Study of ΛN interaction via the A=4 mirror Λ hypernuclei: $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$

Department of Physics
Tohoku University

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TORIJIN-EFES- FJNSP LIA * Joint Workshop on:

“Next Generation Detector System for Nuclear Physics with RI beams”

GANIL, February 14-15, 2008

February, 15

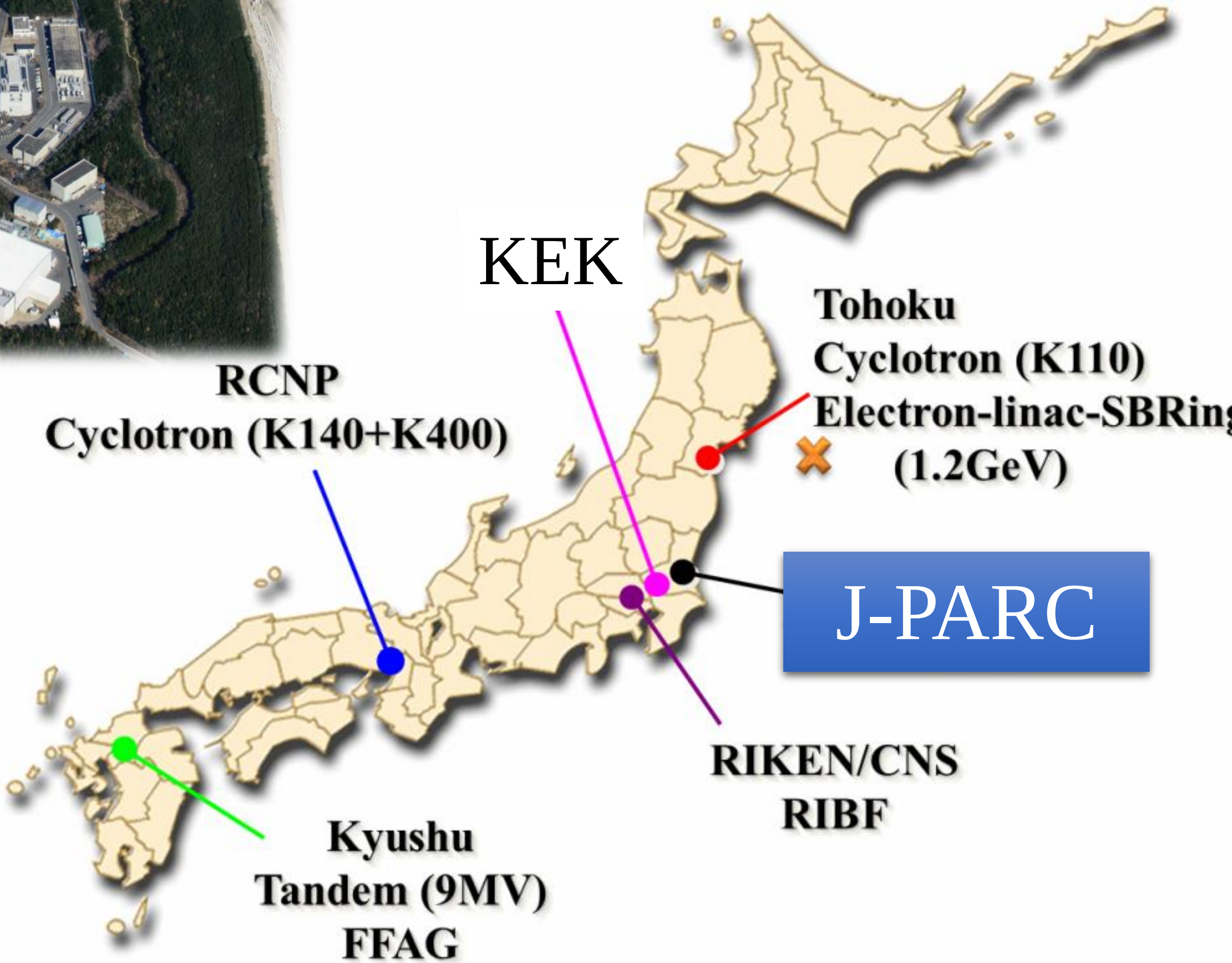
Gamma-ray arrays

9:00	EXOGAM2, the upgrade of EXOGAM: E Clement+M Tripon (GANIL)
9:30	Digital Signal Processing for Germanium Detector: H Fukuchi (RIKEN)
10:00	AGATA: C Theisen (SPhN)
10:30	Hyper Ball: T Koike (Tohoku)
11:30	New crystals: C. Dathy (Saint Gobain)
12:00	GASPARD: D Beaumel (IPNO)
12:30	PARIS : J.P. Wieleczko (GANIL)

Organizers:

Gilles de France (GANIL)
Patricia Roussel-Chomaz (GANIL)
Susumu Shimoura (CNS, University of Tokyo)
Tohru Motobayashi (RIKEN)


J-PARC


KEK
Tohoku
Cyclotron (K110)
Electron-linac-SBRing
(1.2GeV)
RCNP
Cyclotron (K140+K400)
J-PARC
RIKEN/CNS
RIBF
Kyushu
Tandem (9MV)
FFAG

Our story and data: *J. Radiol. Prot. 34 (2014) 675*

OPEN ACCESS
IOP Publishing | Society for Radiological Protection   Journal of Radiological Protection

J. Radiol. Prot. 34 (2014) 675–698   doi:10.1088/0952-4746/34/3/675

Selected as highlights of 2014

Comprehensive data on ionising radiation from Fukushima Daiichi nuclear power plant in the town of Miharu, Fukushima prefecture: The Misho Project

T Koike[1], Y Suzuki[2], S Genyu[3], I Kobayashi[4], H Komori[4], H Otsu[5], H Sakuma[6], K Sakuma[6], E M Sarausad[7,8], K Shimada[9], T Shinozuka[9], H Tamura[1], K Tsukada[1], M Ukai[1], T O Yamamoto[1] and for The Misho Project[2]

Contents

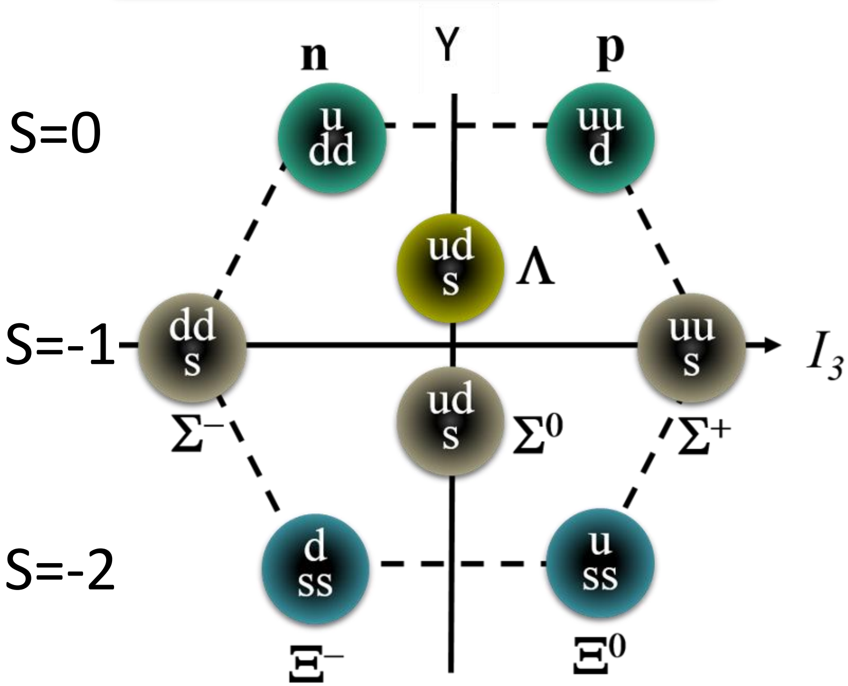
- Introduction
  - what we know about ΛN interaction
- Experimental confirmation of charge symmetry breaking in ΛN interaction
  - A=4 mirror Λ hypernuclei
- Theoretical studies
- Summary

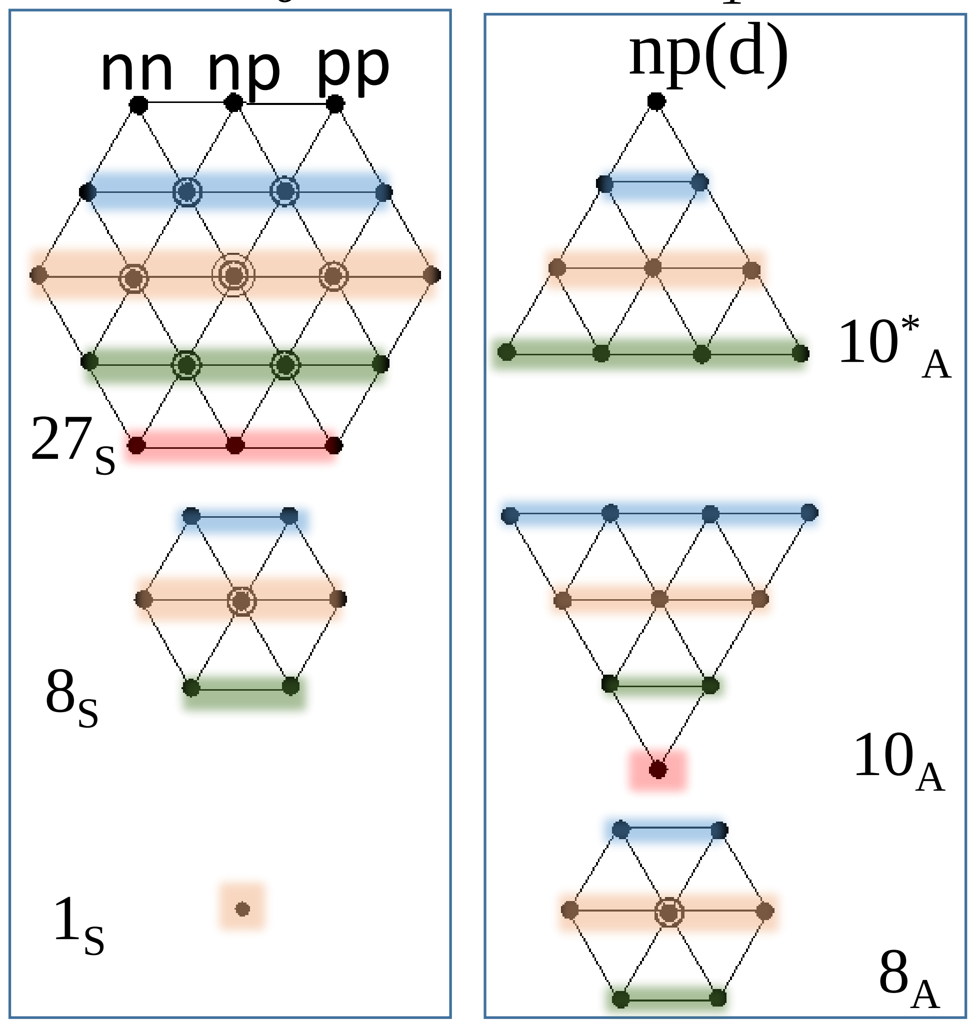
Baryon-Baryon interaction

$$8 \otimes 8 = \boxed{27_S \oplus 8_S \oplus 1_S} \oplus \boxed{10^*_A \oplus 10_A \oplus 8_A}$$

$^1S_0$ $\qquad$ $^3S_1$

Baryon octet: $J^{\pi}=1/2^{+}$





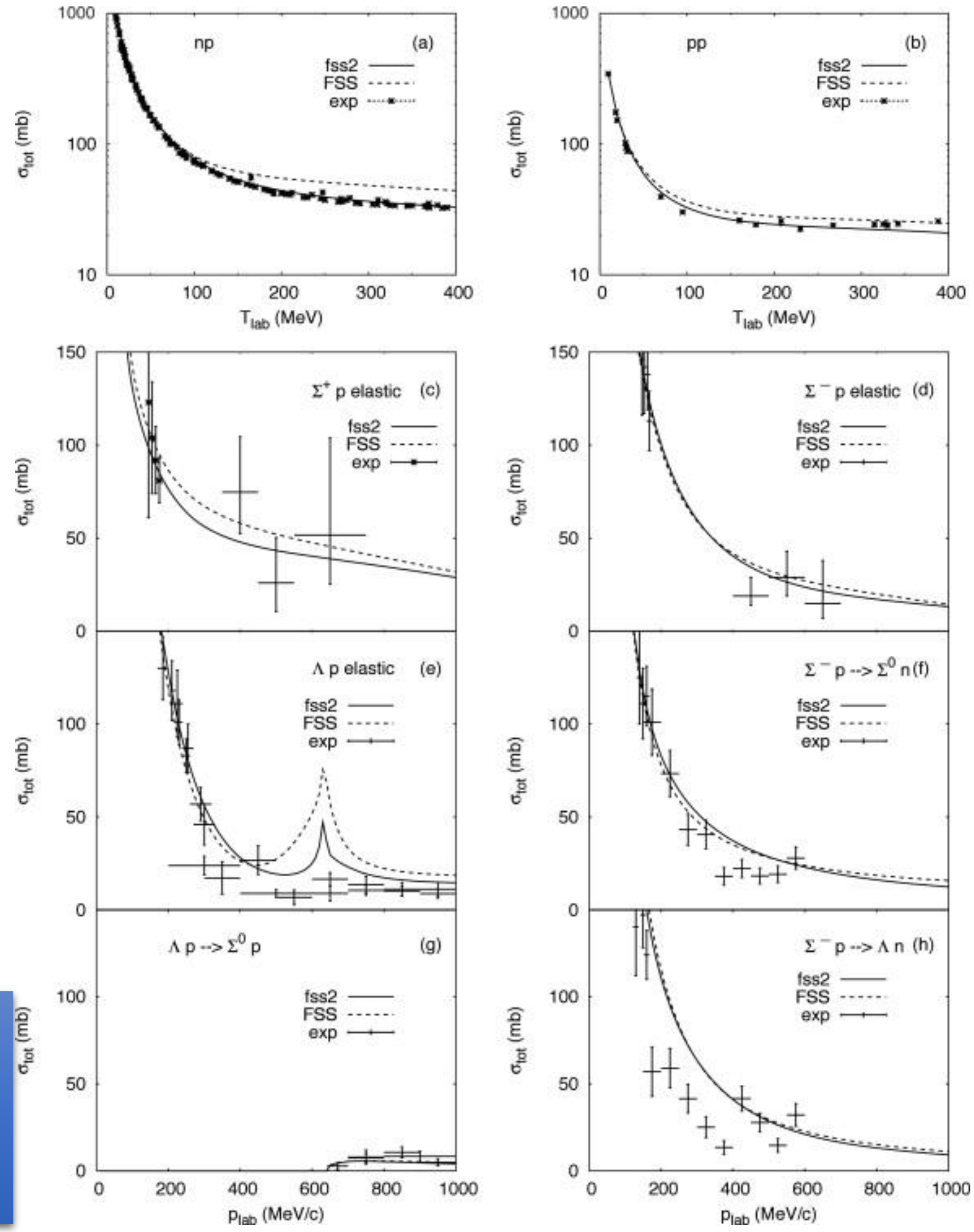
In SU(3)$_f$ limit, no mixing among different multiplets.

