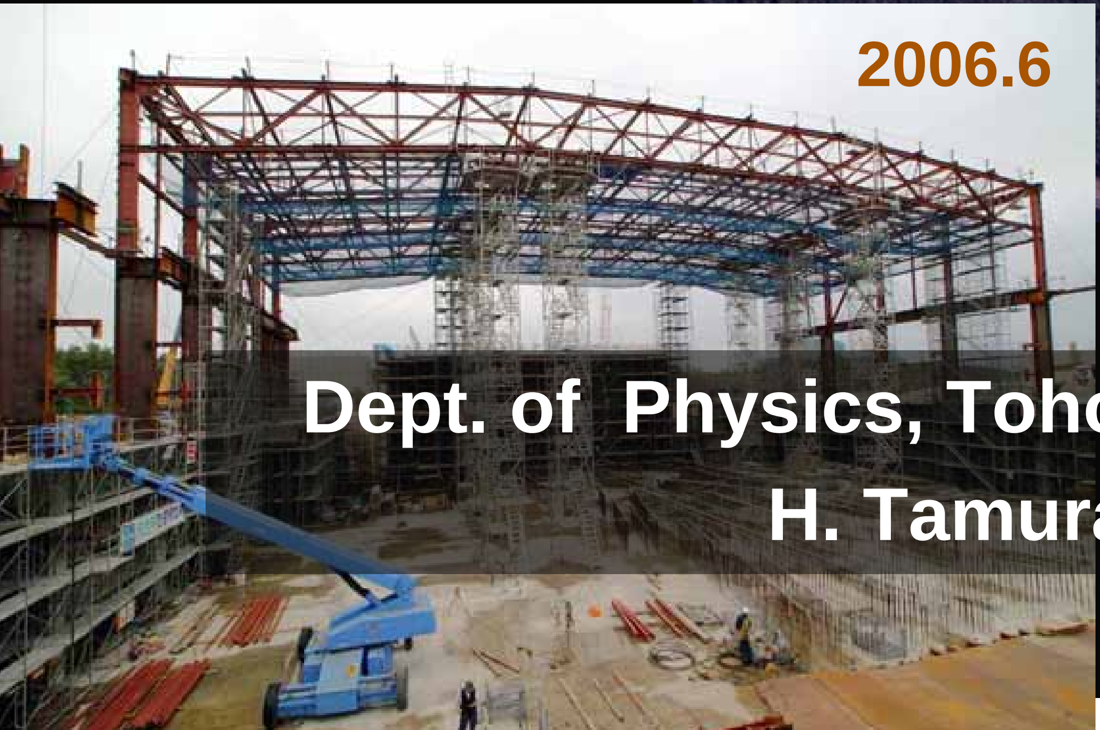
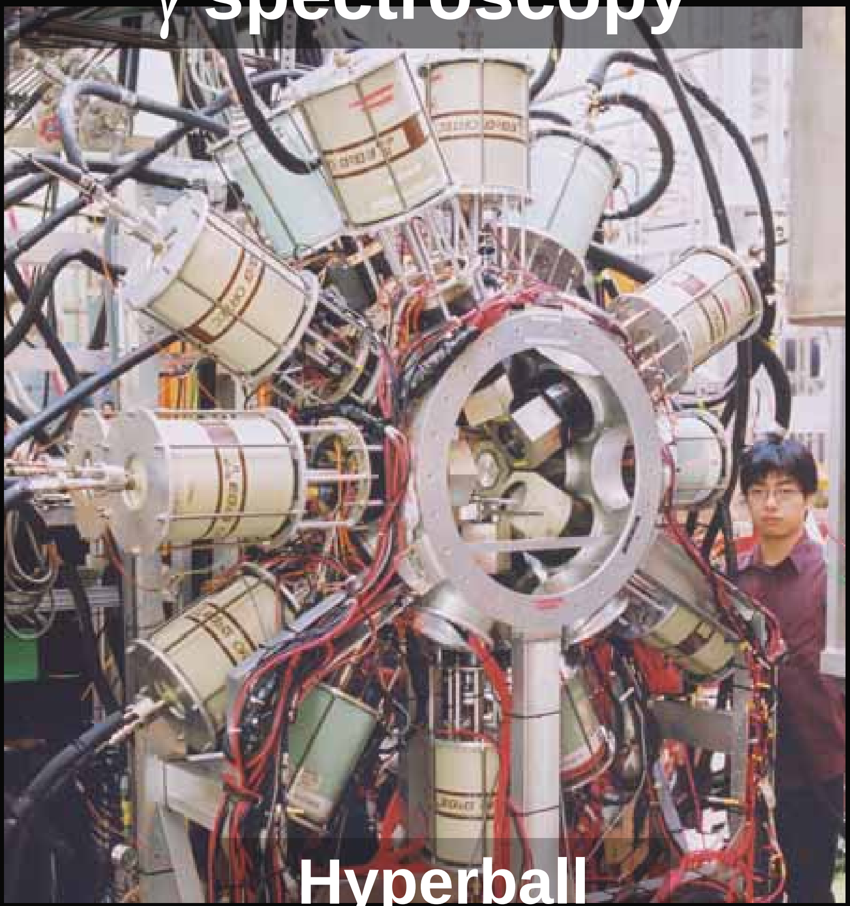
KEK Nuclear Theory WS
Aug. 2, 2006

