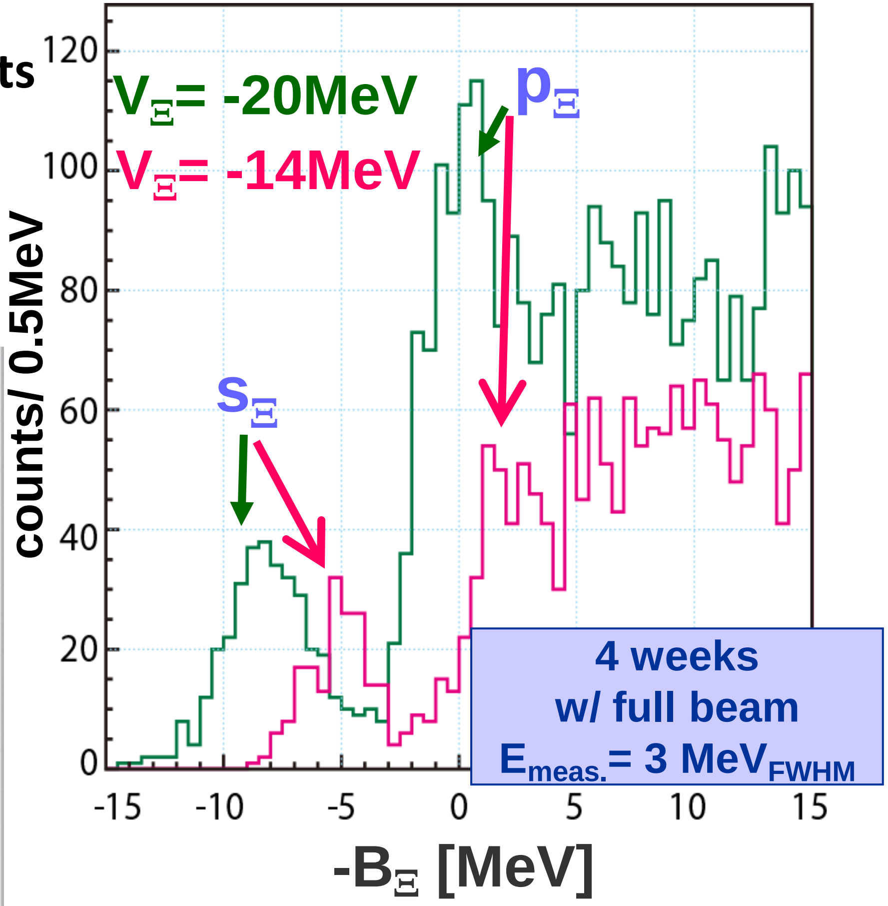
T. Nagae

S. Kanatsuki (Kyoto)

2.9×10^{10} K^-/day
ΔM< 2 MeV

New spectrometer (S-2S) is under construction

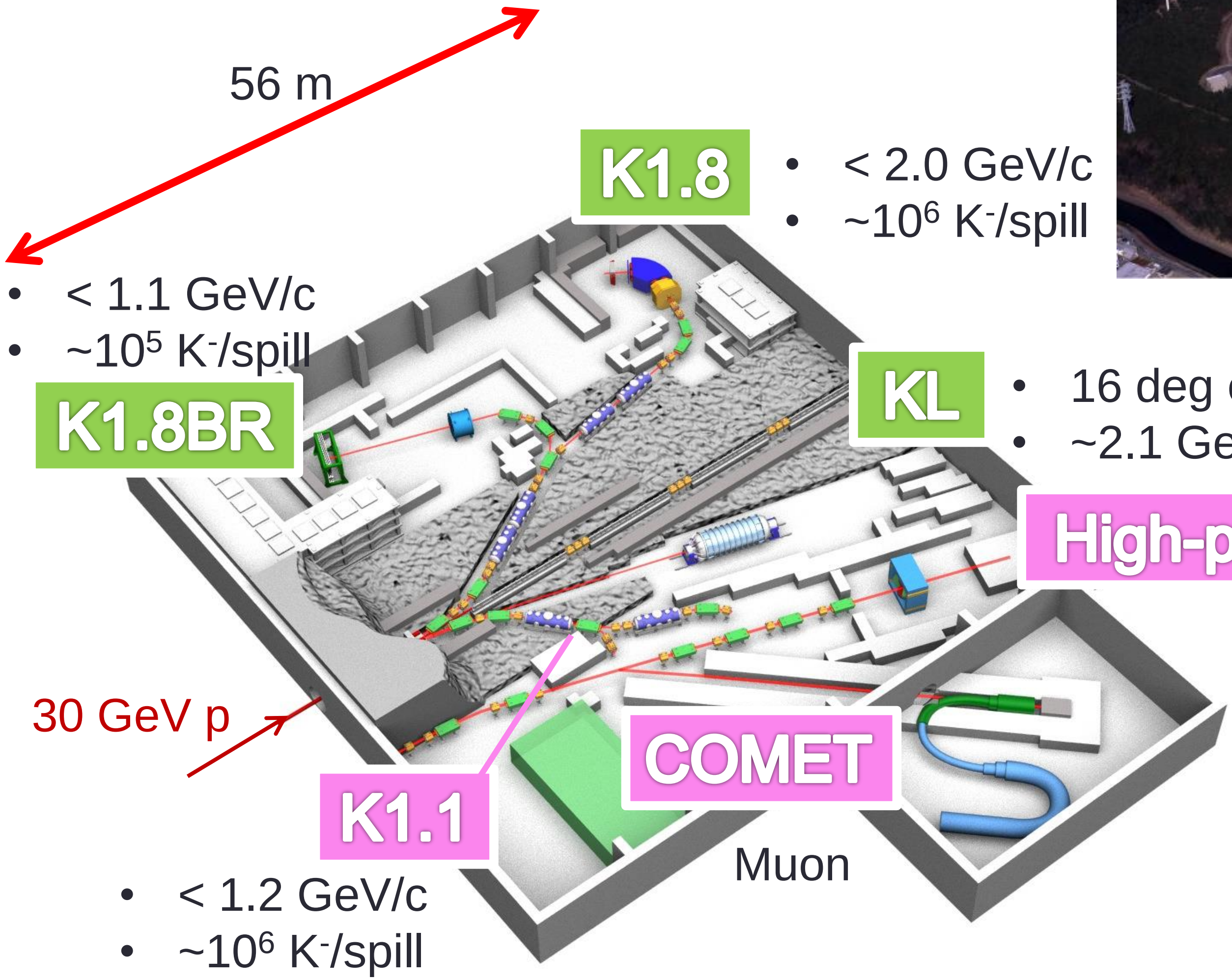
Expected $^{12}C(K^-,K^+)\,^{12}_{\Xi}Be$ Spectrum