Difficulties of YN scattering experiments

NN data ～4000
YN data ～ 40

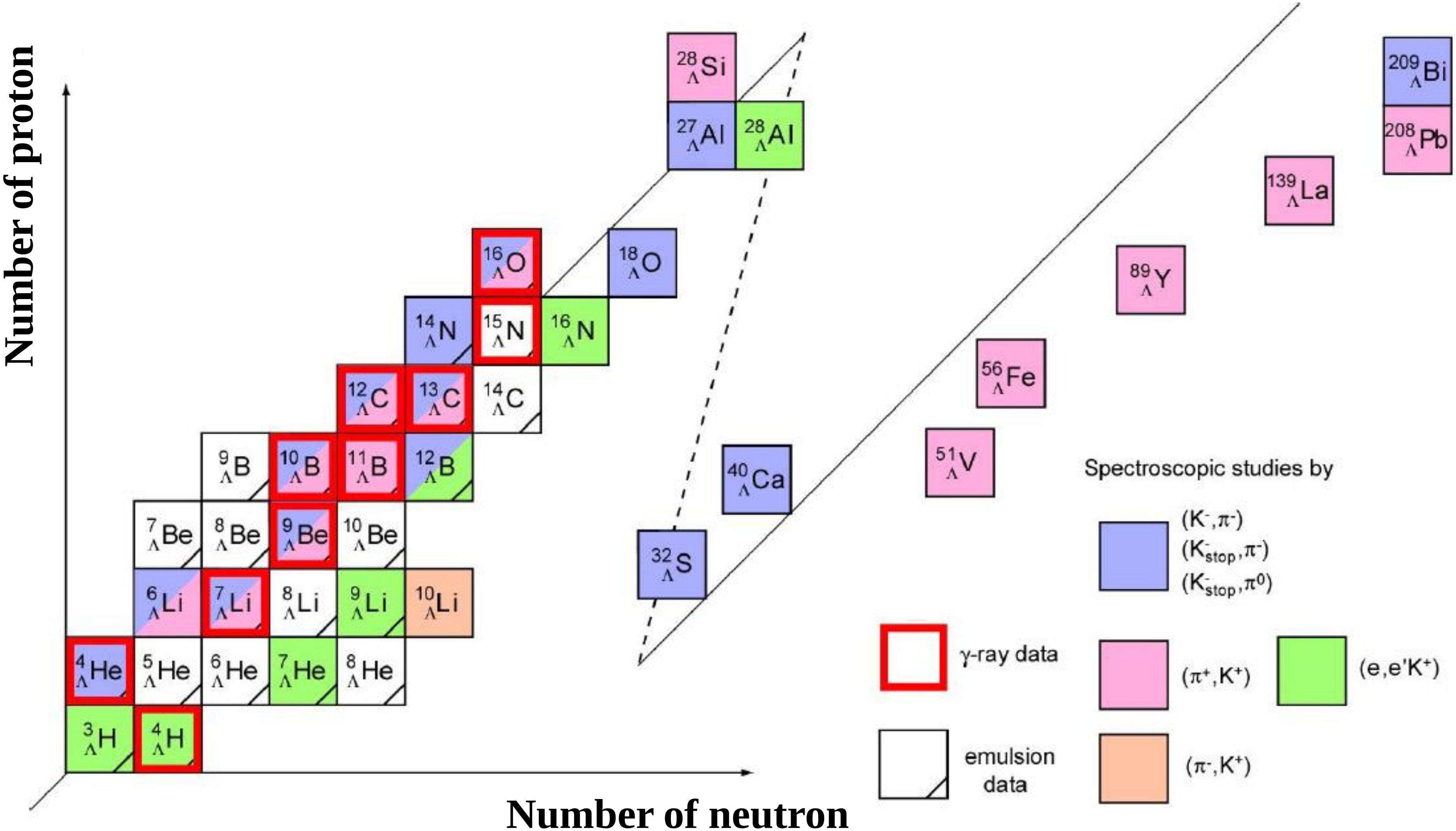
- τ_{Λ} : 263 ps
- $\tau_{\Sigma-}$: 148 ps
- $\tau_{\Xi-}$: 164 ps

Extraction of YN interaction information from structures of hypernuclei



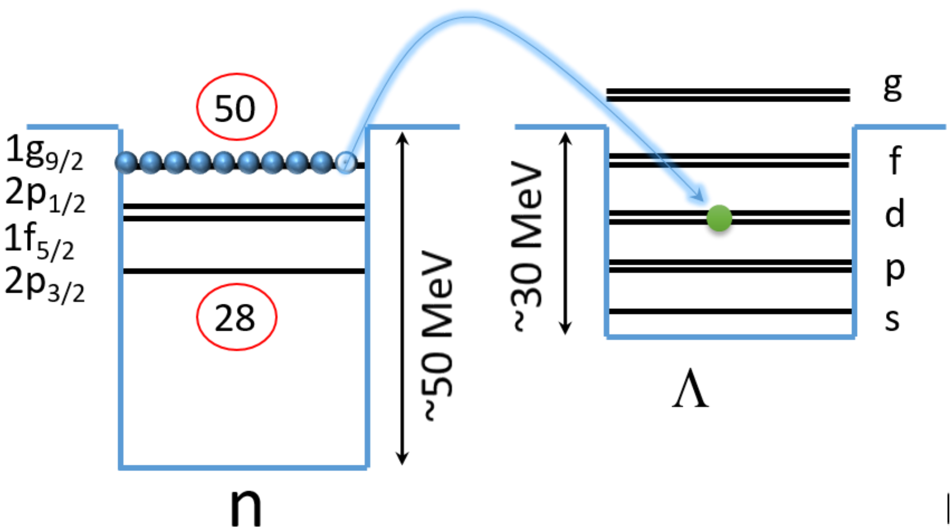
Prog. Nucl. Part. Phys. 58 (2007) 439.

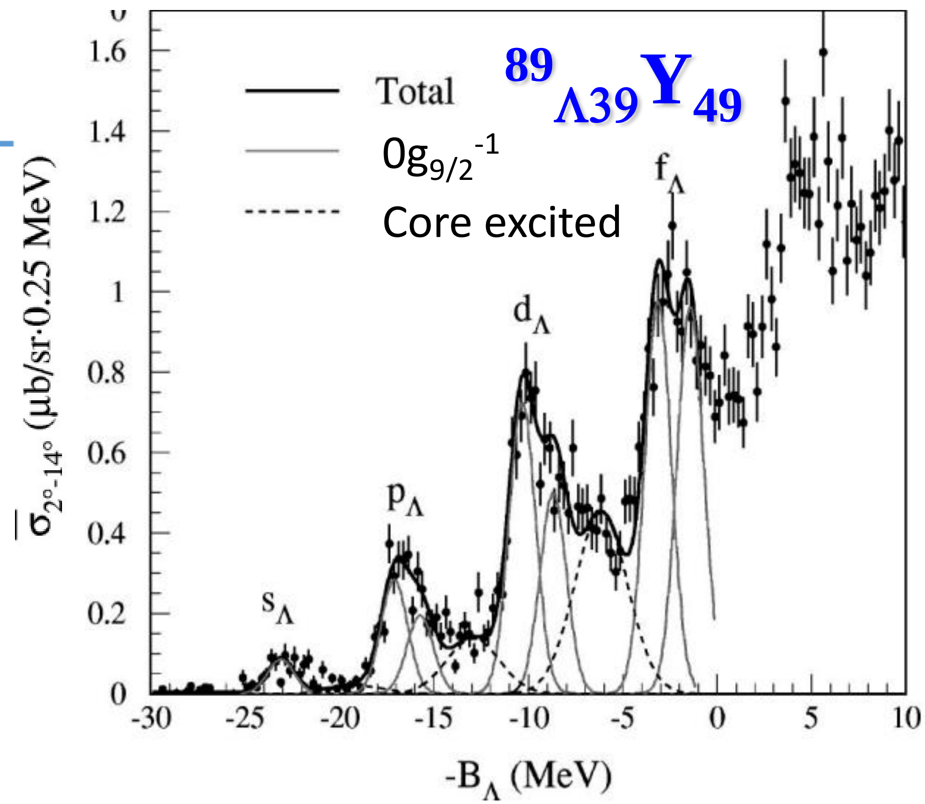
Λ Hypernuclear chart

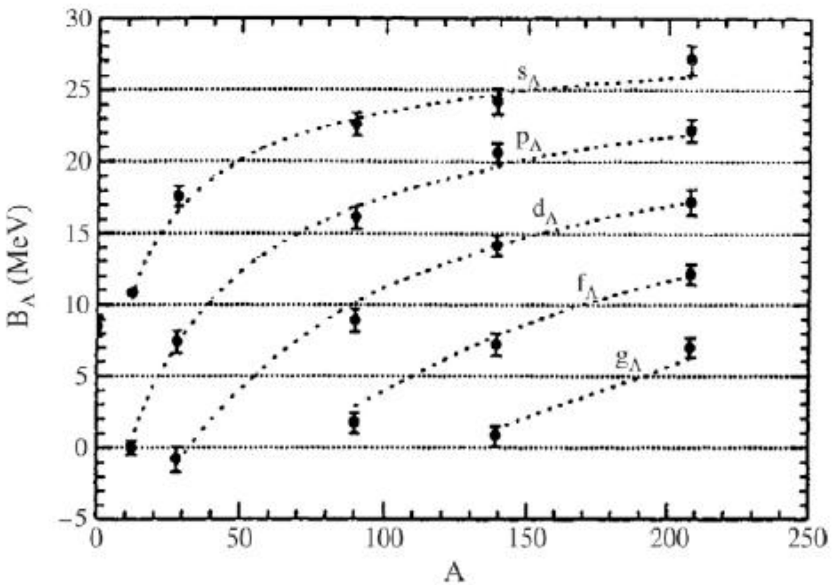


Courtesy of H. Tamura

Missing mass spectroscopy







Prog. Part. Nucl. Phys. 57 (2006) 564

^{89}Y(π^+,K$^+$)$^{89}{}_{\Lambda}$Y [KEK E369]

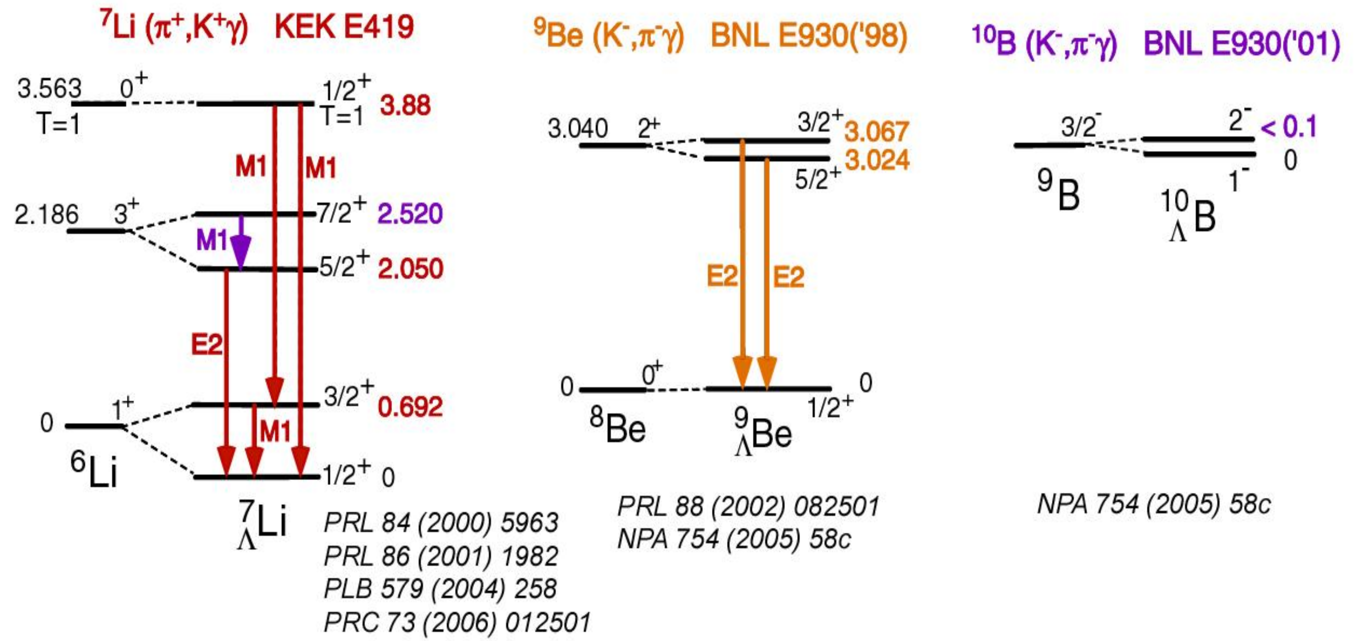
Counter experiment:

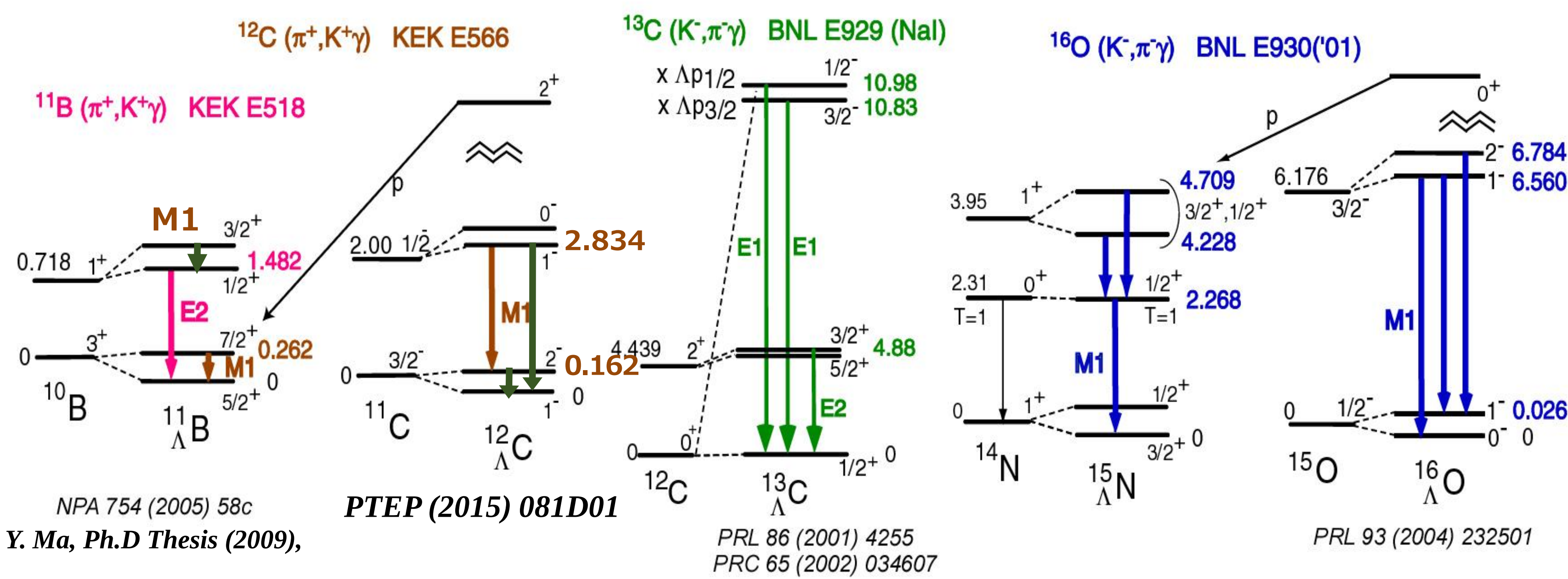
SKS magnet

FWHM= 1.6 MeV

Phys. Rev. C. ***64*** *044302 (2001)*

γ-ray transitions in *p*-shell hypernuclei



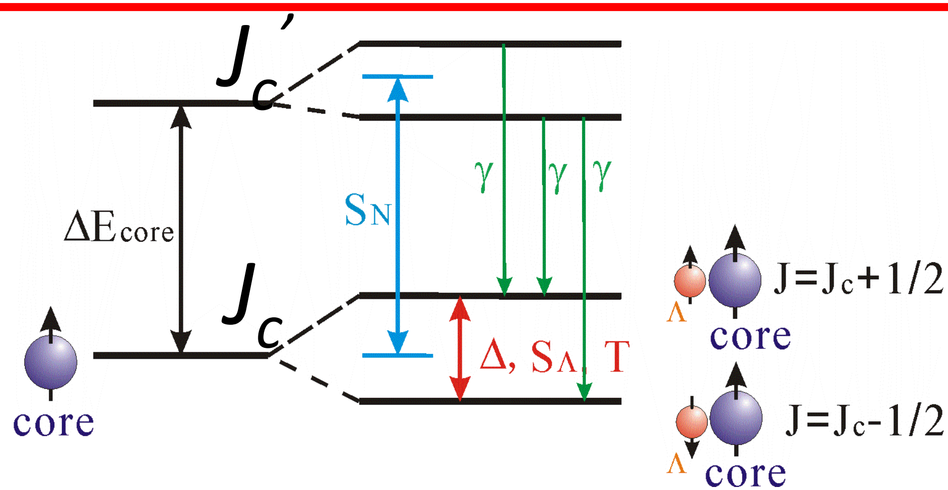


Effective two-body ΛN interaction

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

Δ $\qquad S_\Lambda$ $\qquad S_N$ $\qquad T$

p-shell : 4 radial integrals for $p_N s_\Lambda$ w.f.

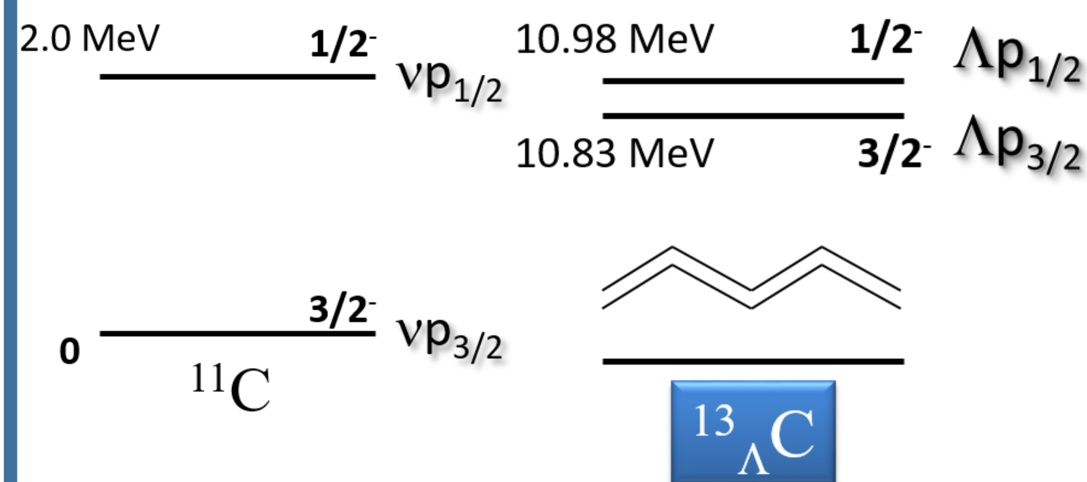


spin-spin Δ=0.43 or 0.33 MeV
Λ spin-orbit: S_Λ =–0.02 MeV
N spin-orbit S_N =-0.4
Tensor T =0.03

D. J. Millener, NPA 881 (2012) 298.

	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
${}^{7}_{\Lambda}$Li	$7/2^+$	$5/2^+$	74	557	−32	−8	−71	494	471
${}^{9}_{\Lambda}$Be	$3/2^+$	$5/2^+$	−8	−14	37	0	28	44	43
${}^{11}_{\Lambda}$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	$3/2_2^+$	$1/2_2^+$	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

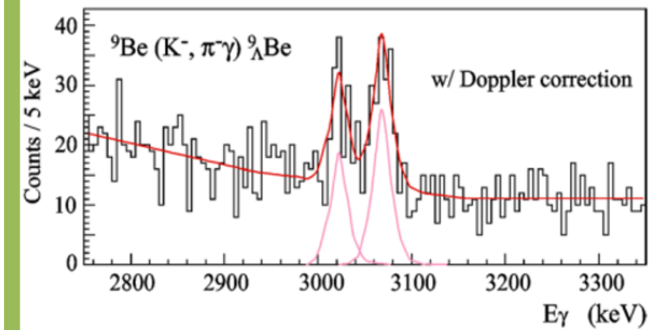
Small ΛN spin-orbit force

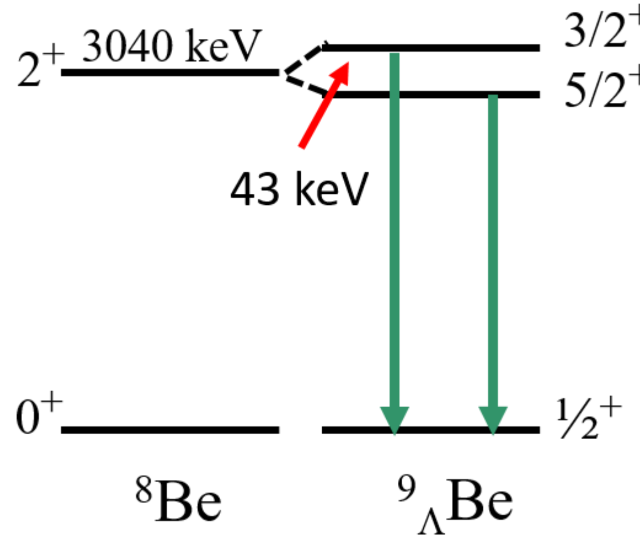


$^{13}C(K^-,\pi^-)^{13}{}_{\Lambda}C$
BNL E929
γ-ray spectroscopy
NaI(Tl) array

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

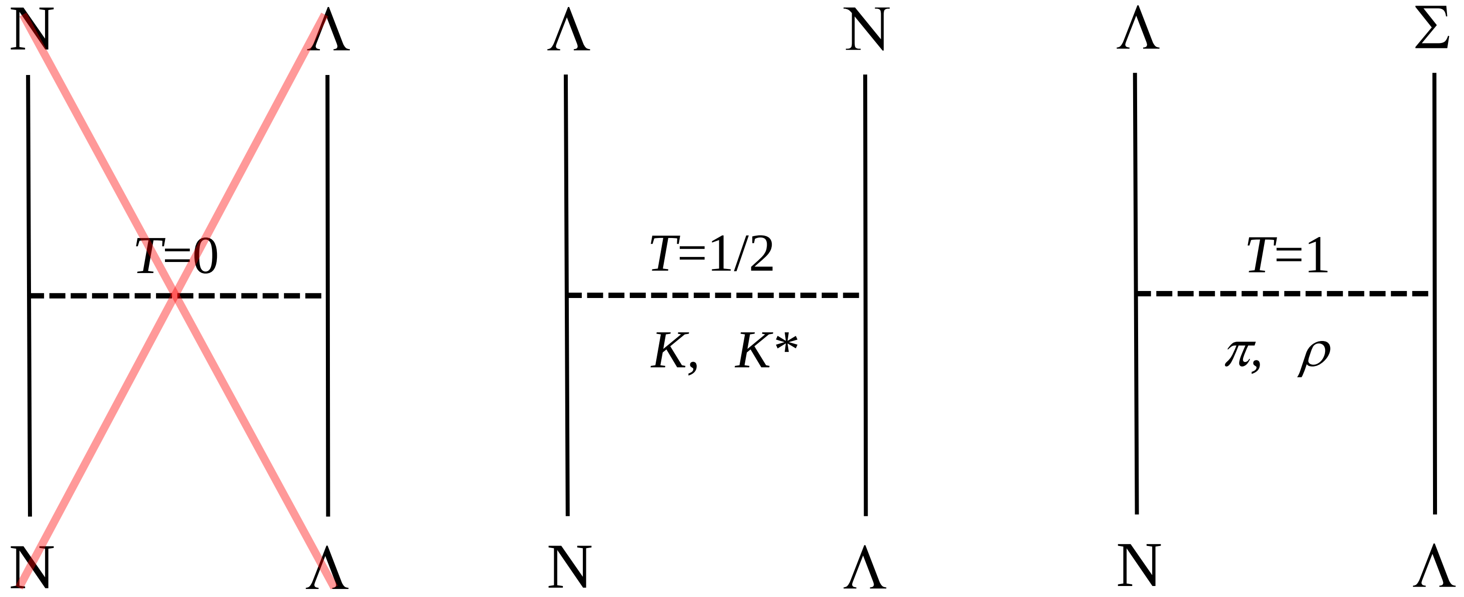
(K^-,π^-) E930 @BNL
Hyperball





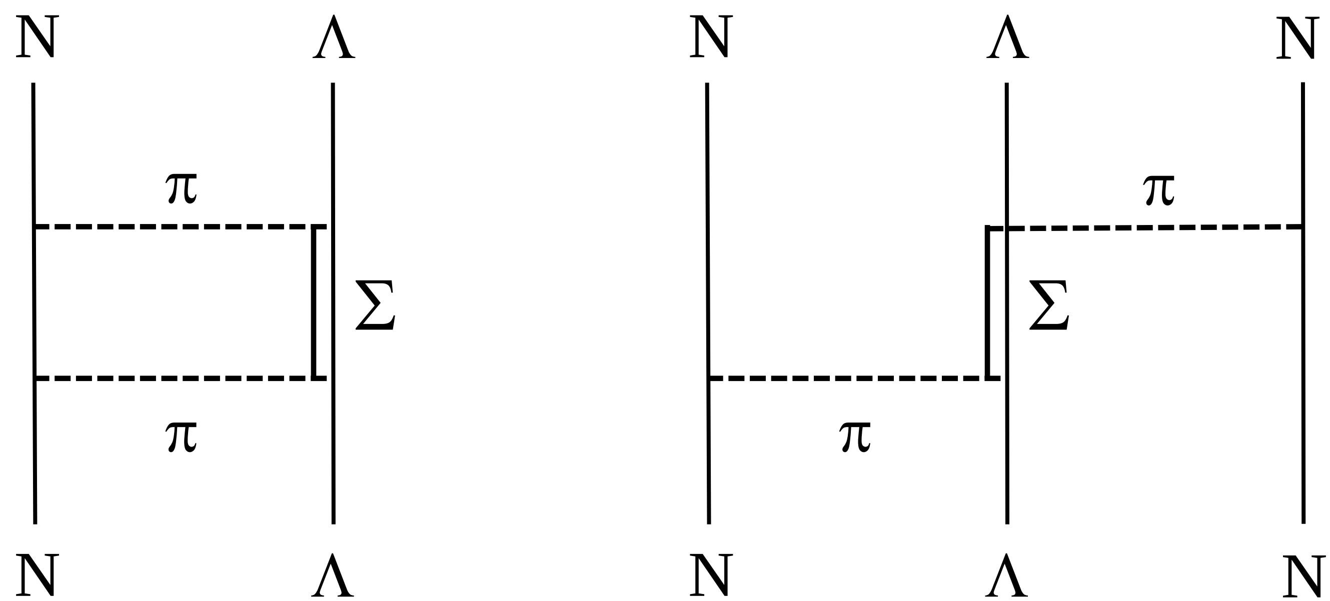
H. Akikawa et al, PRL 88 082501 (2002)