Present Status and Future Plans of Hypernuclear experiments
-- S = -1 sector --



Dept. of Physics, Tohoku University
H. Tamura

Contents

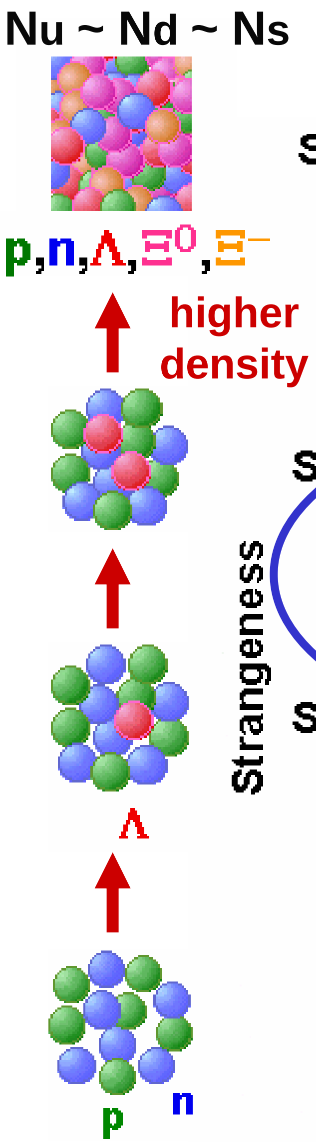

γ spectroscopy
Hyperball


$(e,e'K^+)$ spectroscopy
HKS @JLab

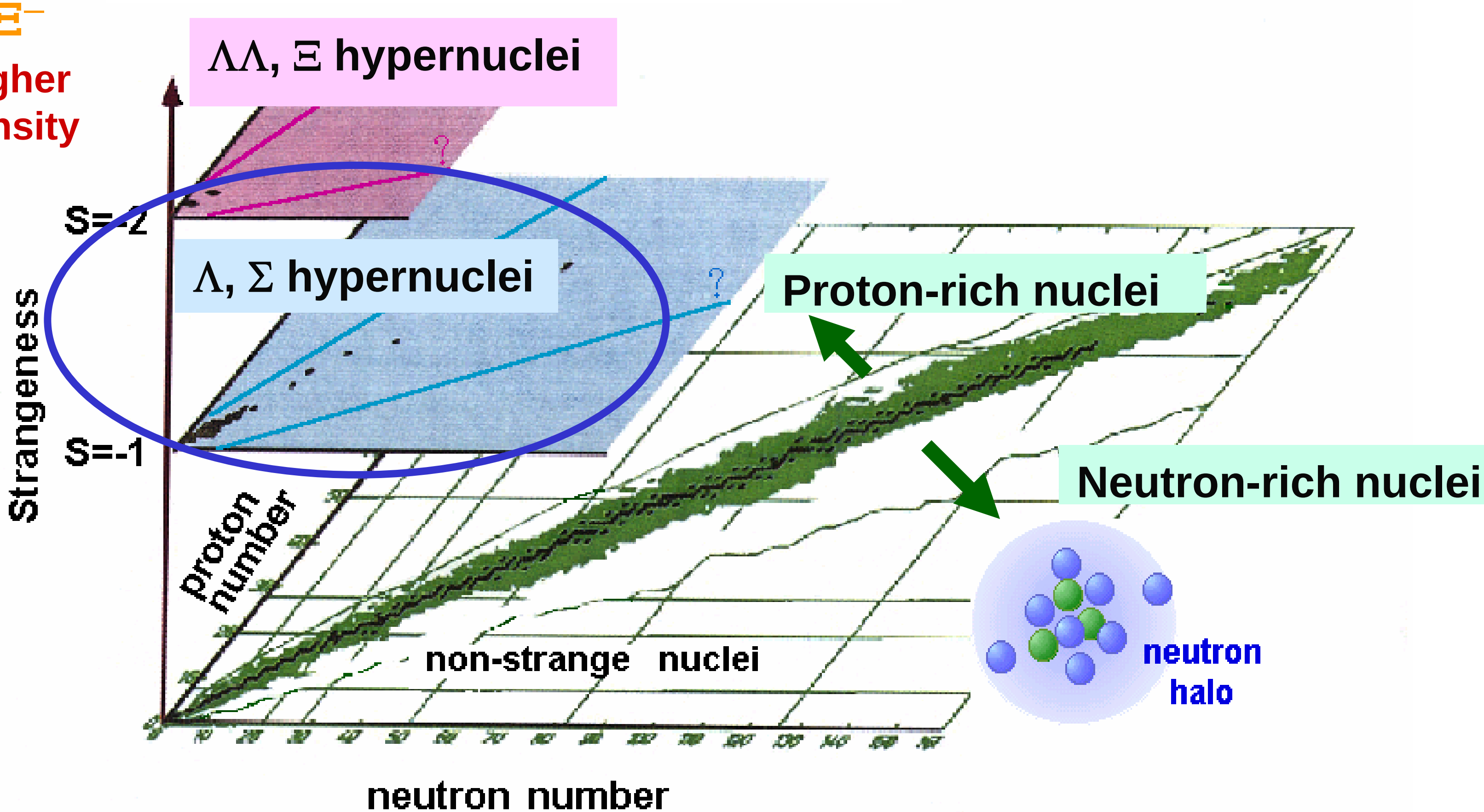

(π^-,K^+) spectroscopy
Weak decays
SKS @KEK

1. Introduction

World of matter made of u, d, s quarks

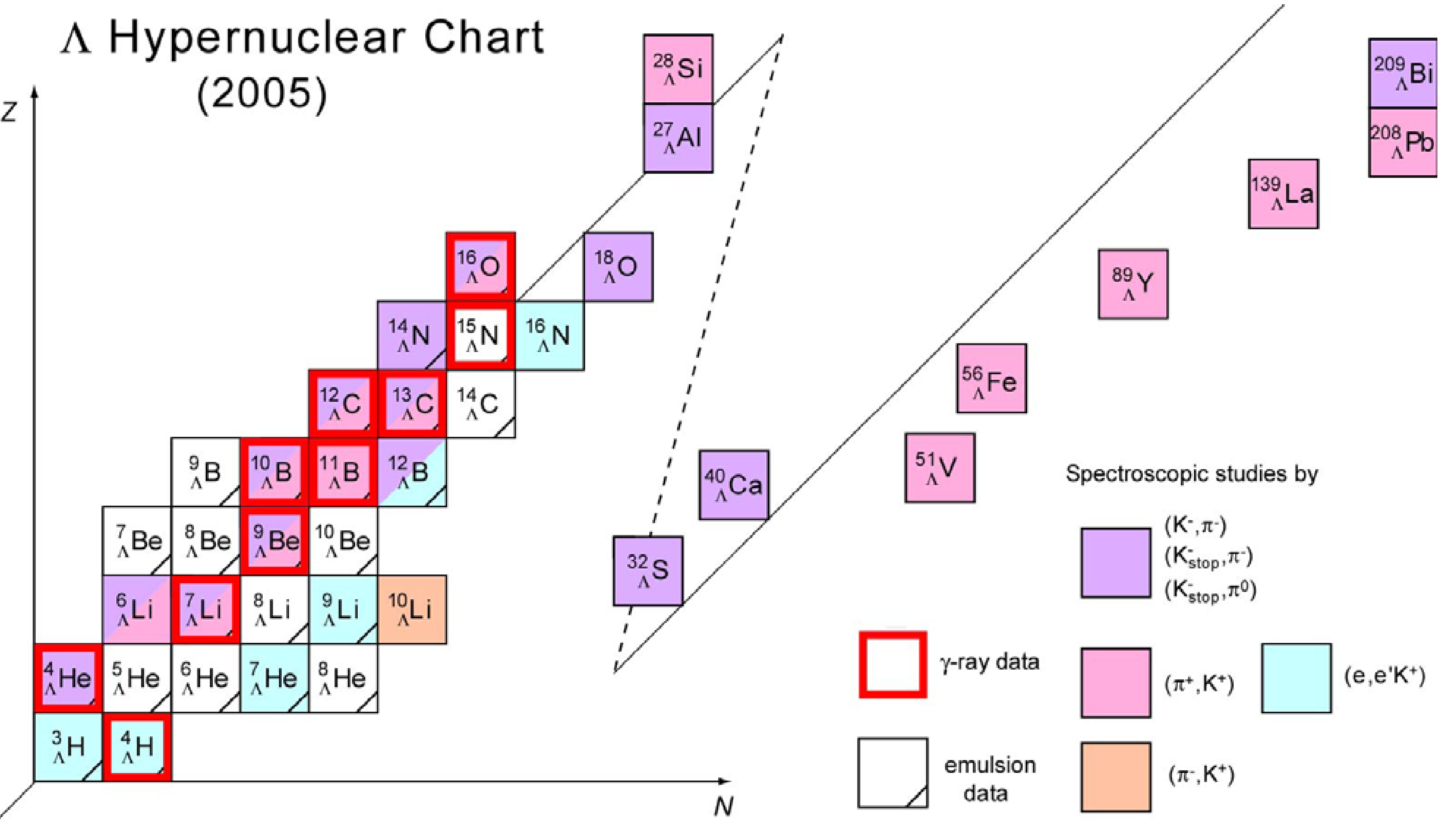


S: Strangeness in neutron stars ($\rho > 3 - 4\ \rho_0$)
Strange hadronic matter ($A \rightarrow \infty$)



3-dimensional nuclear chart

Present Status of
Λ Hypernuclear Spectroscopy

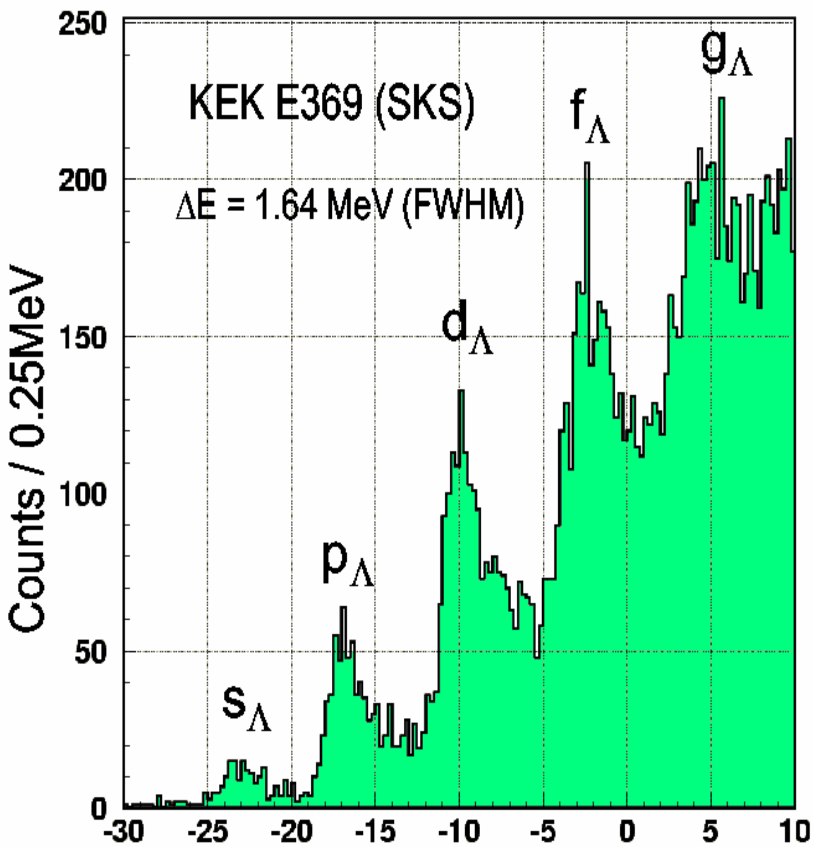


Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

(π^+,K^+) data and ΛN interaction

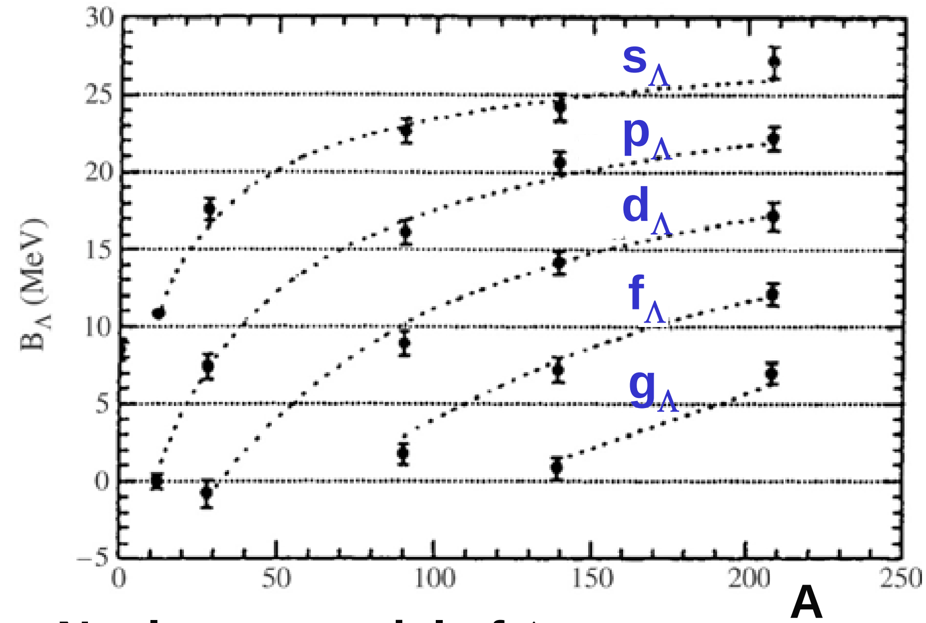
SKS at KEK-PS

^{89}Y (π^+,K^+) $^{89}{}_{\Lambda}$Y



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

Hotchi et al., Phys.Rev.C 64 (2001) 044302



-> Nuclear potential of Λ

U_{Λ} = - 30 MeV (c.f. U_N = -50 MeV)

-> spin-averaged central force of ΛN

Better resolution is necessary for

ΛN spin-dependent forces, ΛN-ΣN force, ..

γ, (e,e'K$^+$) spectroscopies

Unified understanding of B-B interactions in the quark (+meson) picture together with Σ and Ξ hypernuclear data

Present status of BB interactions from Hypernuclei

Established **Data** | **To be studied** **Necessary data**

S=-1

- **ΛN:** U_Λ = -30 MeV B_Λ, ^{89}Y (π^+,K^+) $^{89}{}_\Lambda$Y, etc.
  LS, spin-spin, tensor   γ-ray data ($^4{}_\Lambda$H, $^7{}_\Lambda$Li, $^9{}_\Lambda$Be, $^{13}{}_\Lambda$C, $^{16}{}_\Lambda$O, etc.)
  ΛN-ΣN   ($^3{}_\Lambda$H / $^4{}_\Lambda$H / $^5{}_\Lambda$He)
  odd-state force, r-dependence, charge symmetry breaking
  More γ-ray data, high resolution (e,e'K^+) and (π^-,K^+) data

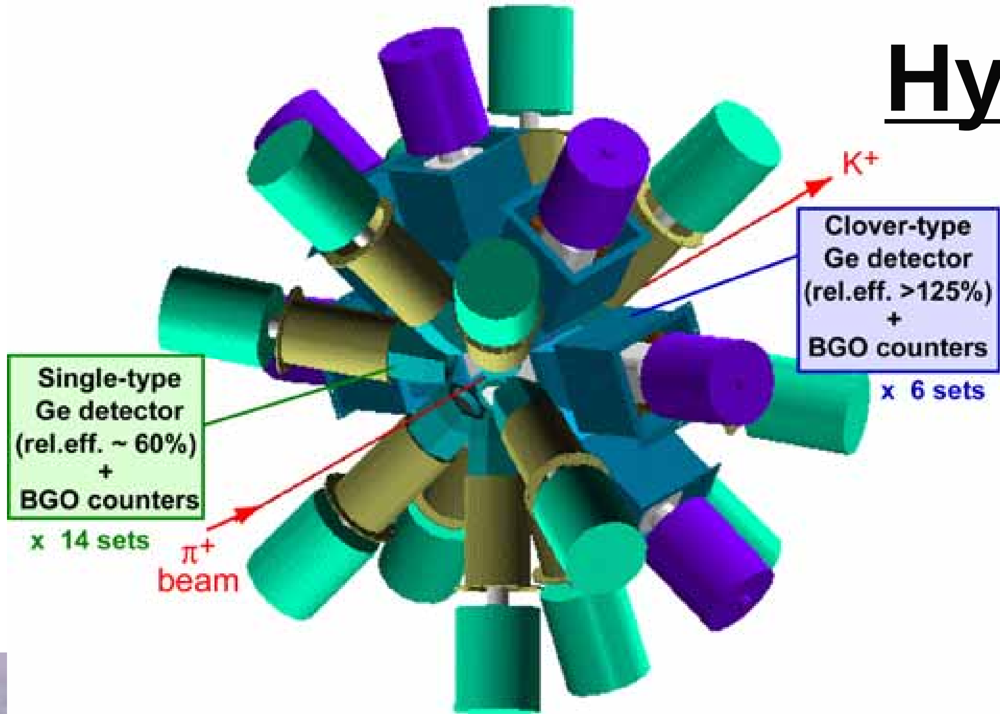
- **ΣN:** U_Σ strongly repulsive ^{28}Si (π^-,K^+) $^{28}{}_\Sigma$Si,..
  strong isospin-dependence $^4{}_\Sigma$He (T=1/2, T=3/2)
  LS   ΣN scattering data
  U_Σ, spin-isospin dependence   High resolution (π^-,K^+) $^A{}_\Sigma$Z data