4 weeks
w/ full beam
$E_{meas.}$= 3 MeV_{FWHM}

4. Future Plan:
Extension of Hadron Hall

Present Hadron Hall



56 m

K1.8

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

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

K1.8BR

KL

- 16 deg extraction
- ~2.1 GeV/c K^0

High-p

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

30 GeV p

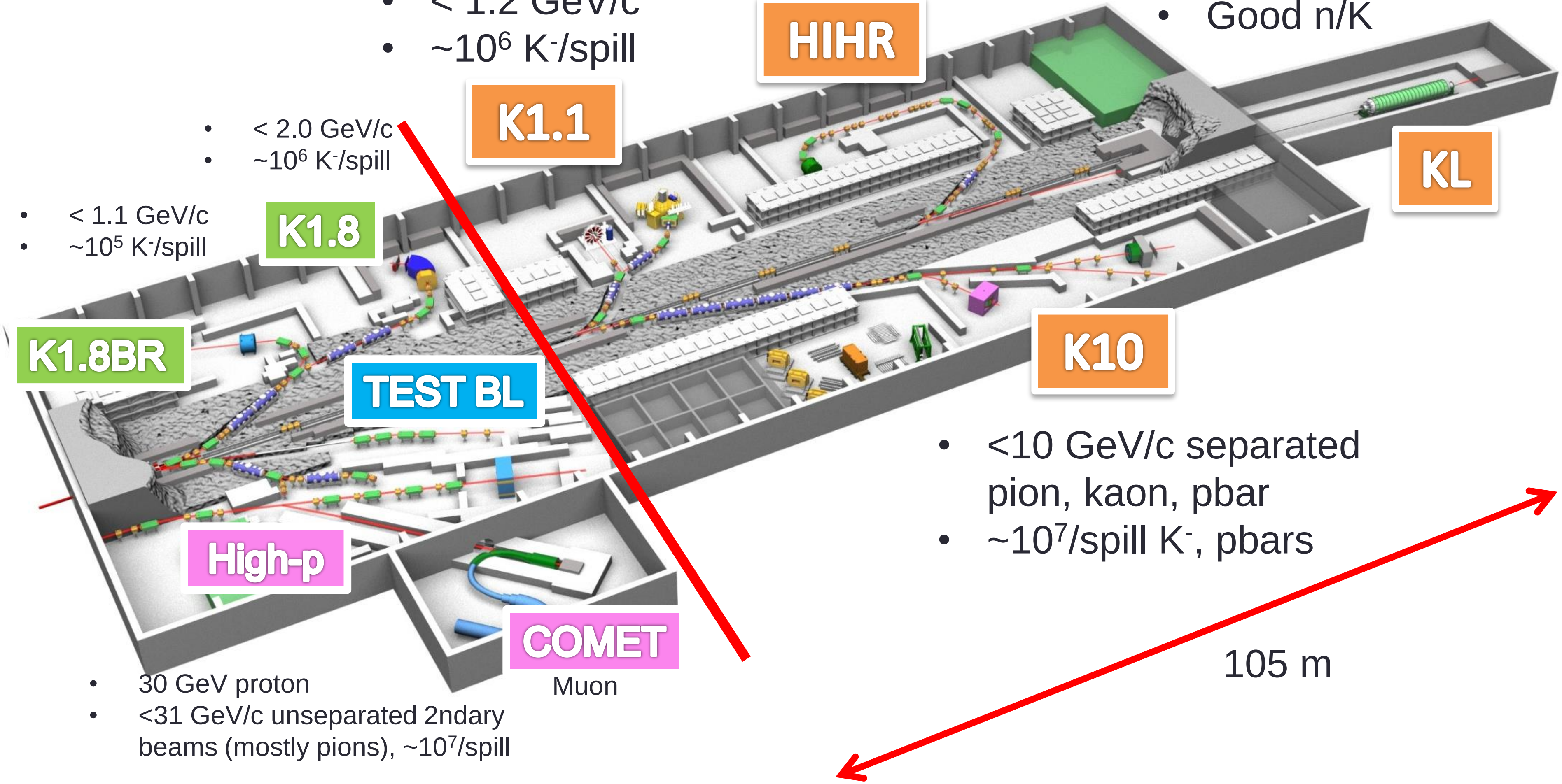
K1.1

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

COMET

Muon

Extended Hadron Hall (Plan)