ΛN interaction

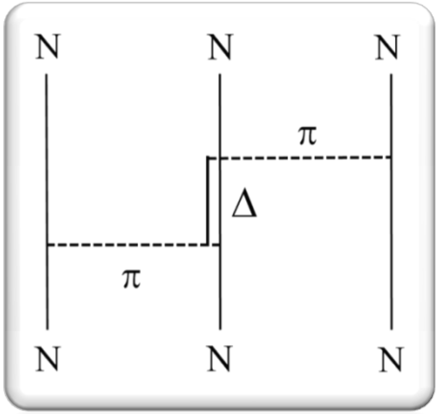


No one pion exchange because of isospin conservation
→ ΛN interaction is medium to short in range

ΛN interaction: ΛN-ΣN coupling



Two-body Three-body



$(m_\Sigma - m_\Lambda) \approx 75$ MeV $< (m_\Delta - m_N) \approx 300$ MeV

➡ ΛNN > NNN

Summary on ΛN interaction studies

- Experimentally most well studied among YN interaction
- Spin dependent term determined for p-shell by γ-ray spectroscopy
- Independent particle picture is valid for also Λ
  - $U_\Lambda/U_N \sim 2/3$
- Small spin-orbit force (by an order of magnitude)
  - Magic number for Λ → HO shell gap
- One pion exchange forbidden (medium to short range nuclear force)
  - Zero isospin of Λ
- ΛN-ΣN coupling is stronger than the nuclear counter part
  - $m_\Sigma - m_\Lambda \approx 75$ MeV

Large charge symmetry breaking (CSB) ?

Experimental breakthroughs in 2015

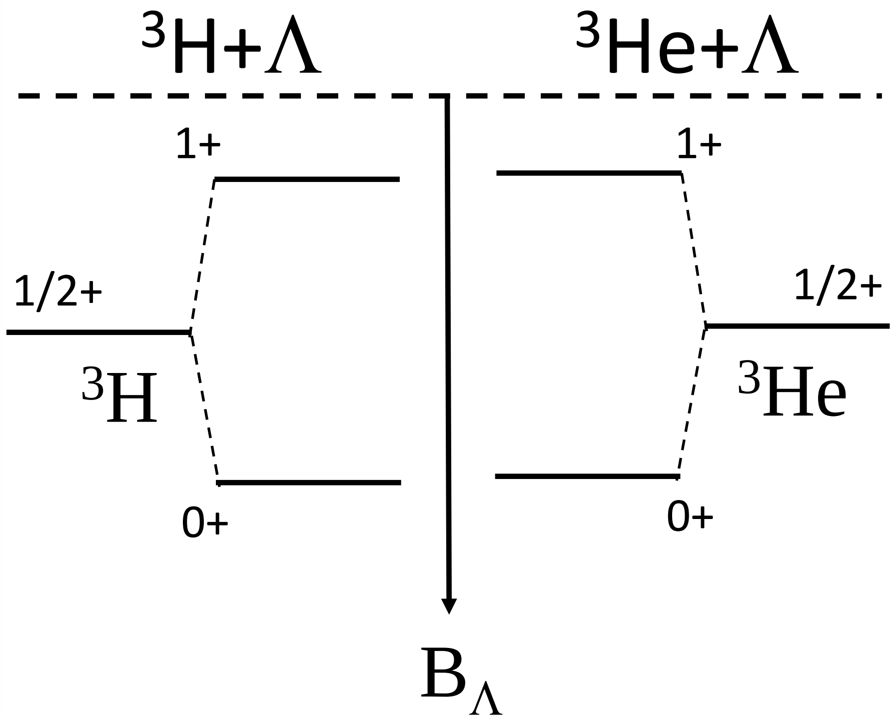
Experimental confirmation of large charge symmetry breaking (CSB) in ΛN interaction

How much energy (B_Λ) the system will gain by adding Λ in A=3 nuclear system?

Λ has no charge!!

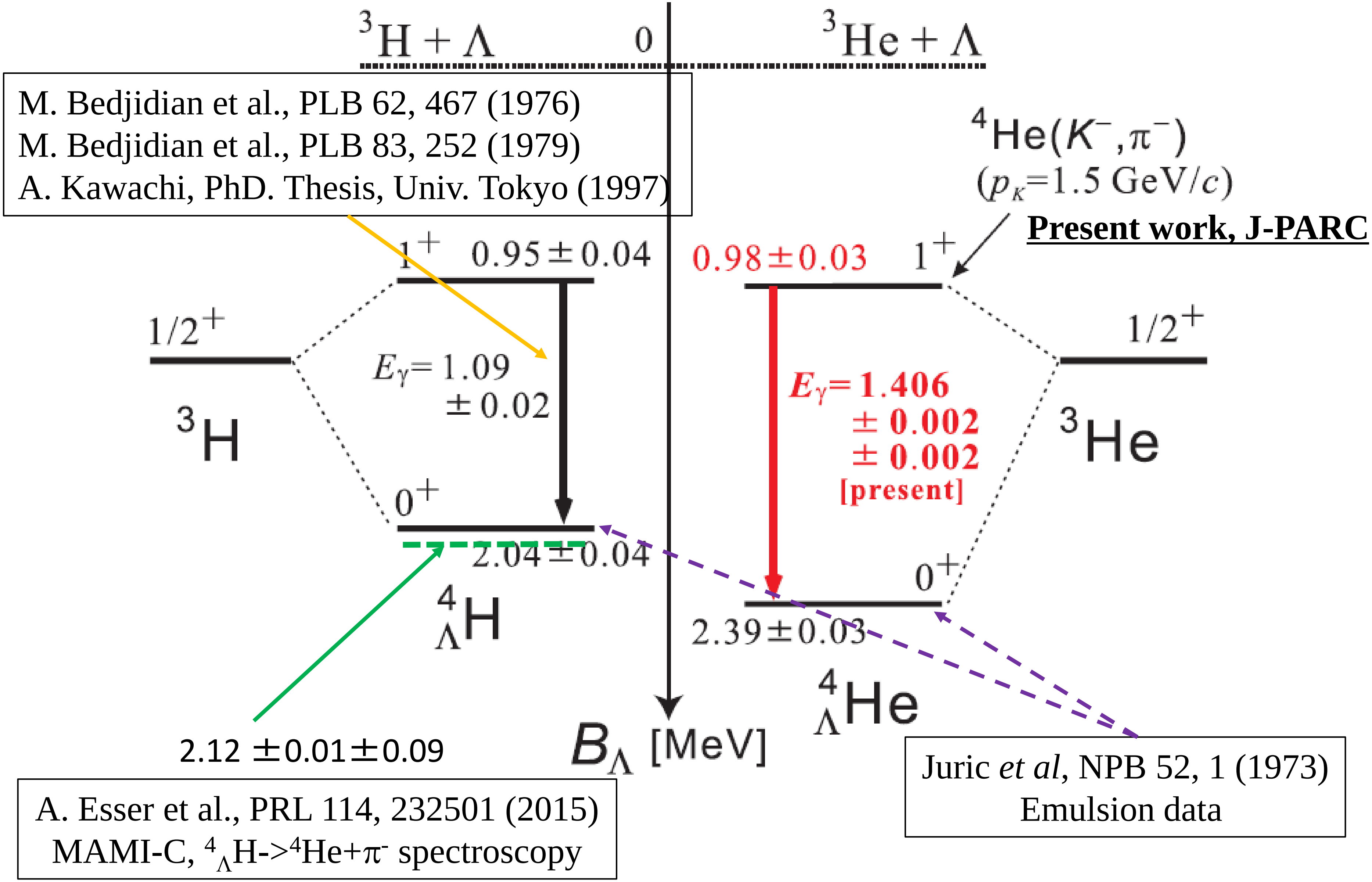
- ΔB_Λ: measure of pure (no Coulomb contribution) CSB effect of ΛN interaction.
- ΔB_Λ would be the same or much smaller than NN
- A few keV sensitivity via γ-ray spectroscopy with bound excited states.

<u>naïve expectation</u>



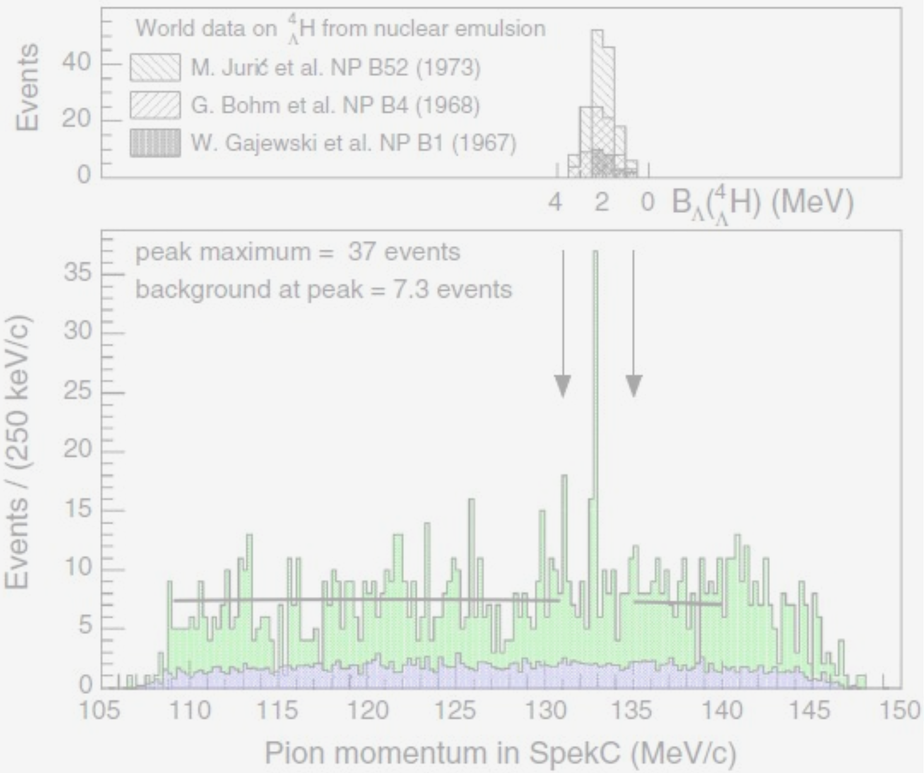
$$(J_{core} = \tfrac{1}{2}) \otimes (J_\Lambda = \tfrac{1}{2})$$

A=4 mirror Λ-hypernuclei



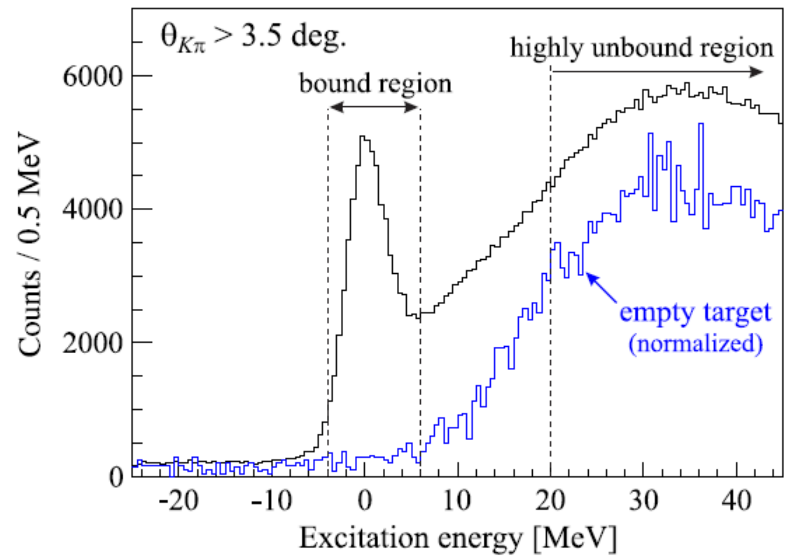
Experimental breakthroughs

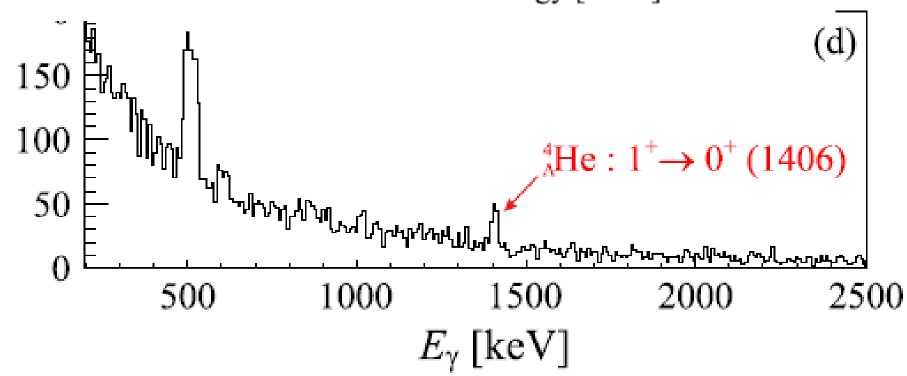
Binding energy of ${}^{4}_{\Lambda}$H (0^{+})