S=-2

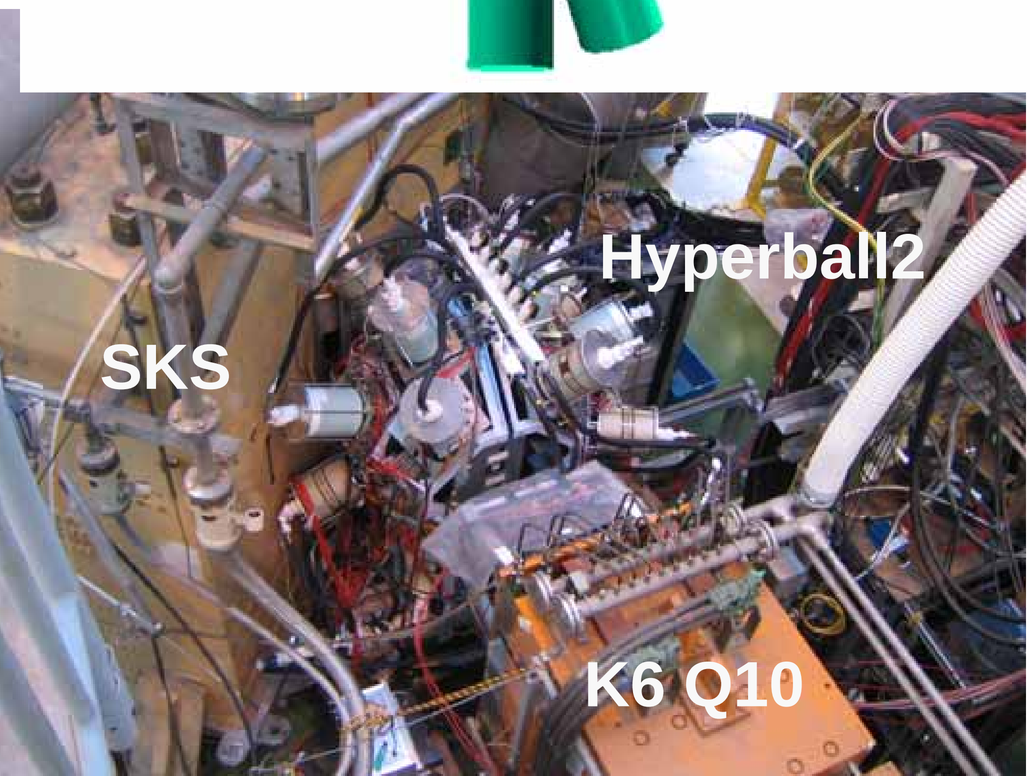
- **ΛΛ:** weakly attractive ($\Delta B_{\Lambda\Lambda}$= 1.0 MeV) $^6{}_{\Lambda\Lambda}$He
- **ΞN:** U_Ξ (~ -14 MeV? ^{12}C(K^-,K^+) $^{12}{}_\Xi$Be)
  spin-isospin dependence
  ΞN-ΛΛ
  H dibaryon resonance?
  H-like correlation in nucleus?
  } High resolution (K^-,K^+) $^A{}_\Xi$Z data
  More $_{\Lambda\Lambda}$Z events and their decays

2. γ-Ray Spectroscopy

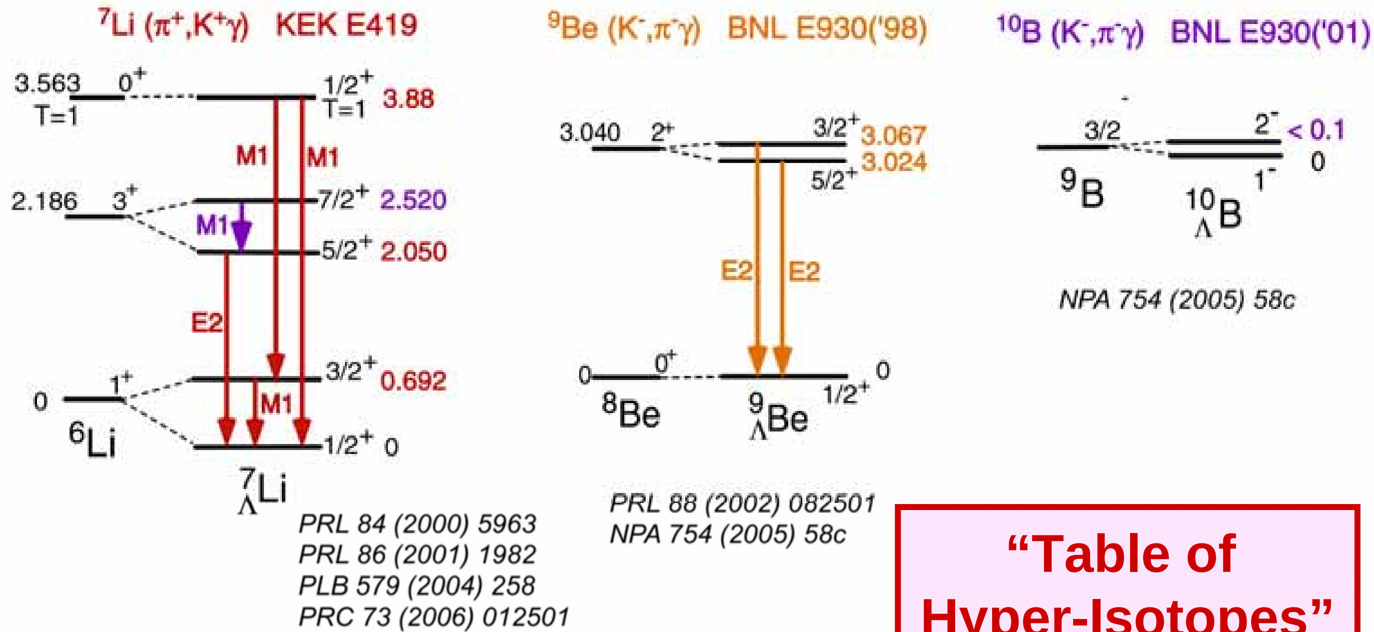
Hyperball2 (2005~)



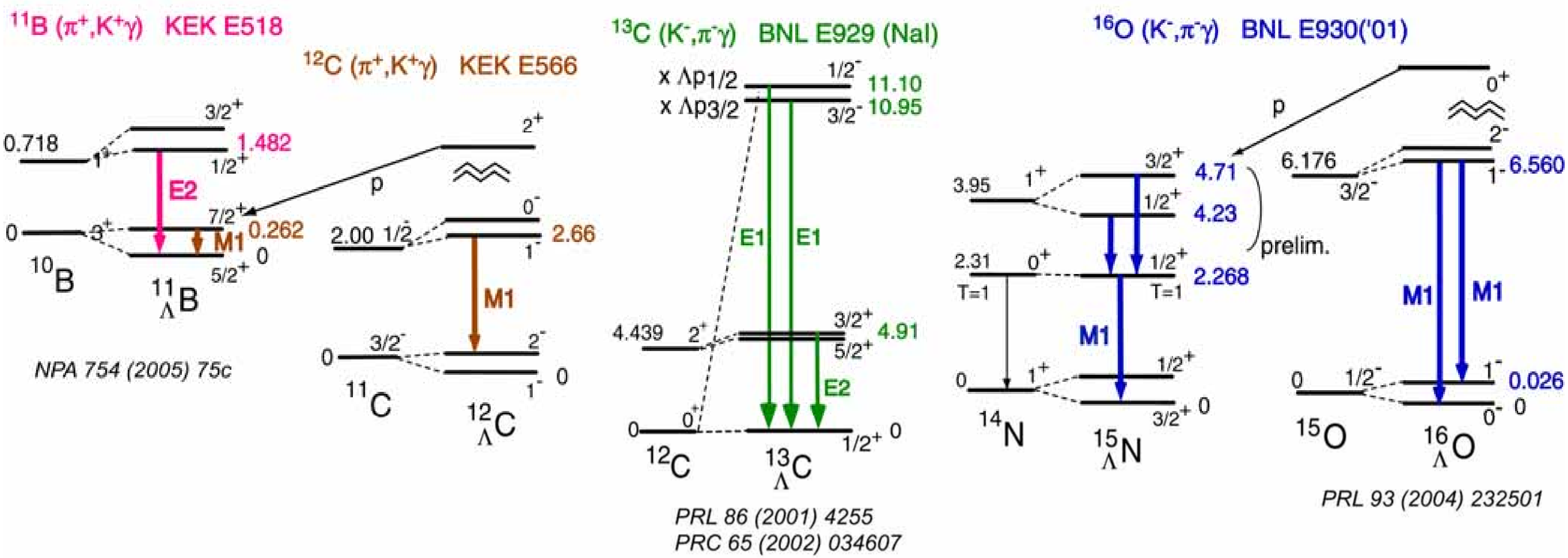
Efficiency 2.5% -> 5%



Status of hypernuclear γ spectroscopy



"Table of Hyper-Isotopes"



ΛN Spin-dependent interactions and γ spectroscopy

- **Two-body ΛN effective interaction**

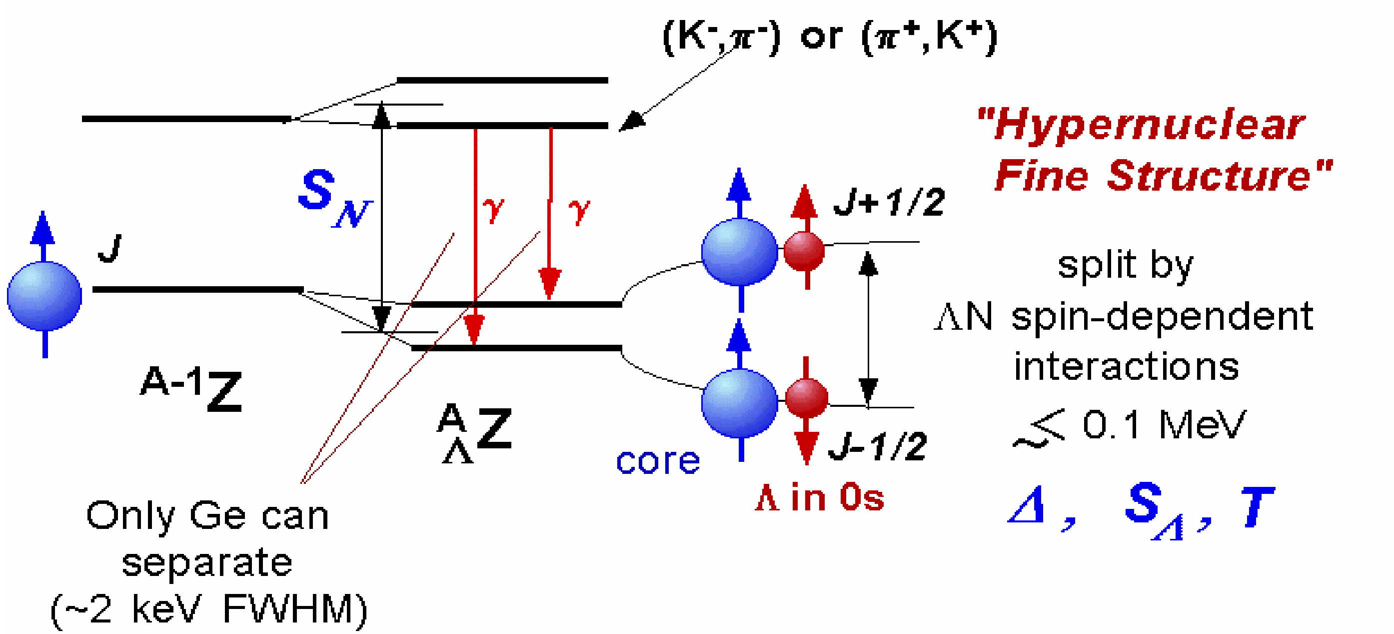
Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