- < 2.0 GeV/c
- 1.8×10^8 pion/spill
- x10 better $\Delta p/p$

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

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

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

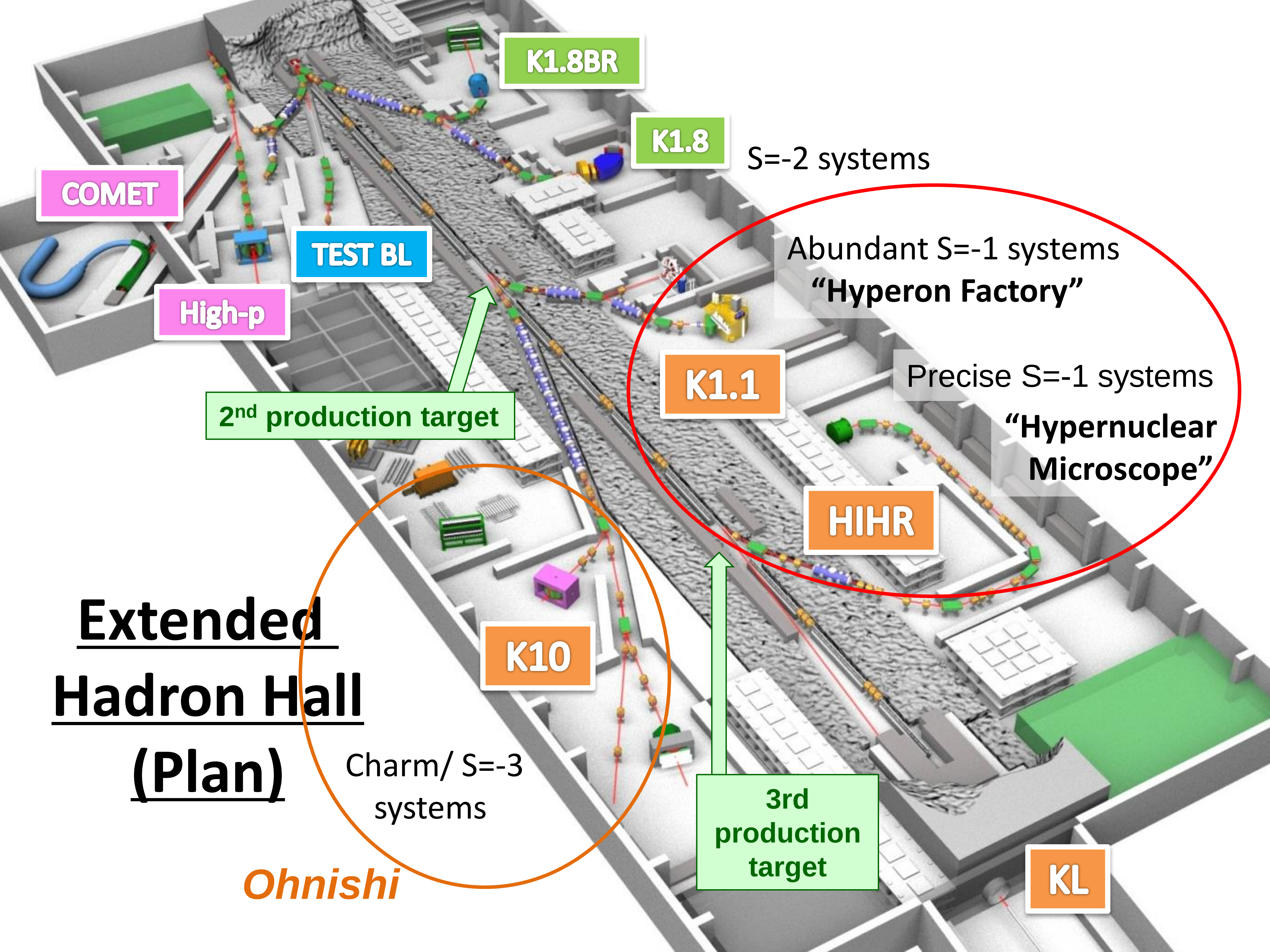
- < 1.1 GeV/c
- ~10^5 K^-/spill

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

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

Muon

Extended Hadron Hall (Plan)



S=-2 systems

Abundant S=-1 systems
"Hyperon Factory"

Precise S=-1 systems
"Hypernuclear Microscope"

2nd production target

3rd production target

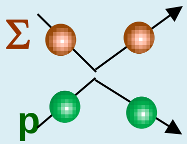
Charm/ S=-3 systems

Ohnishi

K1.1 beam line

Intense K beams for abundant production of S=-1 hyperons and kaons

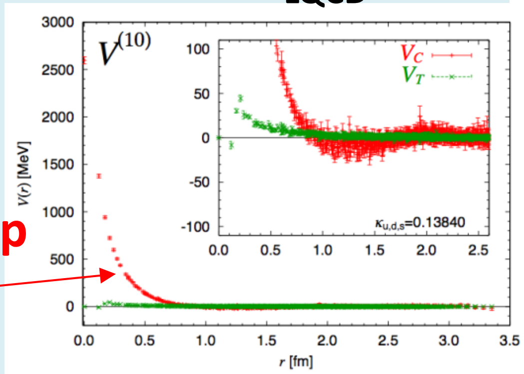
Establish B-B interactions



Σp, Λp scattering

High statistical data of dσ/dΩ
and spin observables with wide p

LQCD



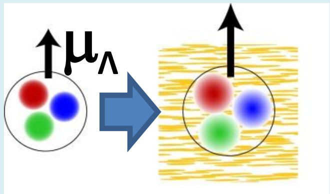
Quark Pauli effect in Σ^+p (S=1) channel
-> one of the origins of BB repulsive core