Phys. Rev. Lett. 114, 232501 (2015)

Energy of ${}^{4}_{\Lambda}$He ($1+\rightarrow0^{+}$)





Phys. Rev. Lett. 115, 222501 (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]

(J-PARC E13 Collaboration)

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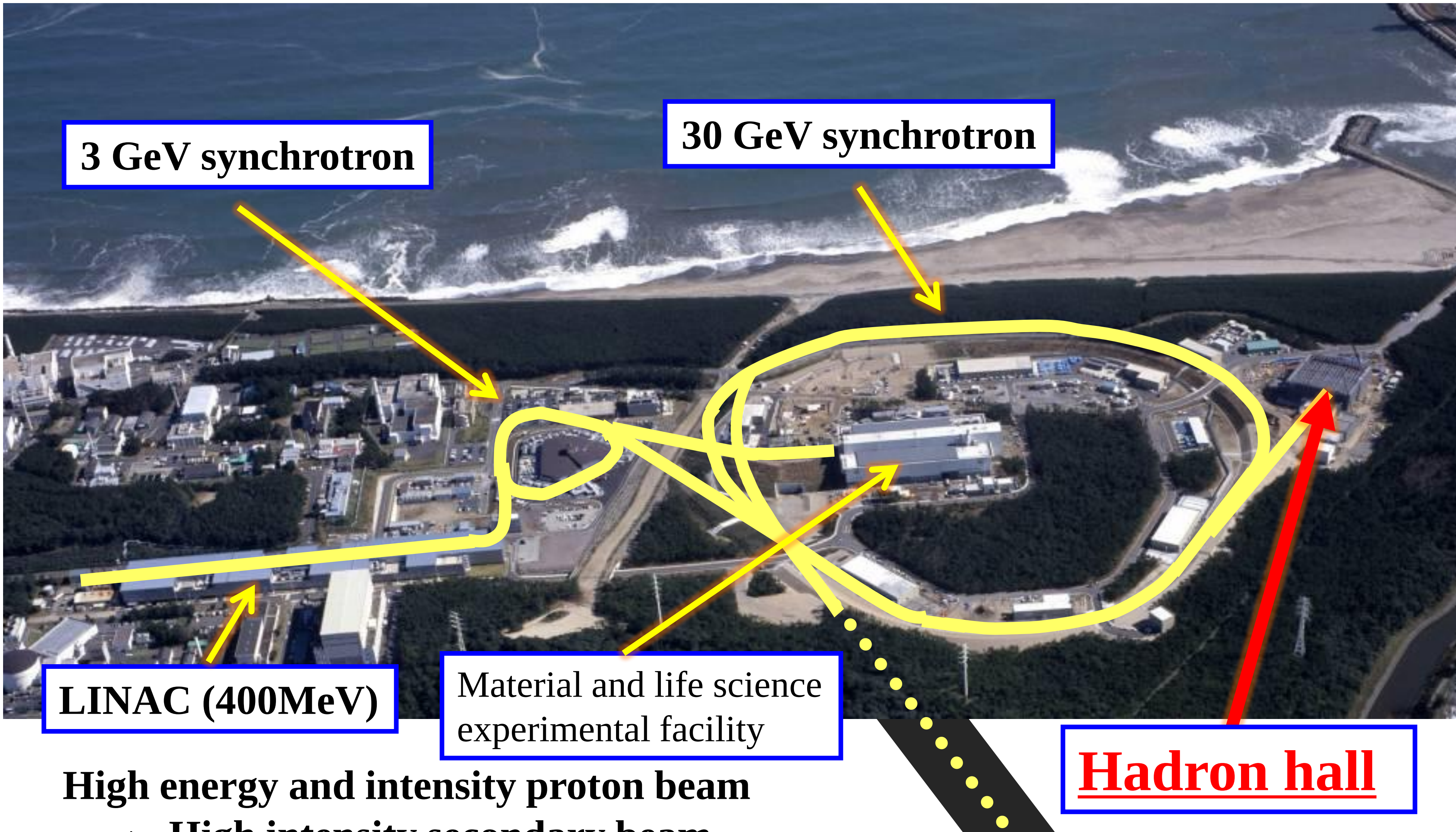
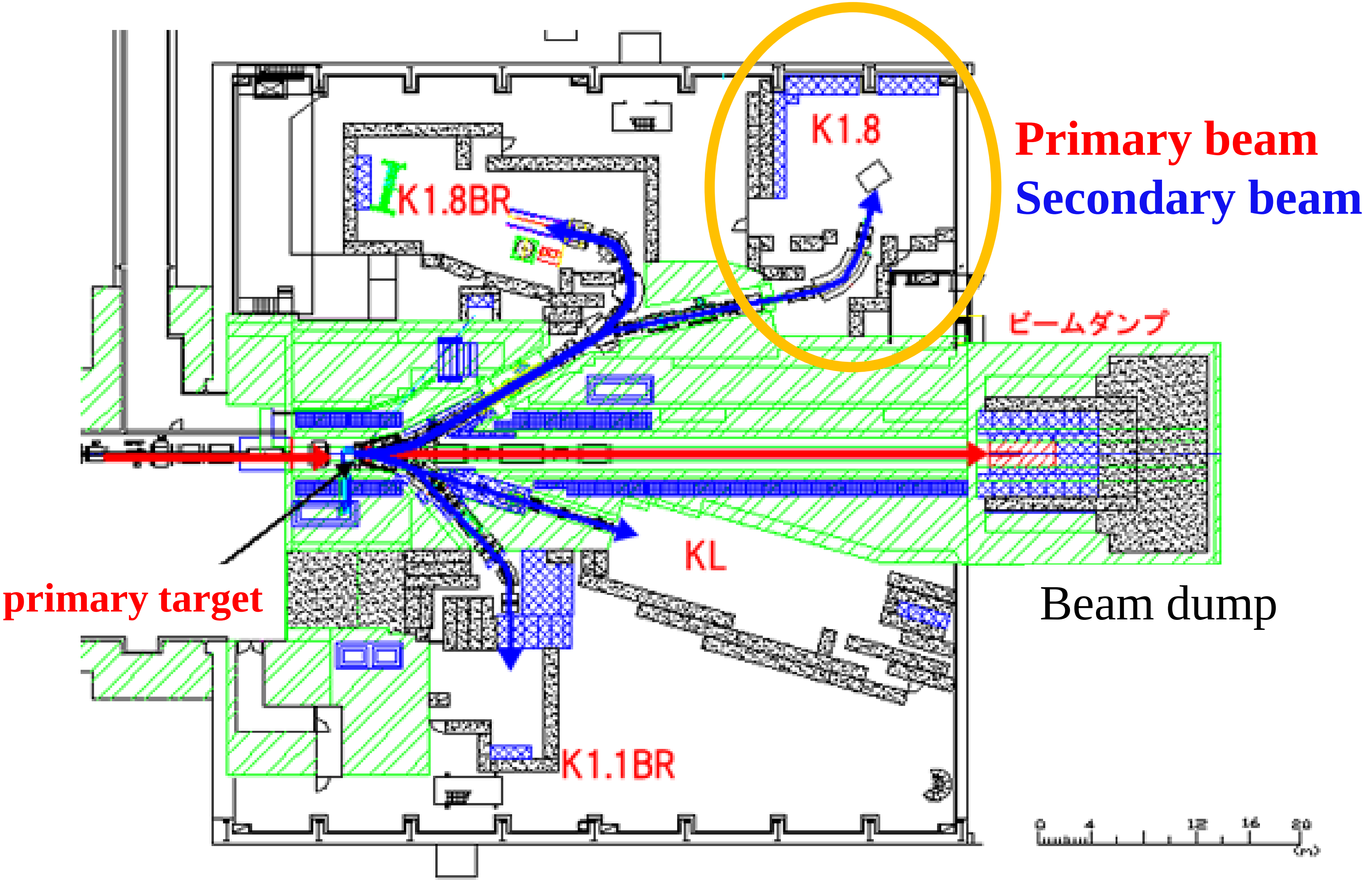
J-PARC

(Japan Proton Accelerator Research Complex)



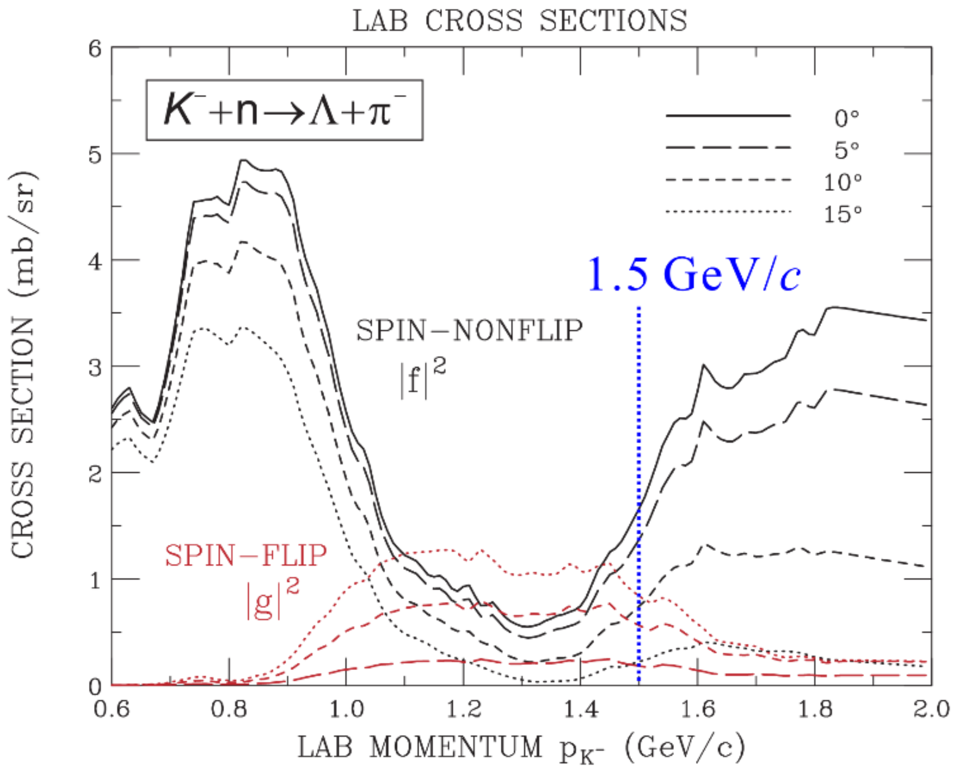
High energy and intensity proton beam
→ High intensity secondary beam

Hadron Experimental Facility



γ-ray spectroscopy of $^4_\Lambda$He (J-PARC E13)

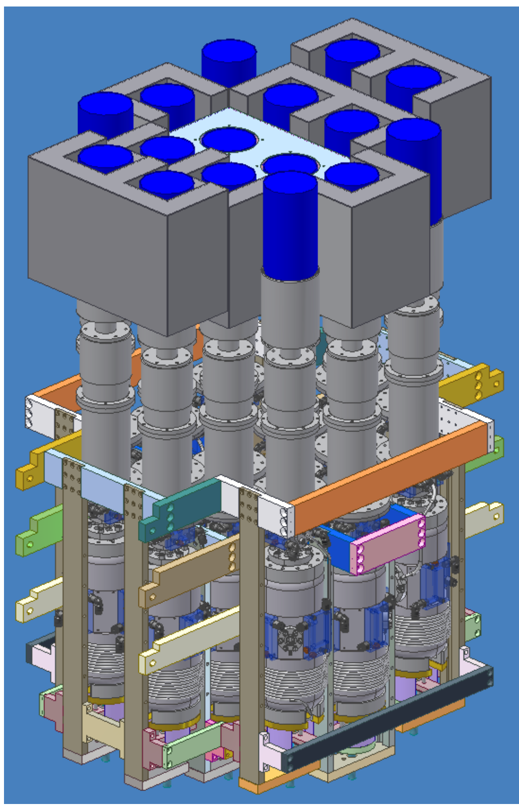
Reaction: ^{4}He(K$^-$,π$^-$)$^4_\Lambda$He
Beam mom.: P_{K-}=1.5GeV/c
Target: Liq. 4He, 2.8g/cm^2
Reaction-γ coincidence