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

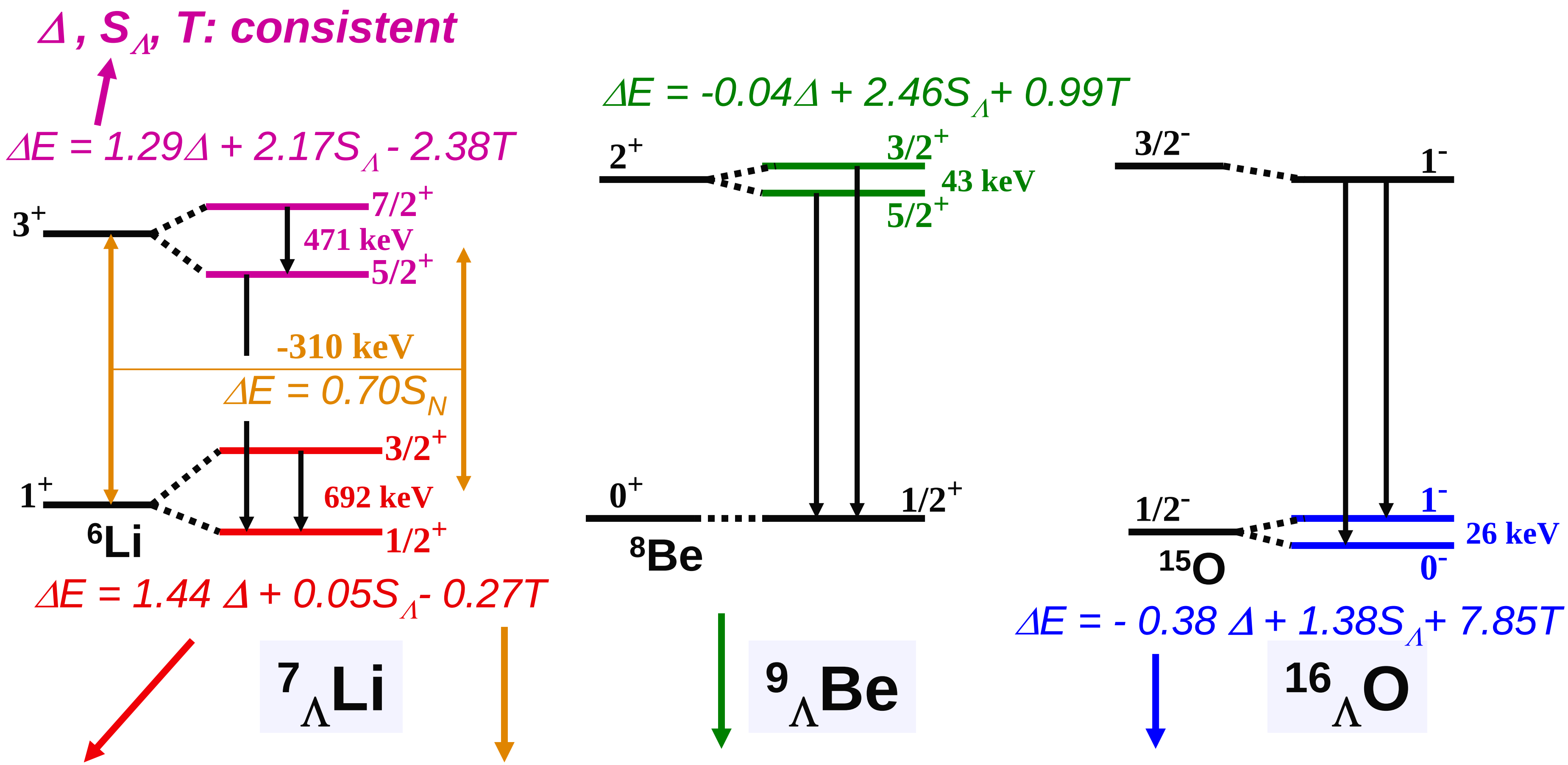
Δ $\qquad S_\Lambda$ $\qquad S_N$ $\qquad T$

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

- **Low-lying levels of Λ hypernucleus**



Determination of the spin-dependent force parameters



Δ = 0.4 MeV S_N = - 0.4 MeV S_Λ = - 0.01 MeV T = 0.03 MeV

PRL 86 ('00) 5963 PRL 88 ('02) 082501 PRL 93 (2004) 232501

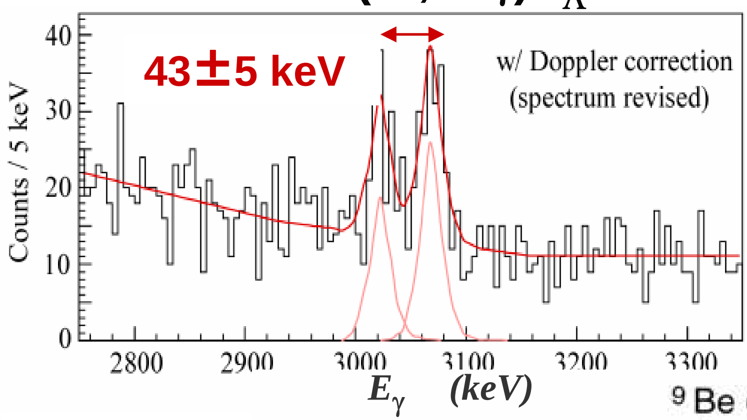
All the spin-dependent force parameters determined.

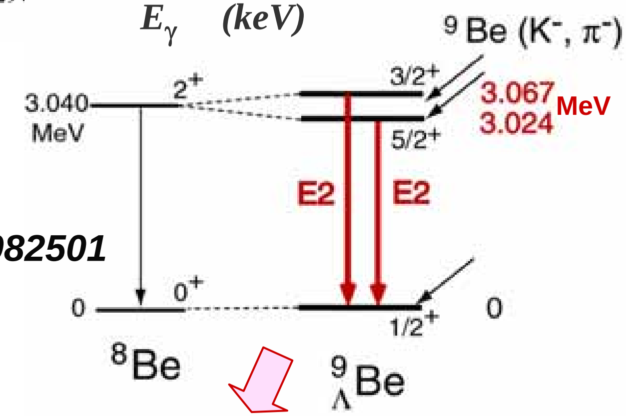
Study of ΛN interaction from γ spectroscopy

BNL E930 (AGS D6 line + Hyperball)

Discovery of "Hypernuclear Fine Structure"

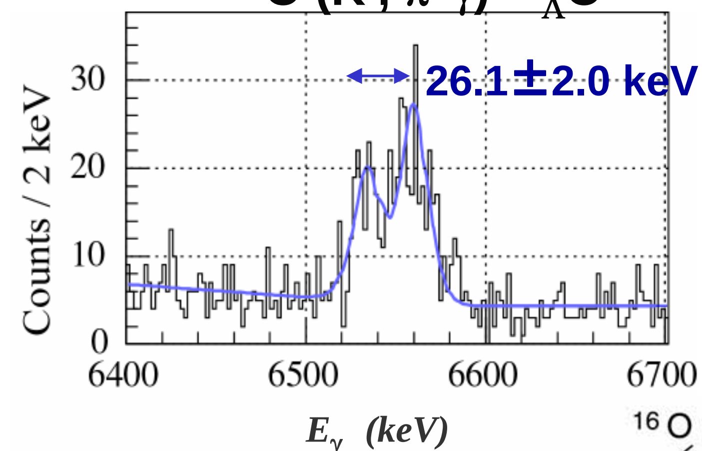
^{9}Be (K$^-$, π$^-$ γ) $^9_\Lambda$Be

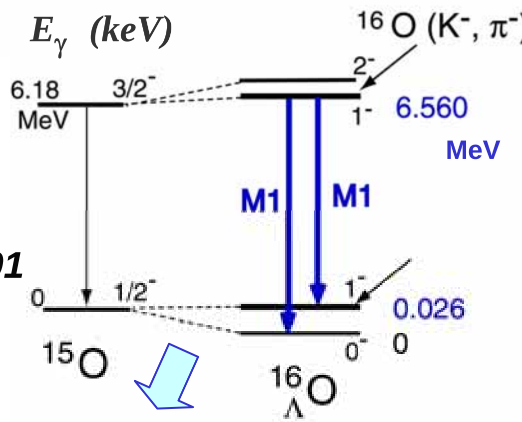




Akikawa et al., PRL 88 (2002) 082501

^{16}O (K$^-$, π$^-$ γ) $^{16}_\Lambda$O





Ukai et al., PRL 93 (2004) 232501

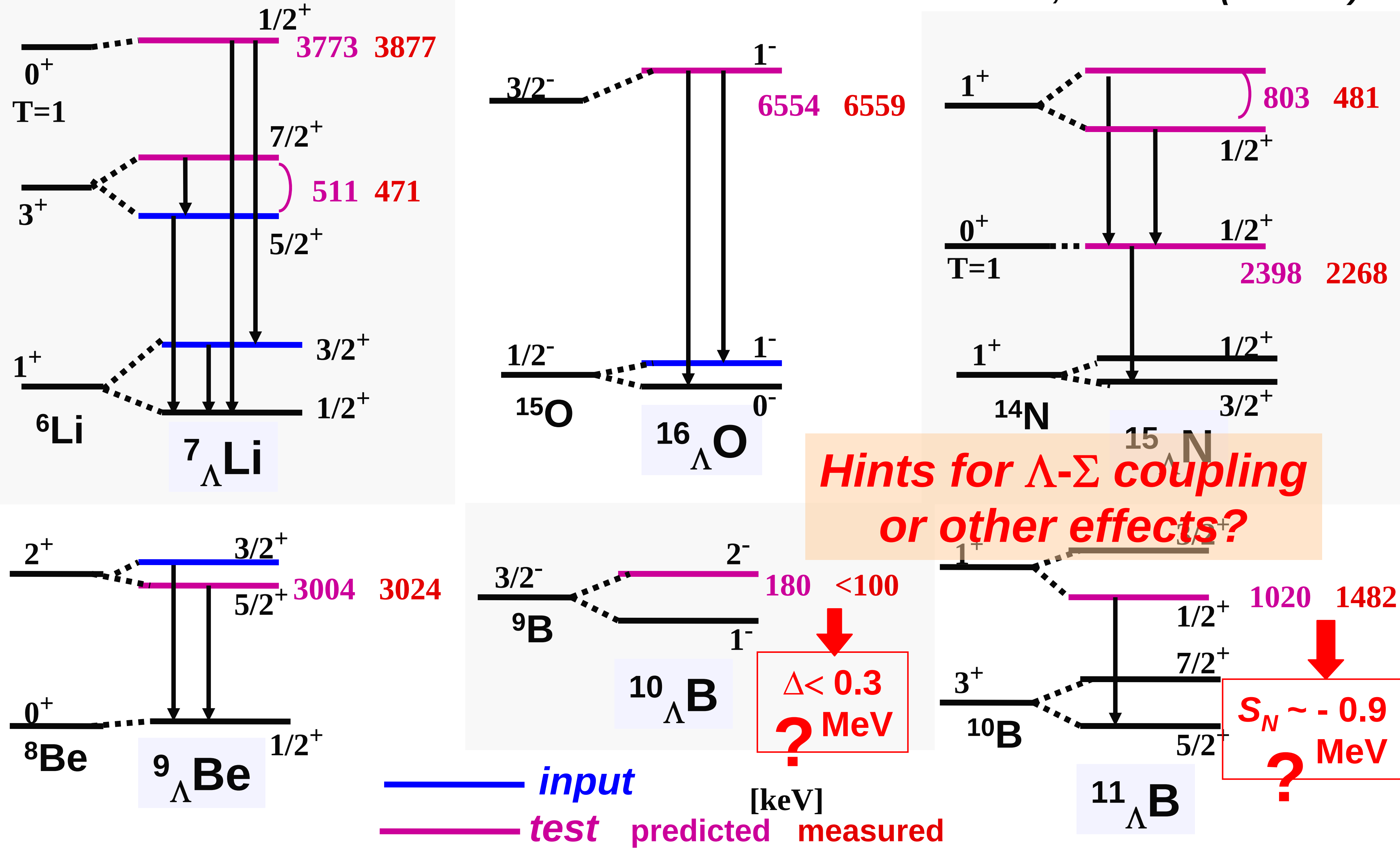
ΛN spin-orbit force: S_Λ = -0.01 MeV
=> *agree with quark-model predictions*

ΛN tensor force: T = 0.03 MeV
=> agree with meson-exchange model predictions

Consistency Test (Millener's framework)

***Δ* = 0.4 MeV, S_Λ = - 0.01 MeV, S_N = - 0.4 MeV, *T* = 0.03 MeV**

+ size correction, ΣΛ effect (Millener)



Comparison with BB interaction models

	Δ	S_Λ	S_N	T	(MeV)
ND	-0.048	-0.131	-0.264	0.018	G-matrix calc. by Yamamoto
NF	0.072	-0.175	-0.266	0.033	
NSC89	1.052	-0.173	-0.292	0.036	
NSC97f	0.754	-0.140	-0.257	0.054	
("Quark"		0.0	-0.4	)	
Exp.	0.4	-0.01	-0.4	0.03	

Strength equivalent to quark-model LS force by Fujiwara et al.