Precise 2-body data essential to extract many-body effects in hypernuclei

Modification of baryons in nuclei

Energy levels, γ-transition rates,
Weak decay rates

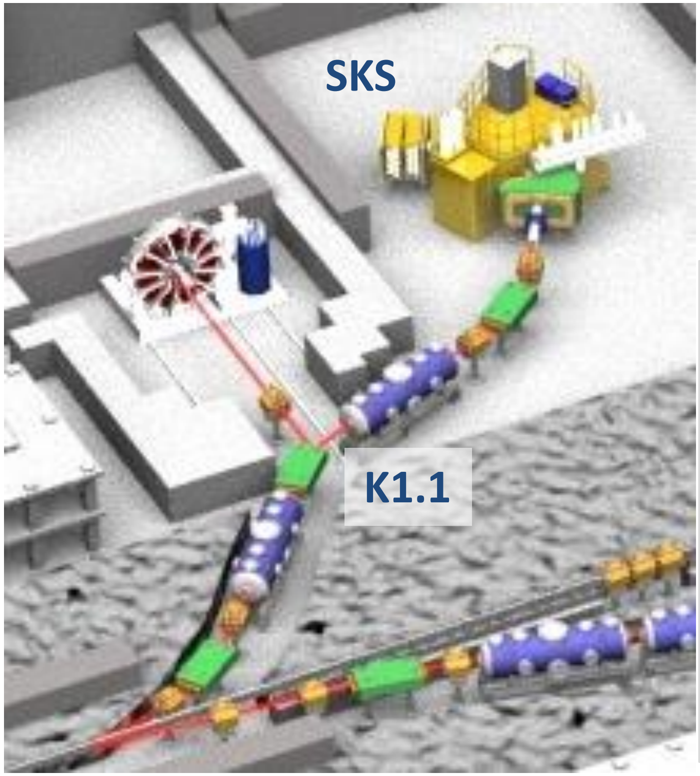
Hypernuclear γ-ray spectroscopy (magnetic moment,
Hypernuclear weak decays Precise structure)



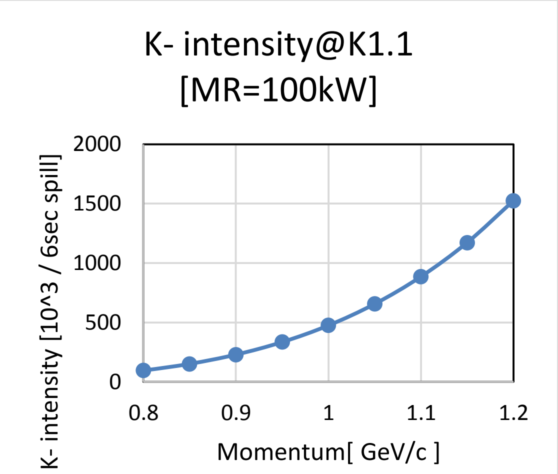
Effect of partial restoration of chiral symmetry?

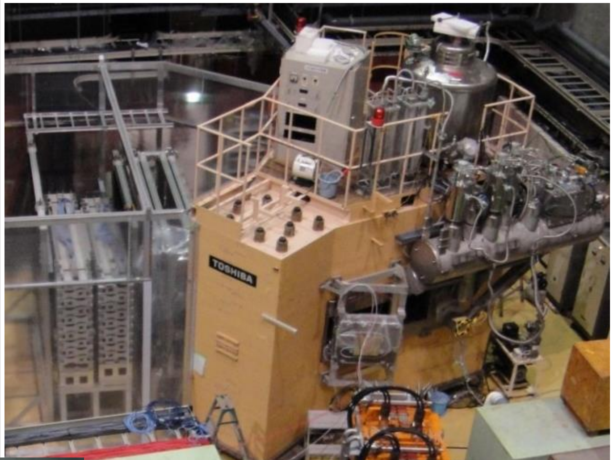
K- atomic X-rays, K- and other mesons in nuclei, ...