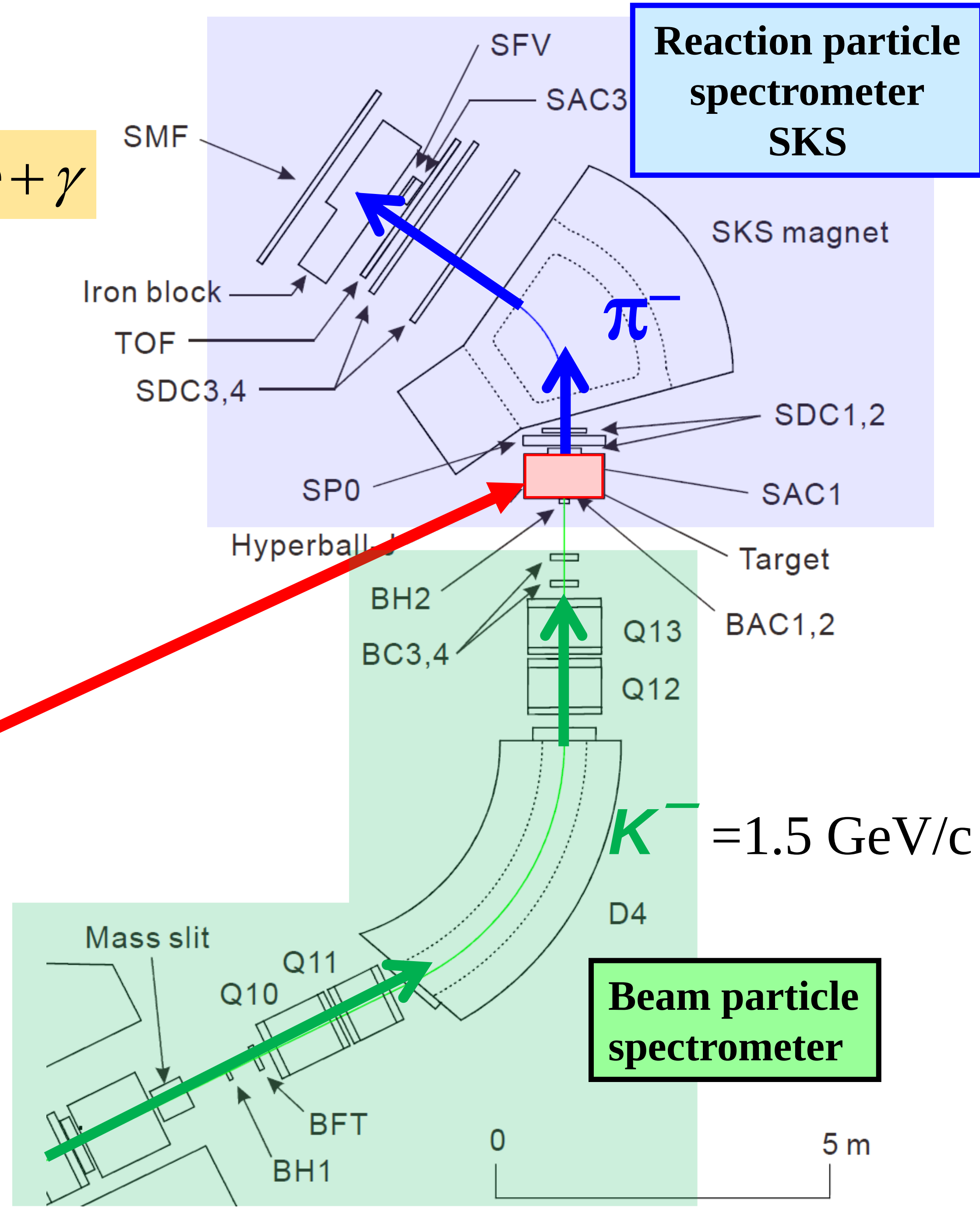
T. Harada, private communication (2006)

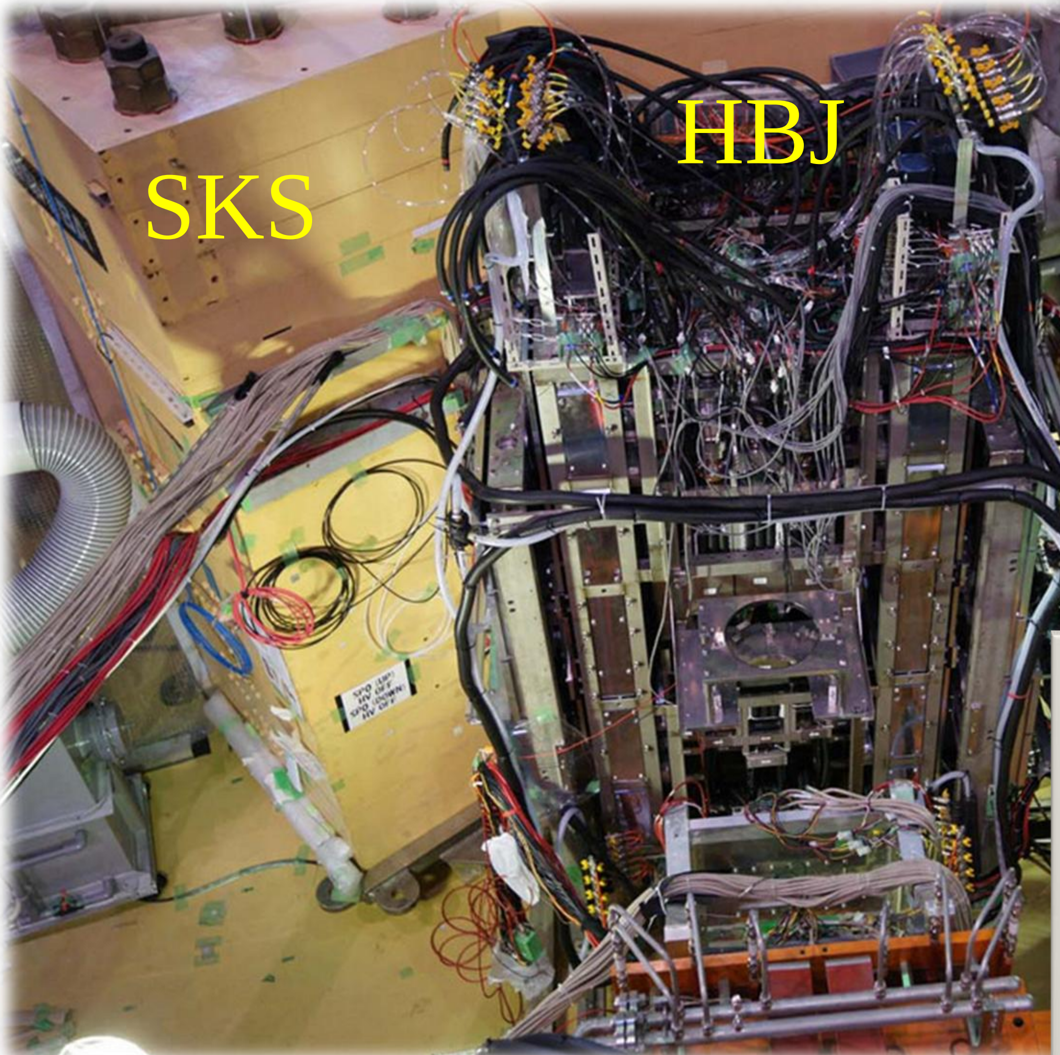
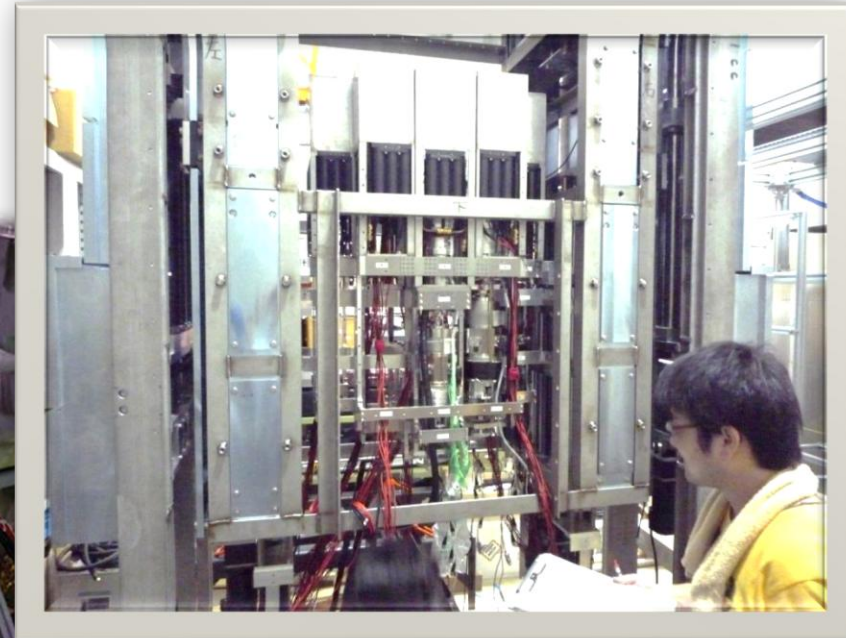
$$^{4}He\,(K^{-},\pi^{-})\,{}^{4}_{\Lambda}\mathrm{He}^{*} \rightarrow {}^{4}_{\Lambda}\mathrm{He}+\gamma$$

Ge-array



Hyperball-J




SKS
HBJ


Liq. He target

A=4 mirror Λ-hypernuclei

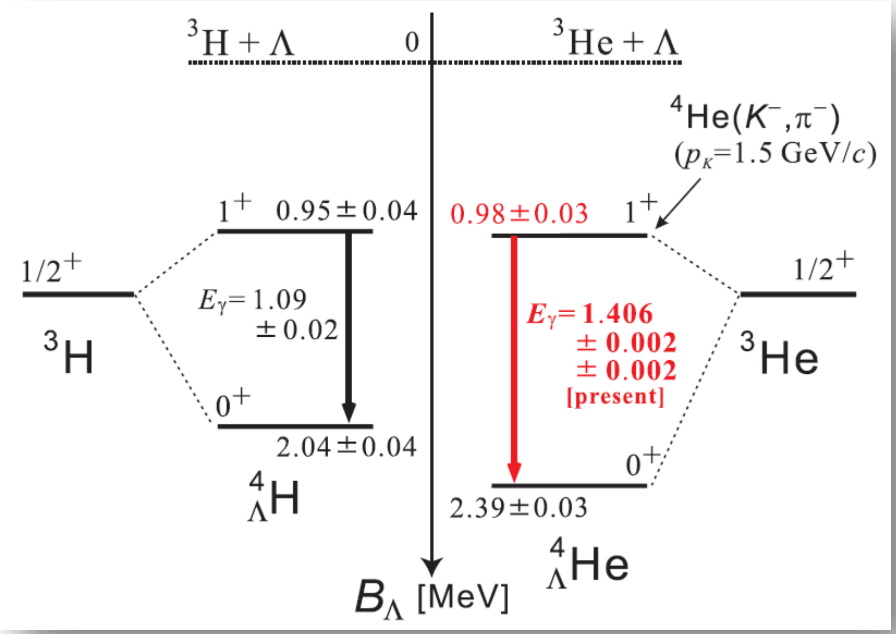
ΔB_Λ (g.s)=B_Λ (0^+;${}^4_\Lambda$He)-B_Λ(0^+;${}^4_\Lambda$H)=270 ± 100 keV

$\Delta E_\gamma(1^+ \rightarrow 0^+)$=$E_\gamma$(${}^4_\Lambda$He)-$E_\gamma$(${}^4_\Lambda$H)=316 ±40 keV

ΔB_Λ (1^+)=B_Λ (1^+;${}^4_\Lambda$He)-B_Λ(1^+;${}^4_\Lambda$H)=50 ± 100 keV

CSB effect in ΛN

- Sizable
- Spin dependent



CSB in mirror nuclei: ^3H & ^3He

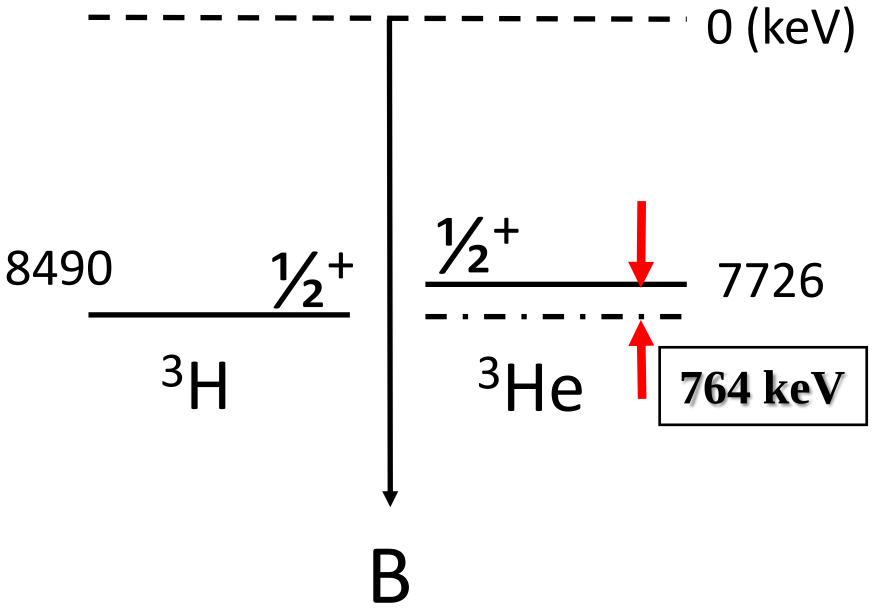


TABLE IV. Contributions of the various terms of the interaction to the ^{3}H-^{3}He mass difference D. The AV18+UIX potential has been used.