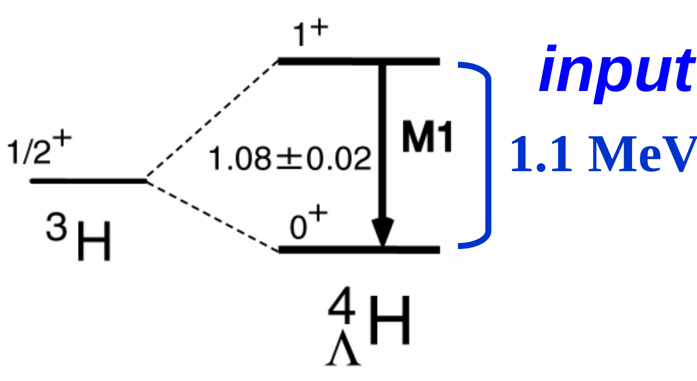
- Spin-orbit forces (S_Λ, S_N) cannot be explained by meson models. Data seems to favor quark models. Consistent with Hiyama et al.

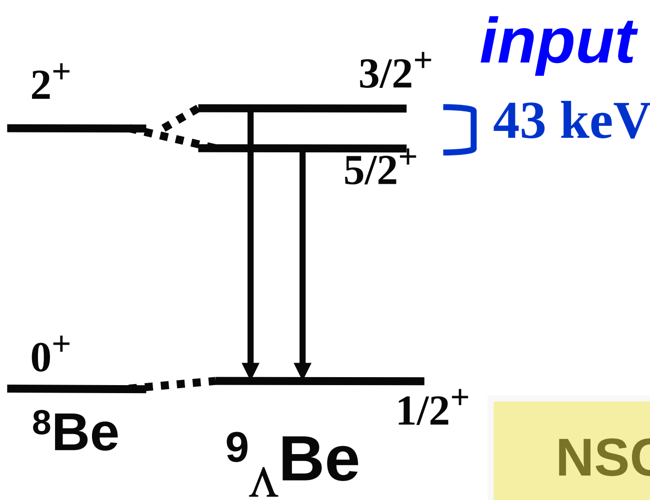
--but ${}^{9}_{\Lambda}$Be calculation by Fujiwara et al. (quark+meson) cannot reproduce it.

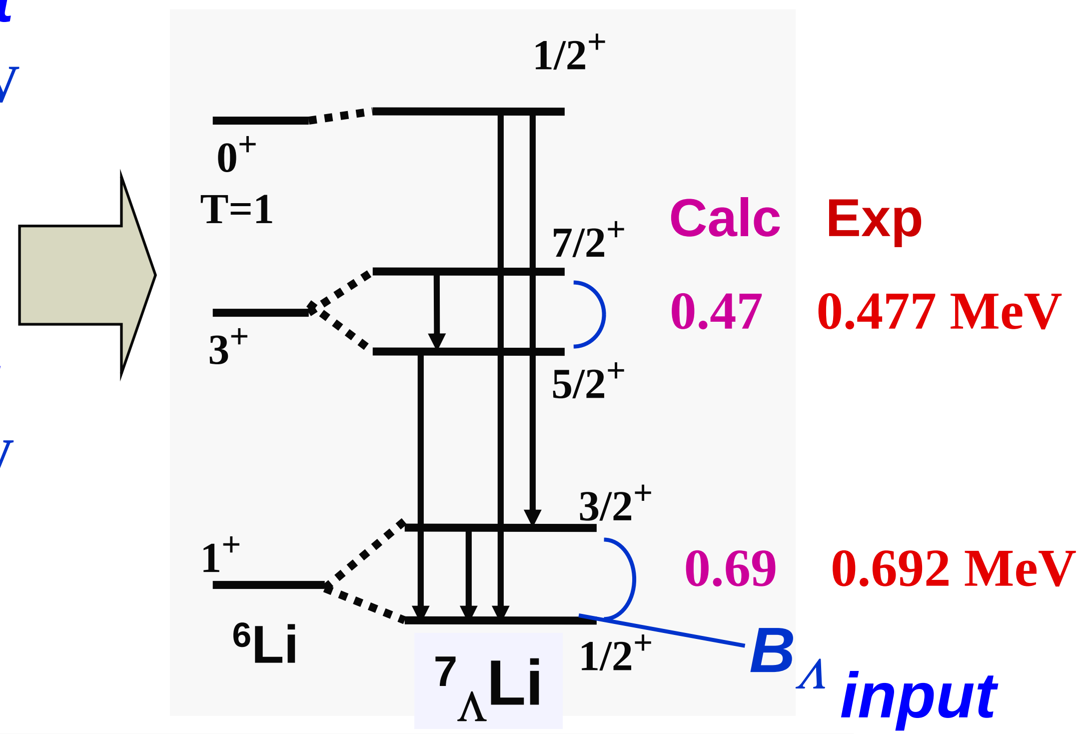
- Tensor forces (T) is well explained by meson-exchange models.

Extraction of YN interaction properties by cluster model

Hiyama et al., PRC submitted.





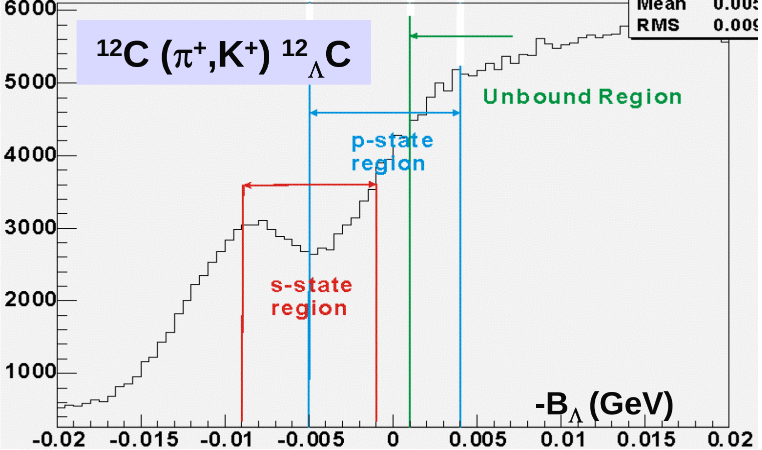


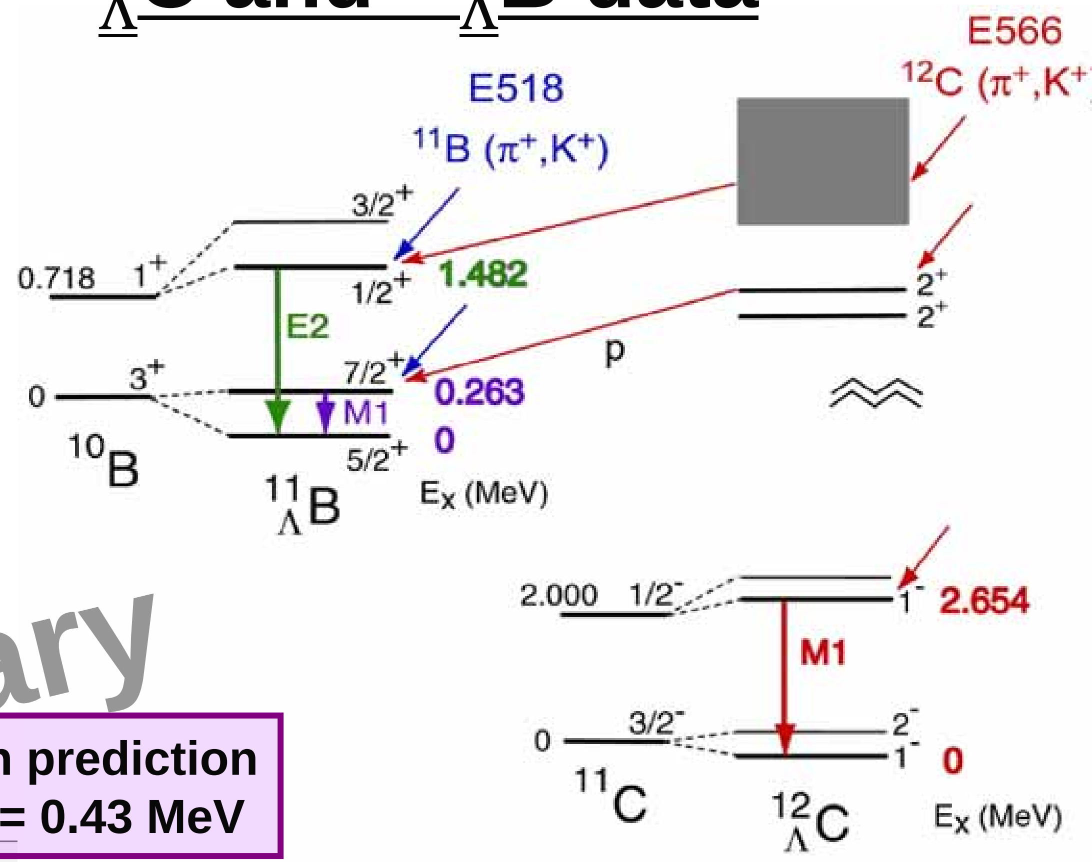
NSC97f

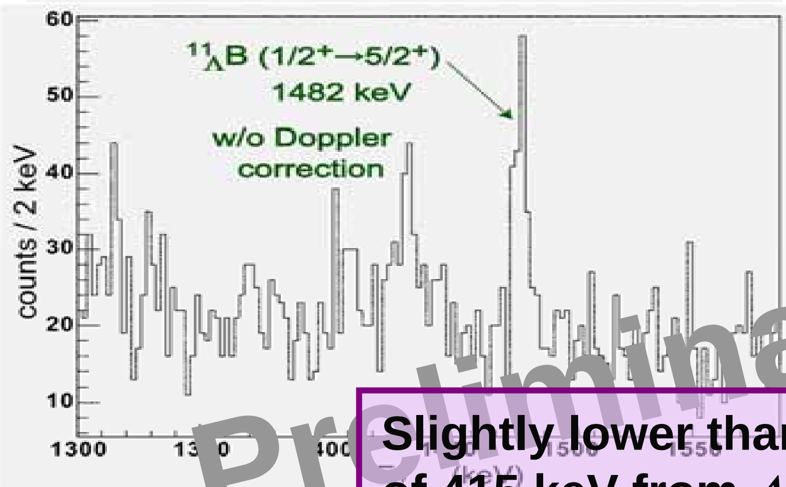
+ V(E1), V(E3), V(O1), V(O3) adjusted

+ V(ALS)= - 0.83 V(SLS)

$^{12}_{\Lambda}$C and $^{11}_{\Lambda}$B data

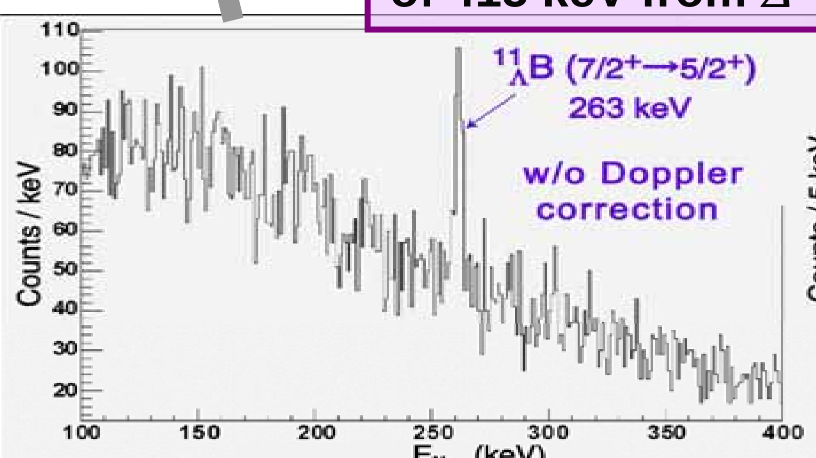


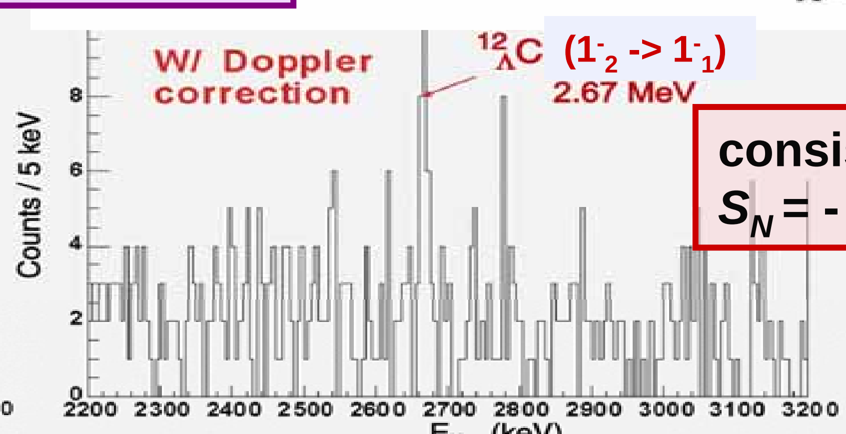




Preliminary

Slightly lower than prediction of 415 keV from Δ = 0.43 MeV





consistent with S_N = - 0.43 MeV

Proposed DAY-1 experiment at J-PARC

$(K^-,\pi^- \gamma)$ at p_K = 1.5 GeV/c

Feasible even with low intensity beam (~2μA)

(1) Spin-flip B(M1) measurement and g_Λ in a nucleus

$^7_\Lambda$Li : Least ambiguities exist and most reliable. (500 hrs)

(2) Further ΛN interaction study from p-shell hypernuclei

$^{10}_\Lambda$B and $^{11}_\Lambda$B: (100+200 hrs)

Confirmation of ΛN spin-dependence
ΛN–ΣN coupling

Inconsistency exists.
Experimental data not enough.
Few-body approach as well as shell model is possible.