K1.1 beam line



- $\pi^{\pm}$, $K^{\pm}$, p^{bar} up to 1.2 GeV/c
- K- intensity ~10^6 /spill（K/π~1）
- Will be moved from the existing hall



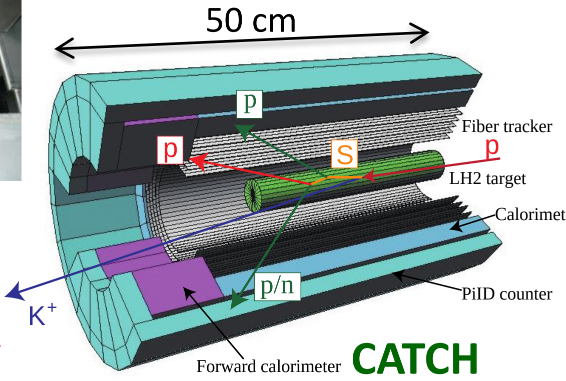


Make best use of the already developed methods and apparatus

Hyperball-J

SKS

- **Large acceptance spectrometer: SKS**
- **Ge detector array for hypernuclei: Hyperball-J**
- **Hyperon scatterinf detector: CATCH**
- **New detectors for weak decay particles and high-energy γ**



CATCH

High-Intensity High-Resolution line (HIHR)

Solve the hyperon puzzle in neutron stars

High resolution (π,K^+) hypernuclear spectroscopy

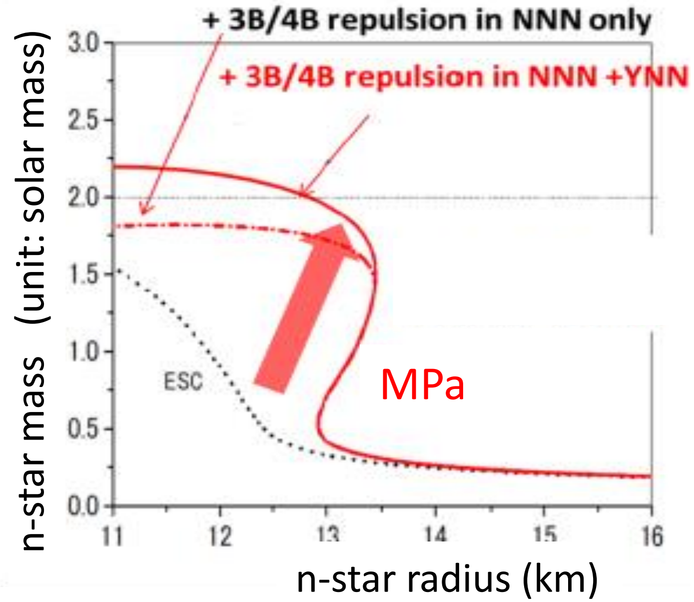
Precise B_Λ data for a wide range of Λ hypernuclei

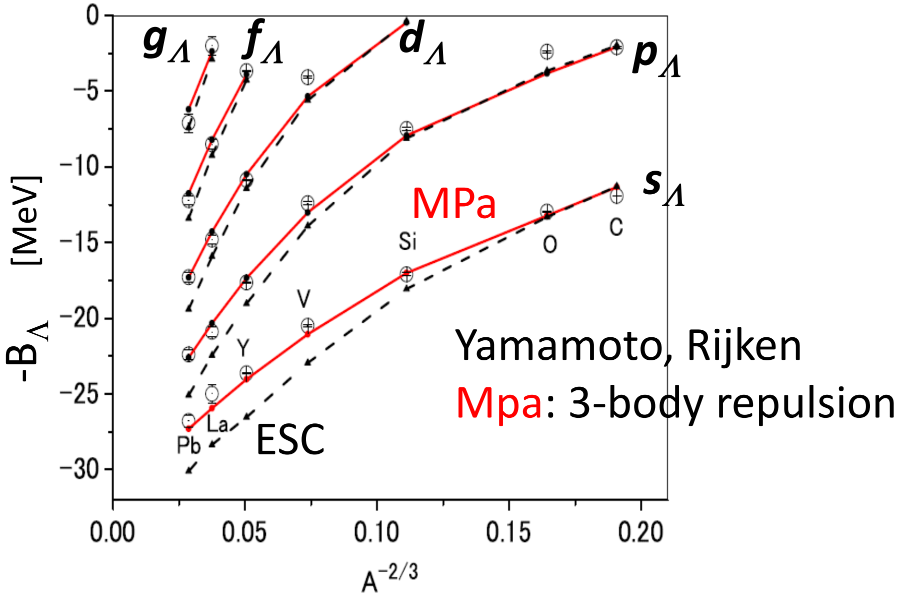
-> Density dependence of ΛN interaction (~ΛNN 3-body force）necessary to solve the "hyperon puzzle"