Interaction term	D (keV)
Nuclear CSB	65
Point Coulomb	677
Full Coulomb	648
Magnetic moment	17
Orbit-orbit force	7
n-p mass difference	14
Total (theory)	751
Experiment	764

Nogga et al., Phys. Rev. C 67 034004 (2003)

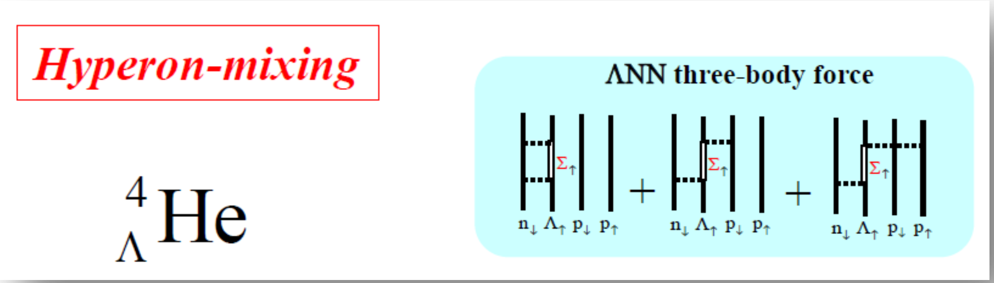
xPT calculation

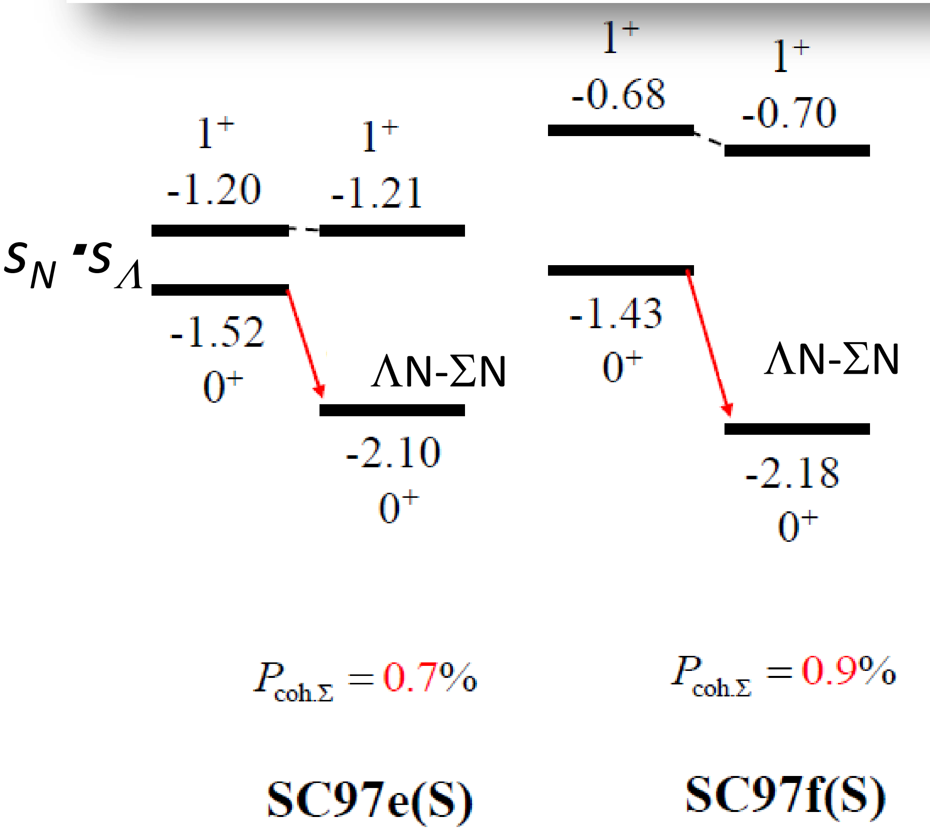
Coulomb	Breit	$\langle E_k \rangle$	Two-body	Three-body	Theory	Experiment
648	28	14	65(22)	5	760(22)	764

J. L. Friar, G. L. Payne, and U. van Kolck, Phys. Rev. C 71, 024003 (2005)

Effect of ΛN-ΣN coupling in $^{4}_{\Lambda}He$

- w.f.: Core + Λ
- ΛNN-3BYN
- Simulated Nijmegen soft-core potential
  - SC97e,f(S)
- Spin doublet spacing in A=4 system
  - $s_N \cdot s_\Lambda$ + ΛN-SN
- Large effect on 0^+
  - Coherent coupling





Y. Akaishi et al., Phys. Rev. Lett. 84 3539 (2000)

Relatively recent theoretical studies

a. A. Nogga et al., PRL88 172501 (2002)
  - ΛNNN four-body calculation
  - NSC97e (ΛN-ΣN tensor term strong)

b. A. Gal PLB 744 352 (2015)
  - Akaishi-formalism + explicit CSB term via mixing of $\Lambda\Sigma^0$ to ΛΣ strong interaction.

c. D. Gazda and A. Gal PRL (in press) , arXiv:1512.01049 (2016)
  - Ab-initio No Core Shell Model (NCSM) with χEFT YN interaction
    - N3LO NN + N2LO NN + LO/NLO YN
    - Inclusion of explicit ΛN-ΣN interaction

(Unit in MeV)	Exp	a	b	c
$B_\Lambda(0^+)$	0.27(10)	0.07	0.22	0.18(10)
$B_\Lambda(1^+)$	0.05(10)	-0.01	0.03	-0.20(2)

Summary

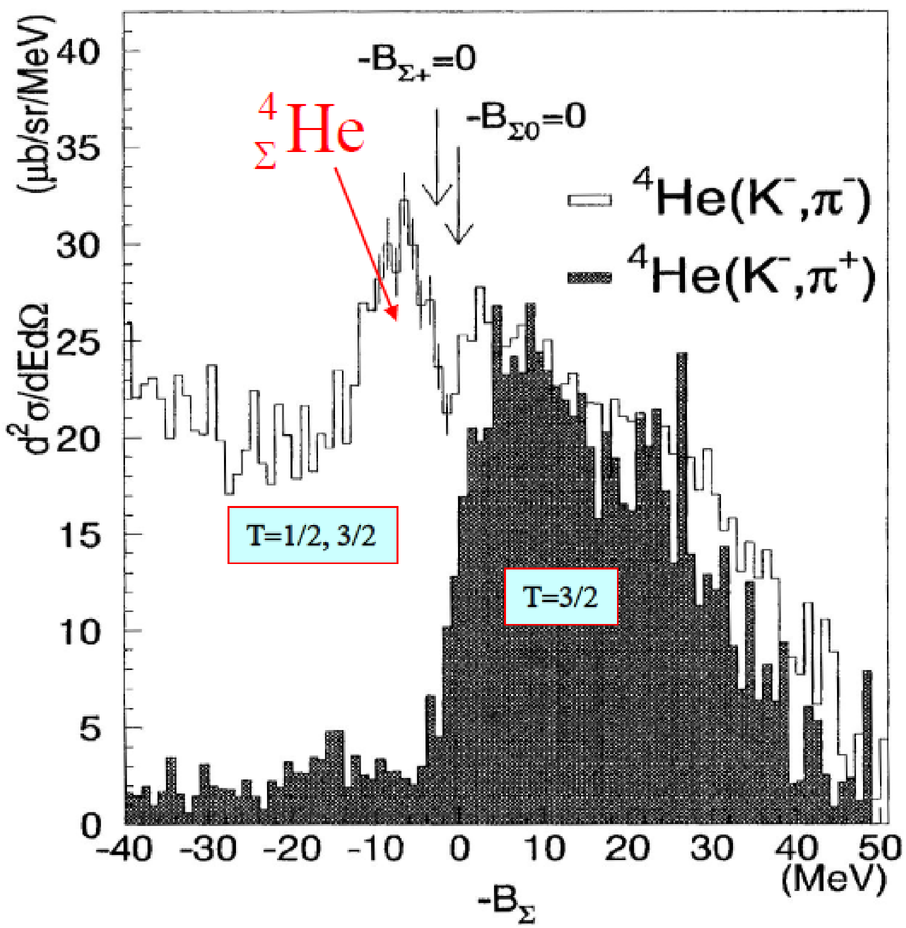
- NN strong interaction to more general baryon-baryon interaction
  - ΛN interaction is the first step with Strangeness=-1
  - YN scattering experiments difficult → study of hypernuclei
- New data on A=4 ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ from MAMI-C and J-PARC
- ΛN CSB is confirmed.
  - Larger than NN (unexpected) → role of ΛN-ΣN 3-body interaction
  - Strongly spin dependent

Experimental progresses have opened a new testing ground for a nuclear few-body calculations.

Observation of a ${}^{4}_{\Sigma}$He Bound State

BNL-AGS (1995-)

VOLUME 80, NUMBER 8 PHYSICAL RE



T. Nagae, T. Miyachi, T. Fukuda, H. Outa,
T. Tamagawa, J. Nakano R.S.Hayano,
H. Tamura, Y. Shimizu, K. Kubota,
R. E. Chrien, R. Sutter, A. Rusek,
W. J. Briscoe, R. Sawafta,
E.V. Hungerford, A. Empl, W. Naing,
C. Neerman, K. Johnston, M. Planinic,
Phys.Rev.Lett. 80(1998)1605.

$$B_{\Sigma^+} = 4.4 \pm 0.3 \text{ MeV}$$

$$\Gamma = 7 \pm 0.7 \text{ MeV}$$

Theoretical Prediction
4.6 MeV
7.9 MeV

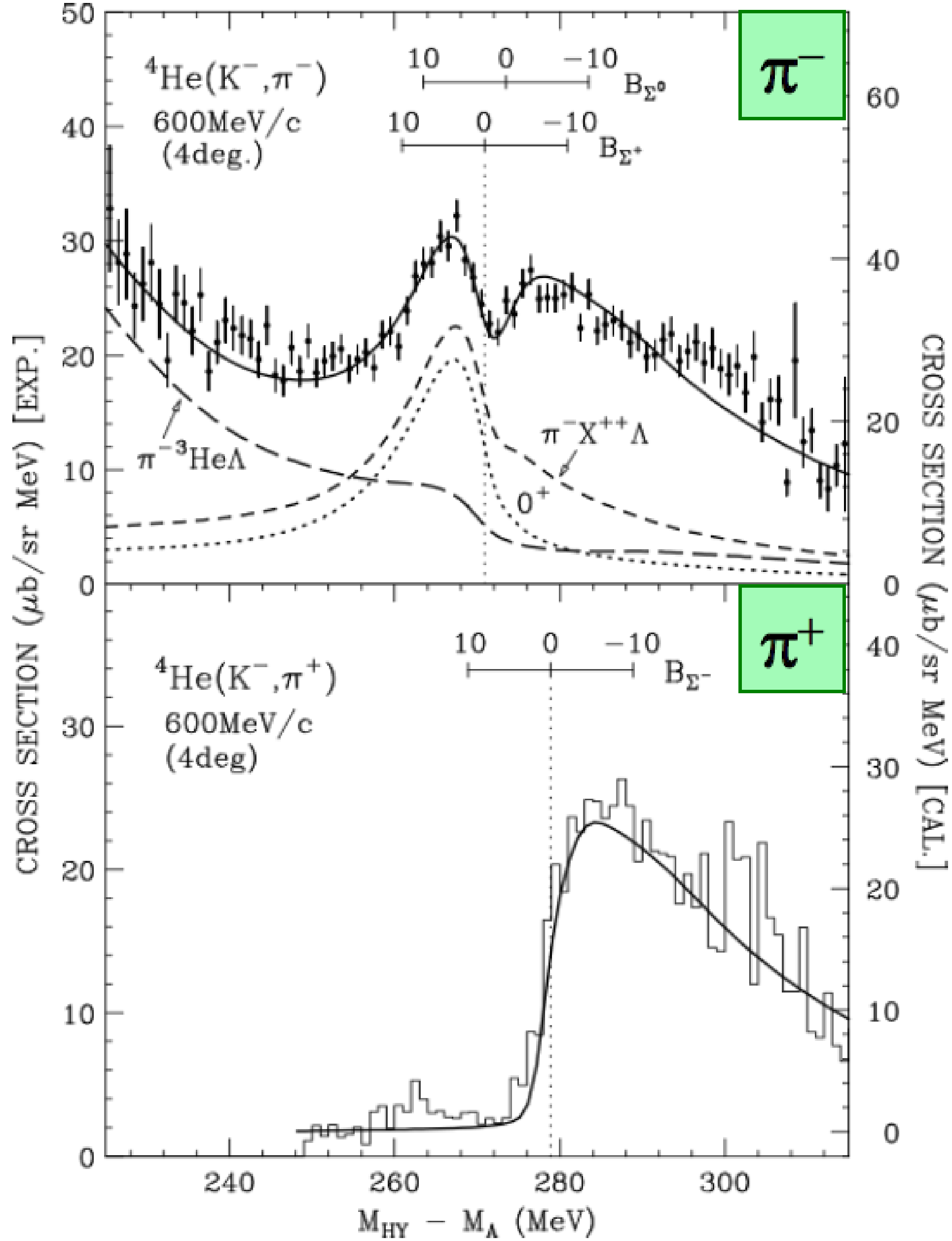
$$T \simeq 1/2$$

$$J^{\pi} = 0^{+}$$

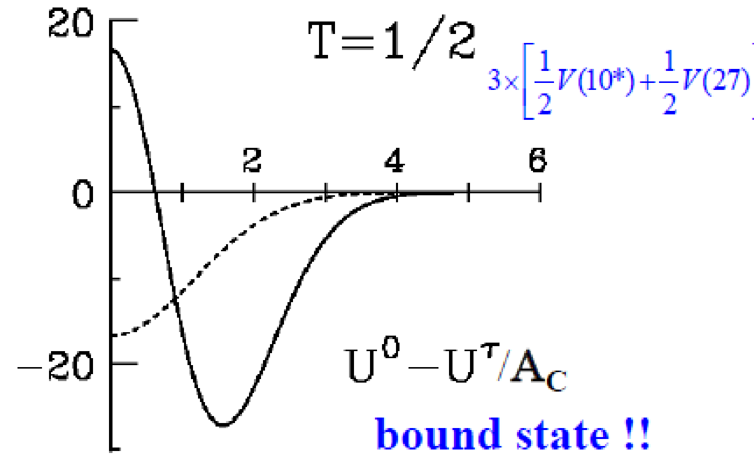
T.Harada, S.Shinmura, Y.Akaishi, H.Tanaka, NPA507(1990)715.