(3) Radial dependence of ΛN interaction from sd-shell hypernuclei

$^{19}_\Lambda$F : Easiest in sd-shell (100 hrs)

(4) Charge symmetry breaking in ΛN interaction and spin-flip property in hypernuclear production

$^4_\Lambda$He : Largest CSB is suggested but previous data is suspicious.
Easiest to observe a spin-flip state (100 hrs)

$(K^-,K^+ \gamma)$ at p_K = 1.8 GeV/c

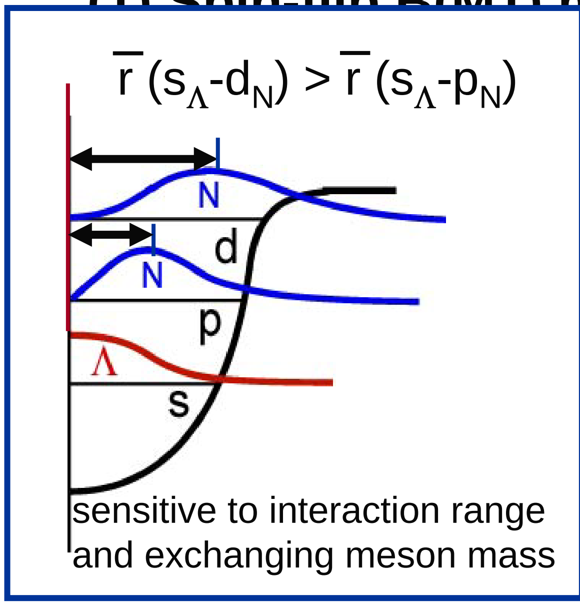
Ξ-atomic X-ray measurement (Ag, Br, Fe,..) -> ΞN interaction

Proposed DAY-1 experiment at J-PARC

$(K^-,\pi^-\gamma)$ at p_K = 1.5 GeV/c

Feasible even with low intensity beam (~2μA)

(1) Spin-flip B(M1) measurement and g_Λ in a nucleus



biguities exist and most reliable. (500 hrs)

action study from p-shell hypernuclei

.00+200 hrs)

Confirmation of ΛN spin-dependence

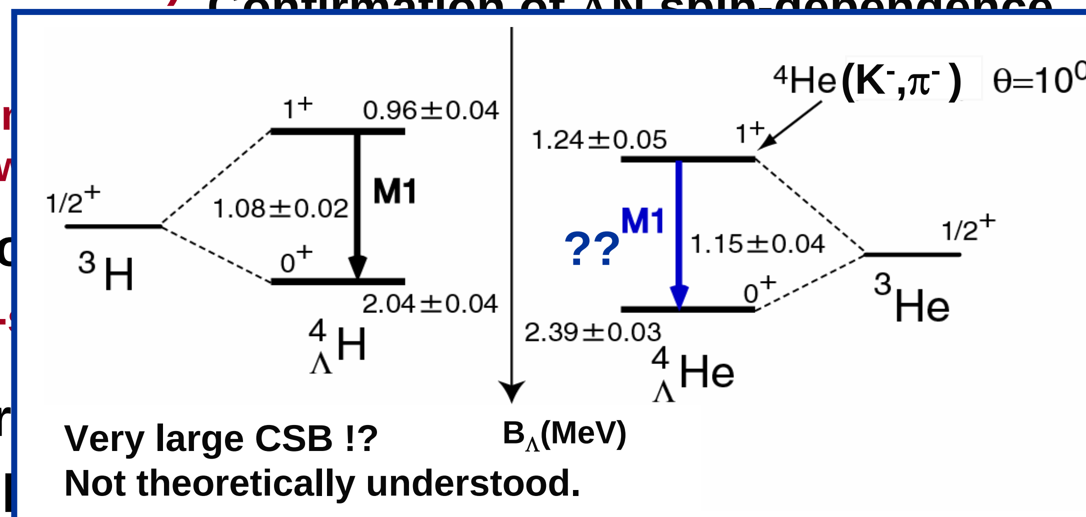
s.

not er

n as w

nce o

n sd-s



(4) Charge symmetry br

spin-flip property in l

$^4_\Lambda$He : Largest CSB is suggested but previous data is suspicious.

Easiest to observe a spin-flip state (100 hrs)

$(K^-,K^+\gamma)$ at p_K = 1.8 GeV/c

Ξ-atomic X-ray measurement (Ag, Br, Fe,..) -> ΞN interaction

B(M1) measurement and g_Λ in nucleus

μ_Λ in nucleus -> medium effect of baryons

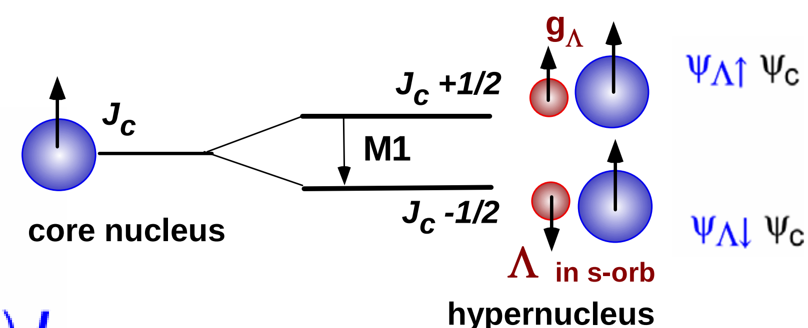
- Direct measurement of μ -- extremely difficult.
- **B(M1) of Λ-spin-flip M1 transition -> g_Λ**

Can be investigated using a Λ in 0s orbit

Established for "hypernuclear shrinkage" in $^{7}_{\Lambda}$Li from B(E2) : *PRL 86 ('01)1982*

~100% **Doppler Shift Attenuation Method**

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



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

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

$$\mu = g_c \boldsymbol{J}_c + g_\Lambda \boldsymbol{J}_\Lambda = g_c \boldsymbol{J} + (g_\Lambda - g_c)\boldsymbol{J}_\Lambda$$

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

Difficulty:

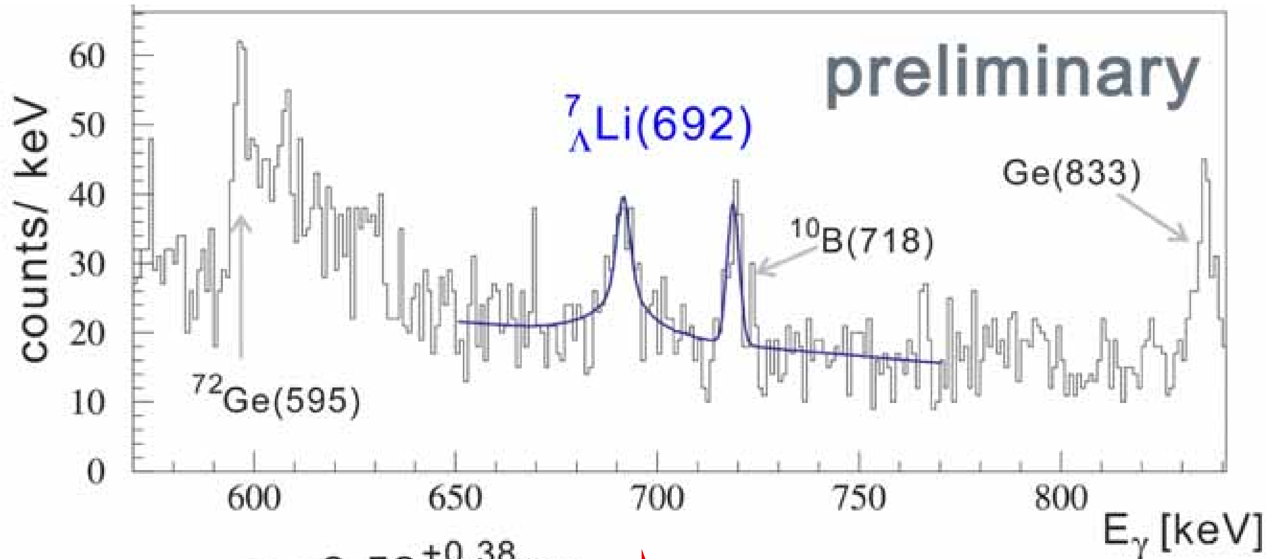
DSAM works only when $\tau \lesssim t_{stop}$

τ is very sensitive to E_γ as B(M1) $\propto 1/\tau \propto E_\gamma^3$. But E_γ is usually unknown.

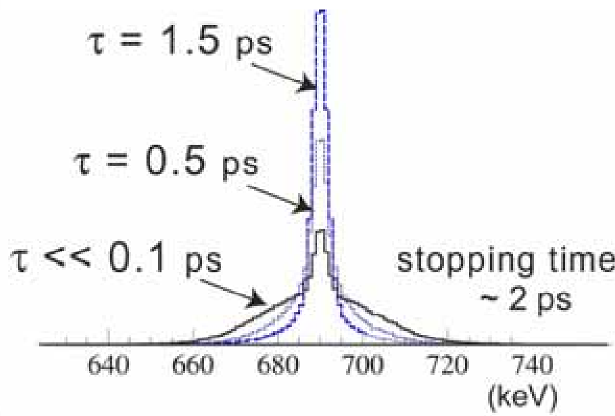
Test data on B(M1) in $^{7}_{\Lambda}$Li (BNL E930)

^{10}B (K$^-$, π^-) $^{10}_{\Lambda}$B*, $^{10}_{\Lambda}$B*(3$^+$) -> $^{7}_{\Lambda}$Li*(3/2$^+$) + ^{3}He

indirect population



simulation



$\tau = 0.58^{+0.38}_{-0.20}$ ps

BR(M1)=100%

$B(M1) = 0.30^{+0.12}_{-0.16}$ [μ_N^2]

$g_\Lambda = 1.1\ ^{+0.4}_{-0.6}\ \mu_N$

preliminary
(statistical error only)

First data of g_Λ in nucleus

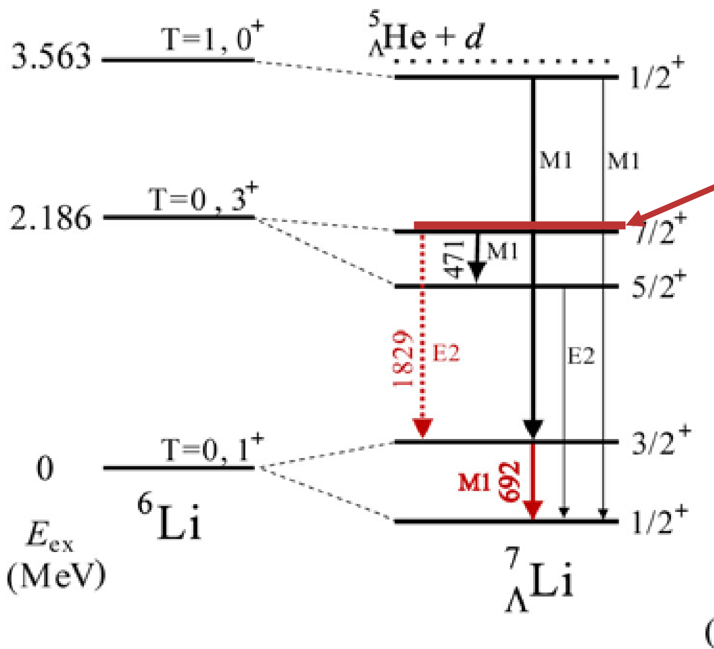
g_Λ(free) = 1.226 μ_N

Indirect population => more background, ambiguities in production

Proposed B(M1) measurement at J-PARC

To avoid ambiguities, we use the best-known hypernucleus, $^{7}_{\Lambda}$Li.