A few 100keV resolution is necessary

-> Momentum dispersion matching beam line and spectrometer

Very high intensity π beams can be utilized（～180Mpion/spill）

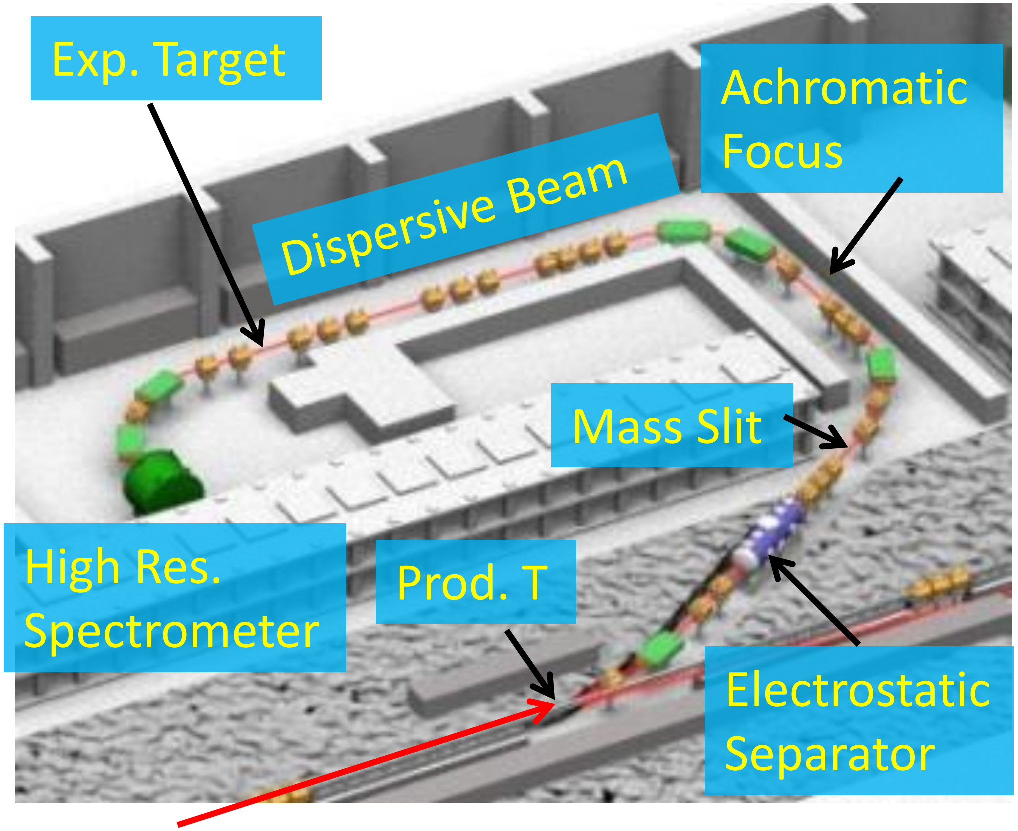


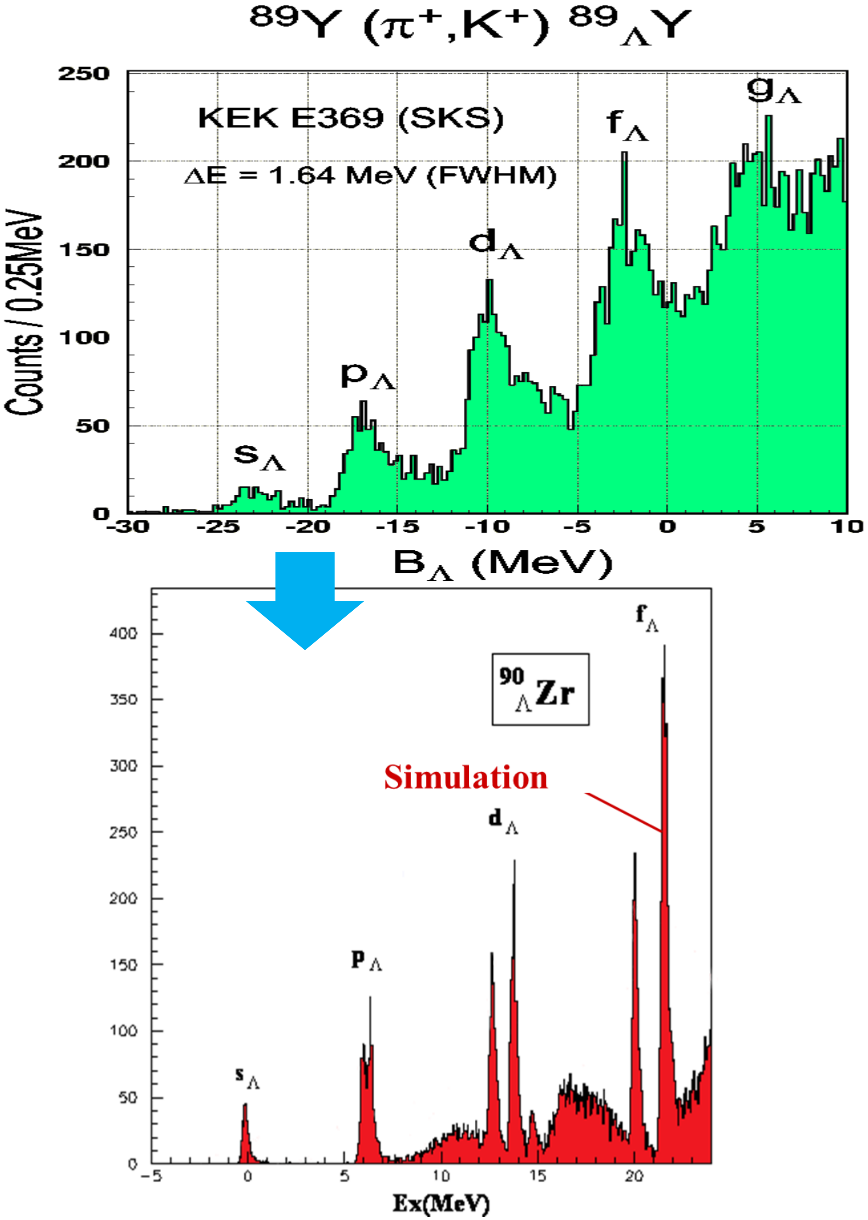


Yamamoto, Rijken

Mpa: 3-body repulsion

High-Intensity High-Resolution line (HIHR)





Intensity: ~ 1.8x10^8 pion/pulse
(1.2 GeV/c, 50 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)
Δp/p ~ 1/10000 (Δm~200 keV)

Prospect

- Selected in the 27 most important large projects in Japan Science Council's "Master Plan"
- Preparing for budget request
- Hope to start construction from 2018

- Call for LOI will be announced near future
  Experimentalist: Your LOIs are very welcome
  Theorists: Please give us your ideas and supports
- An international workshop will be held on March 5-6 at J-PARC.
  => Please join us!

Summary

- Strangeness NP studies BB forces, impurity effects, in-medium baryon properties and behavior, and also provides clues for neutron star matter.
- A large CSB was observed via ${}^{4}_{\Lambda}$He γ-ray measurement. ${}^{19}_{\Lambda}$F γ-rays were also observed.
- SNP at J-PARC is entering the S=-2 world.

  An emulsion experiment for $\Lambda\Lambda$ hyperuclei and Ξ atomic X-rays will run soon.

  A pilot run for ^{12}C(K-,K+) ${}^{12}_{\Xi}$Be was just carried out.

- **Hadron Hall extension plan is moving forward**