Isospin dependence of the (3N)-Σ potentials

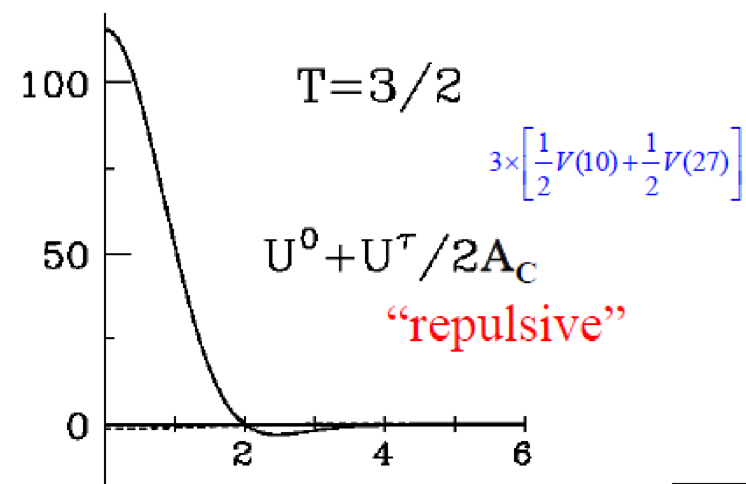
T.Harada, PRL81(1998)5287.



T.Harada, NPA507 (1990) 715.



"repulsive core
+attractive pocket"



■ΛN

U_0 (Λ) ~ (–30) MeV, U_{LS} (Λ) ~ 2 MeV → 精密測定

–38 MeV ?

E13@J-PARC

■ΣN

U_0 (Σ) ~ 斥力的, U_{LS} (Σ) ? →$\Sigma^+ p (=\Sigma^- n)$散乱 E40@J-PARC

■ΛN-ΣN

a few % mixing, ΛNN3体力 →中性子過剰ハイパー核

E10@J-PARC

■ΞN

U_0 (Ξ) ~ (–14)-(–0) MeV ? → (K–,K+)反応, Ξ-原子X線

E03,05@J-PARC

■ΛΛ-ΞN-ΣΣ

mixing prob. ?, H-particle ? →Hybrid-emulsion, ΛΛ相関

E07, P42@J-PARC

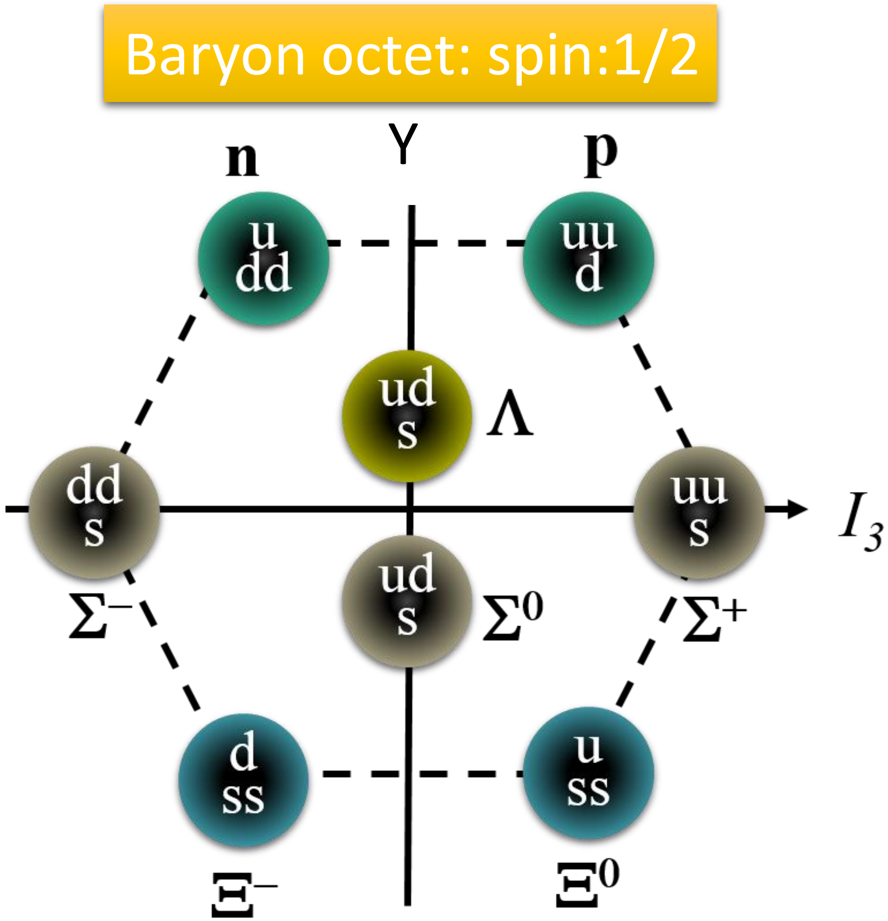
■K^-N-Λ(1405)-πΣ

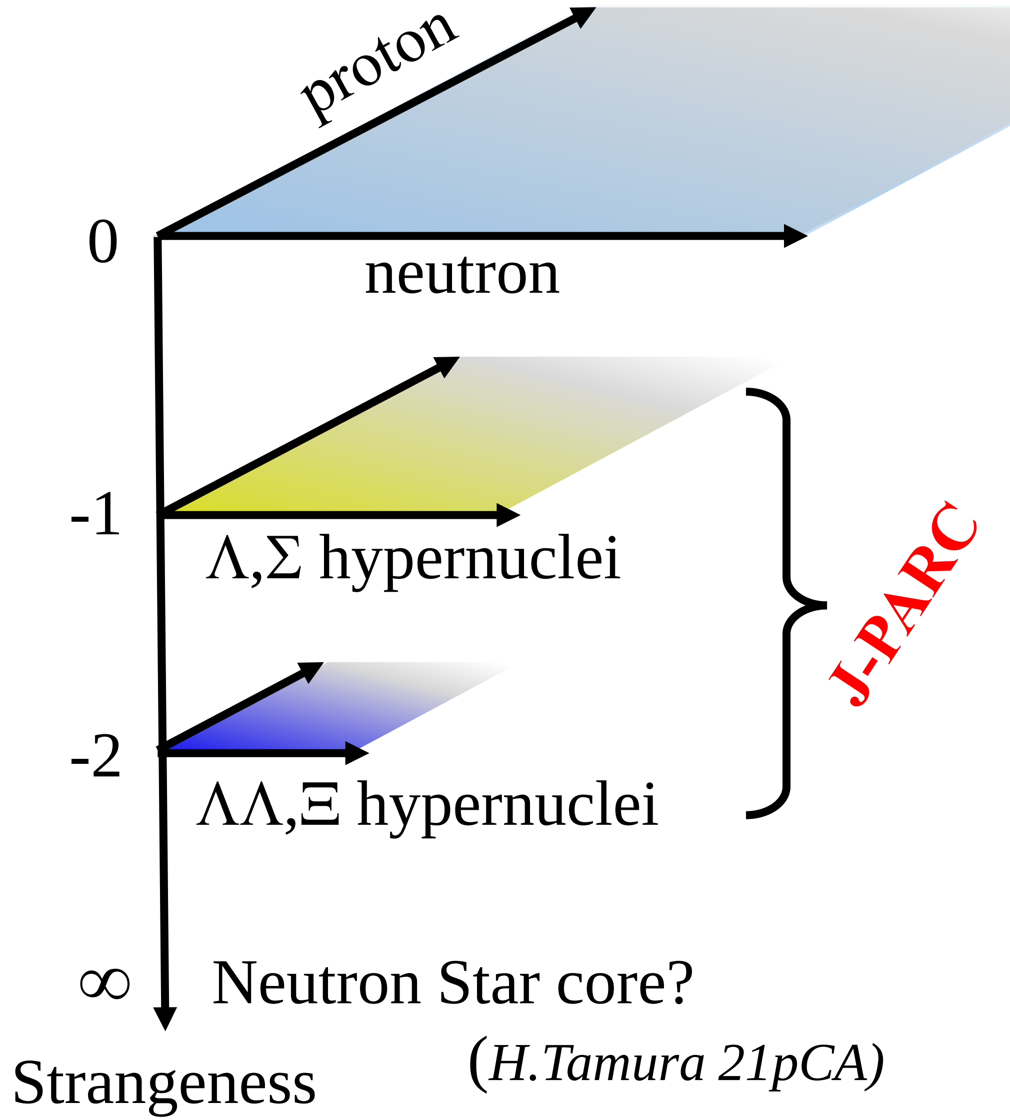
U_0 (K^-) ~ –200 MeV/–50 MeV ? , "K-pp" ?

→ (K^-,N), (π^+,K^+)反応

E15,E23@J-PARC

Strange baryon & Hypernucleus





(*H.Tamura 21pCA*)

CSB in ΛN interaction

$$B_\Lambda({}^4_\Lambda\mathrm{He};\, I\,)=[M_{core}+M_\Lambda]-M({}^4_\Lambda\mathrm{He};\mathrm{g.s})+E_x({}^4_\Lambda\mathrm{He};I)$$

$$-)\quad B_\Lambda({}^4_\Lambda\mathrm{H};\, I\,)=[M_{core}+M_\Lambda]-M({}^4_\Lambda\mathrm{H};\mathrm{g.s})+E_x({}^4_\Lambda\mathrm{H};\, I)$$

$$\Delta B_\Lambda(\, I\,)= -\ \Delta M^{gs}_{HYP}+\Delta E_x(I)$$

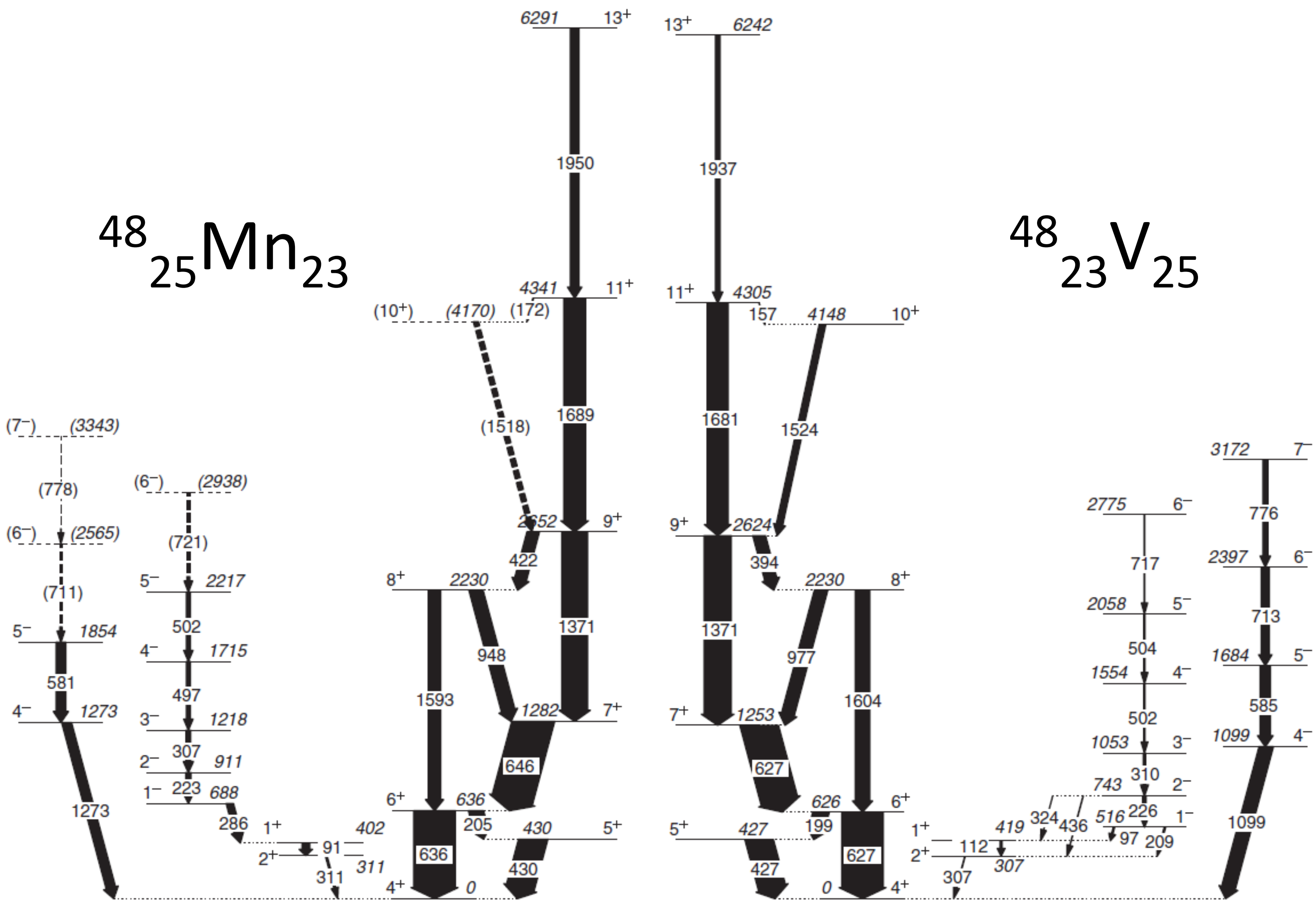
$$\Delta B_\Lambda(1^+)-\Delta B_\Lambda(0^+;\mathrm{g.s})=\Delta E_x(1^+)=\Delta E_\gamma(1^+\rightarrow 0^+)$$

Measure of almost pure CSB in ΛN interaction

$$[M_{core}+M_\Lambda]:\ \mathrm{reference}=0$$

A=7, T=1 iso-triplet hyp. nuclei

Charge symmetry



M. A. Bentley et al., Phys. Rev. Lett. 97 132501 (2006)

Isospin invariance and charge symmetry

- Isospin invariance: $[H_{st}, T^2]=[H_{st}, T]=0$
  - $a_{nn}= a_{pp}= a_{np}$ (scattering length in $^1S_0;T=1$)
- Charge symmetry: $[H_{st}, P_{cs}]=0$ where $P_{cs}=\exp(i\pi T_\alpha)$
  - $a_{nn}= a_{pp}$

a_{pp} = -17.7±0.4 fm
a_{nn} = -18.8 ±0.3 fm
a_{np} = -23.75 ±0.09 fm

$$\frac{\sigma(pp \to d\pi^+)}{\sigma(pn \to d\pi^0)} \neq (\approx)\frac{1}{2}$$

Mostly dominated by EM (Coulomb & π mass difference) effects