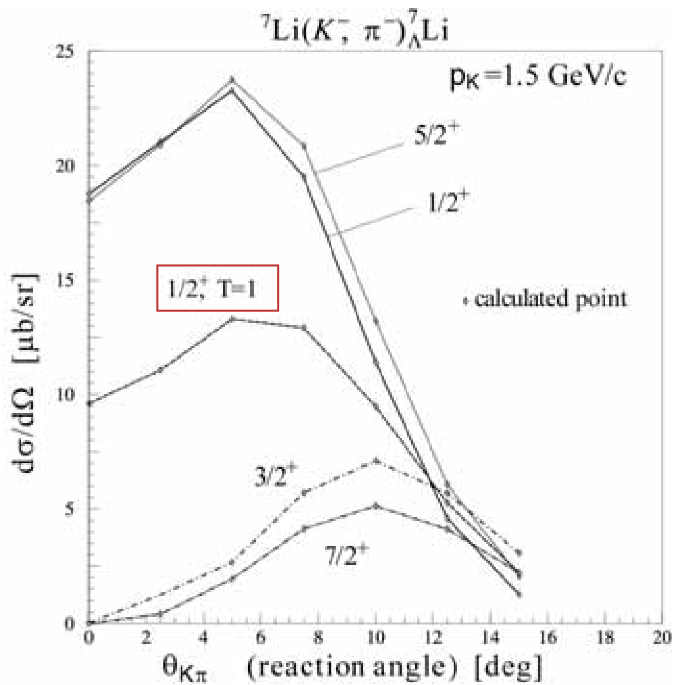
- Energies of all the bound states and B(E2) were measured,
- γ-ray background level was measured,
- cross sections are reliably calculated.
- τ = 0.5ps, t_{stop} = 2-3 ps for 1.5 GeV/c (K^-,π^-) and Li_2O target



	E_{ex} (MeV)	τ (ps) [exp]	τ (ps) [calc]
	3.94		
1/2+	3.877		
7/2+	2.521		1.3~1.6
5/2+	2.050	5.8	9.1
3/2+	0.692	~0.5	0.48~0.56
1/2+	0		

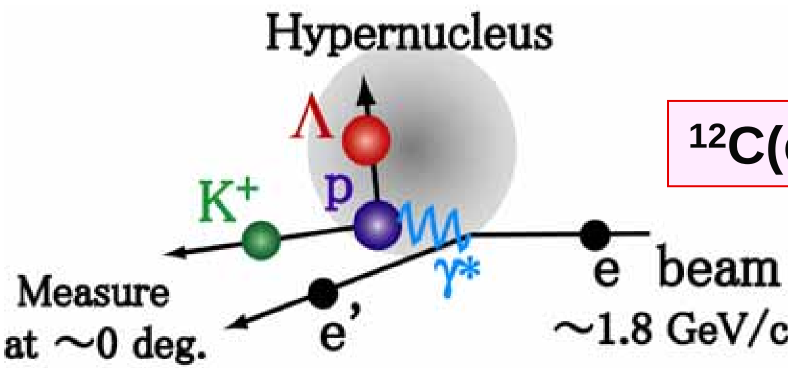
PRL 84 (2000) 5963
PRC 73 (2006) 012501

Calc. by Motoba

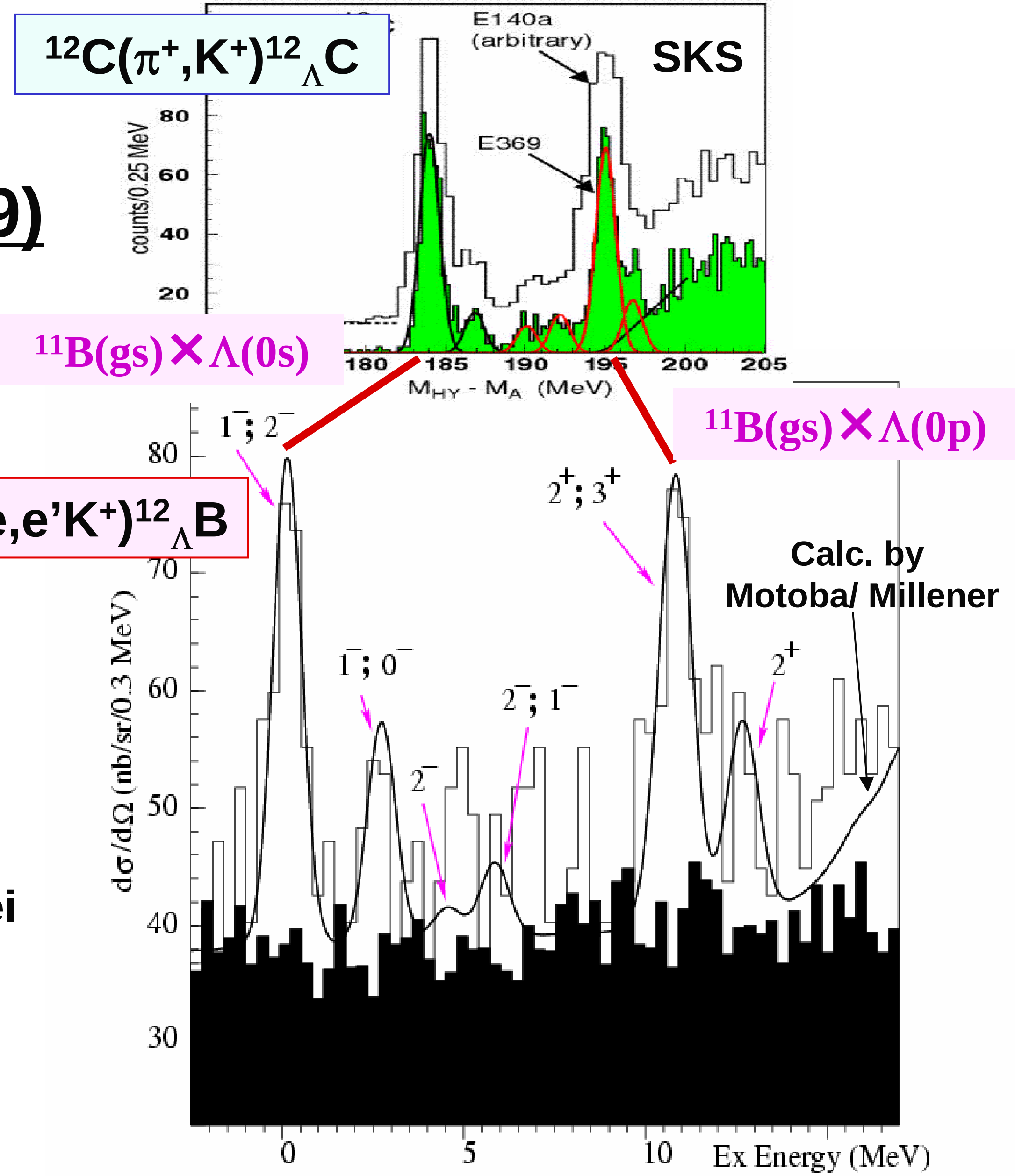


3. $(e,e'K^+)$ Spectroscopy

First (e,e'K$^+$) Data
-- Jlab Hall C (E89-009)

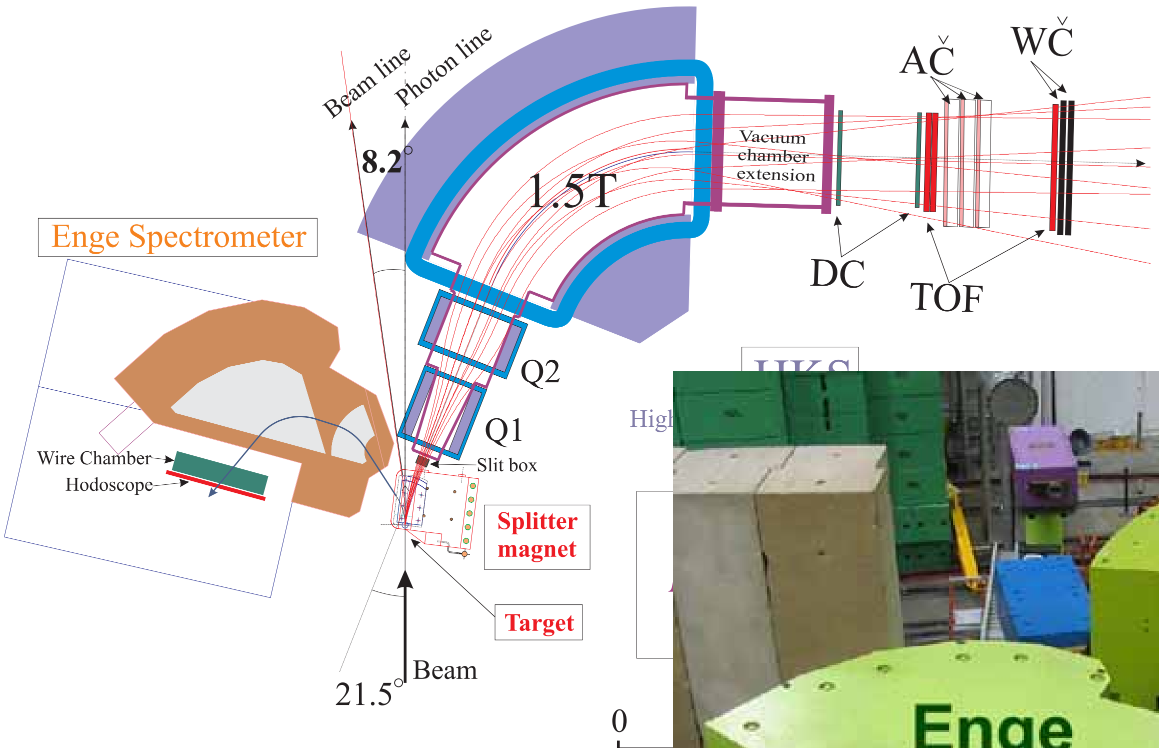


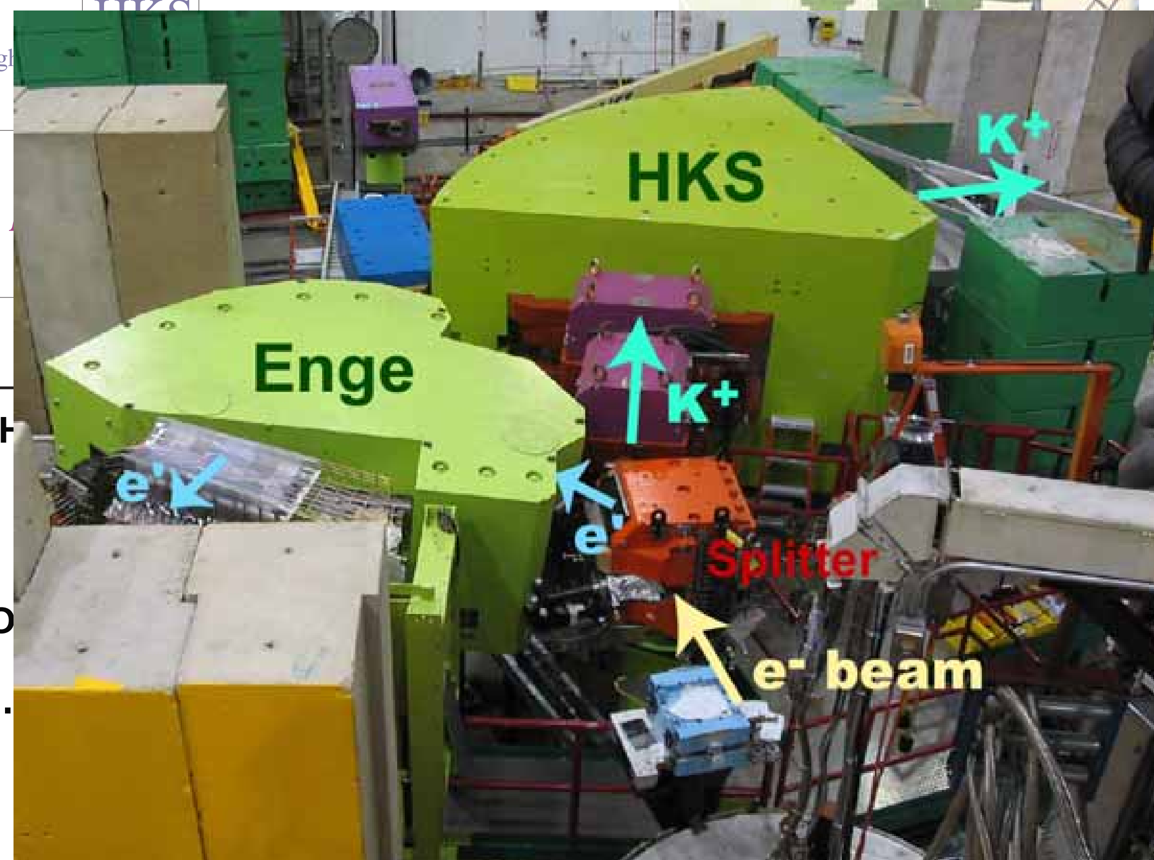
- Spin-flip states
- p->Λ : mirror/ n-rich hypernuclei
- Resolution can be improved.
  - ≧1.5 MeV FWHM by (π^+,K$^+$)
  - ↓
  - 0.9 MeV FWHM by (e,e'K$^+$)
  - ↓
  - 0.3~0.4 MeV FWHM w/ HKS



Miyoshi et al., PRL 90 (2003) 232502.

HKS @ Hall C --Dedicated $(e,e'K^+)$ Spectrometer





High-resolution Kaon Spectrometer (H

***Δp/p* = 5 x 10 $^{-4}$ -> 2 x 10 $^{-4}$ [FWHM]**

***Ω* = 4 msr -> 16 msr (w/ splitter)**

Tilt method

Avoid bremss. & Moeller electron bg.

singles rate ~ 200 MHz → < 1 MHz

=> much higher beam current

heavier targets

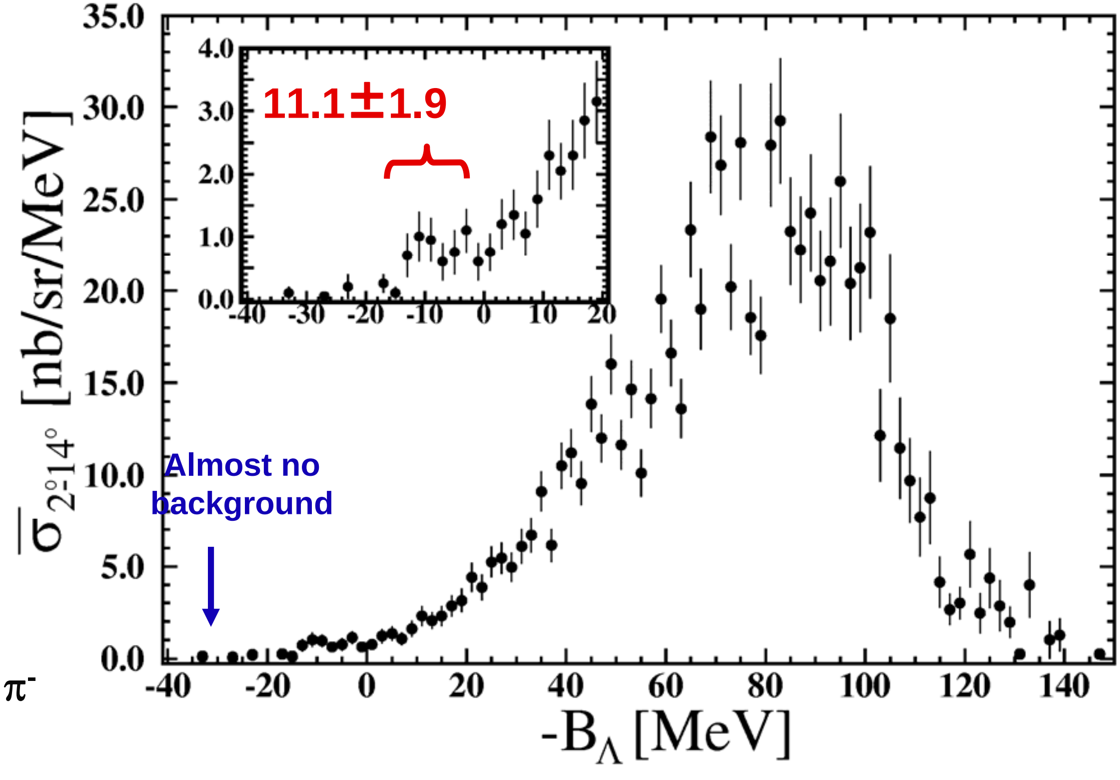
4. Neutron-Rich Λ Hypernuclei

(π^-,K$^+$) Reaction Data (KEK E521, K6+SKS)

1.2 GeV/c ^{10}B (π^-, K$^+$) $^{10}_{\Lambda}$Li

Motivation

- Production mech.
  2-step charge exch.
  (π^-p->π^0n, π^0p->K$^+\Lambda$ etc.)
  Σ^- admixture (π^- p->Σ^- K$^+$, Σ^- p->Λn)
- Λ–Σ coherent coupling
- Behavior of n-halo with a Λ



Results

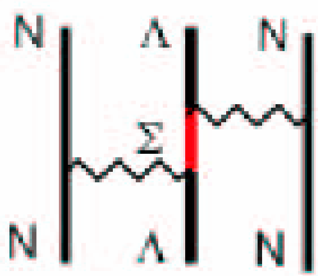
- Larger cross section for 1.2 GeV/c π^- than 1.05 GeV/c
  -> Σ contrbution is large ?
- Cross section for bound region
  (π^-,K$^+$) / (π^+,K$^+$) ~1x10^{-3}

Saha et al., PRL 94 (2005) 052502

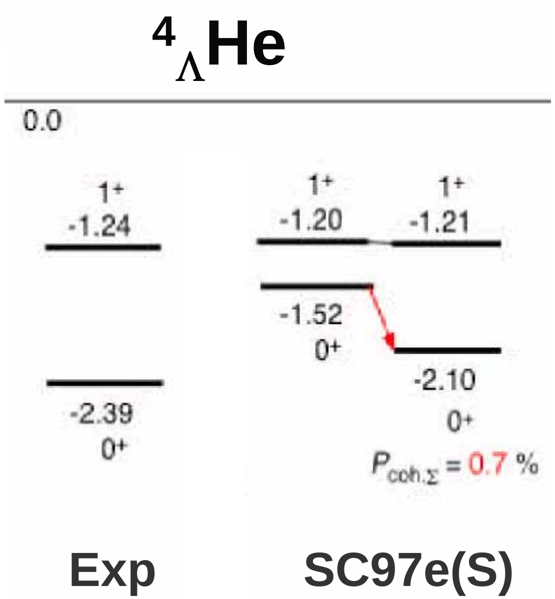
First data on n-rich hypernucleus

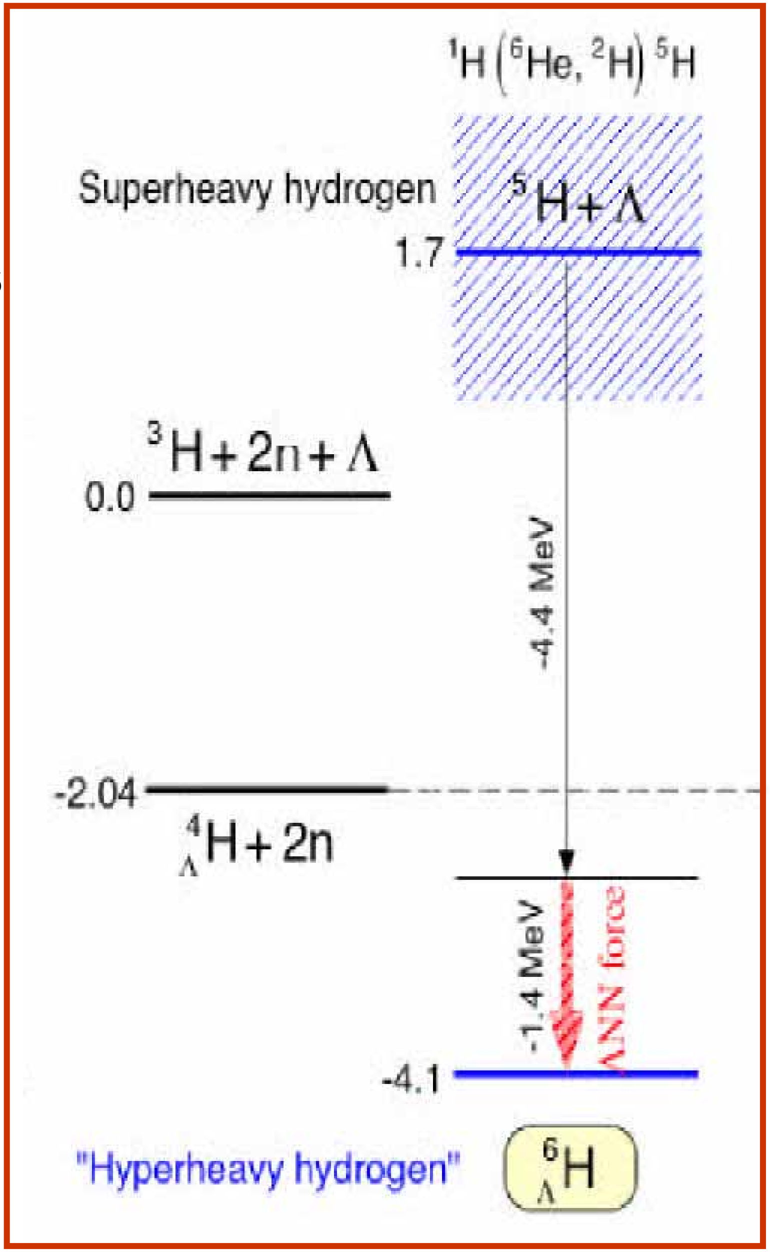
Coherent Λ-Σ coupling and n-rich hypernuclei

- **Correctly describes the binding energies of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H/ $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He**
  (Solves the overbinding problem of $^{5}_{\Lambda}$He)
- **Important for large-T hypernuclei**
- **Large effect on structure and cross sections**



Akaishi et al., PRL 84 (2000) 3539





Study of n-rich hypernuclei at J-PARC

Proposed by Sakaguchi et al.

(π^-,K^+) reaction with SKS and K1.8
10^7 pions/spill -- Not limited by proton beam intensity

$^{6}Li\ (\pi^-,K^+)\ ^{6}_{\Lambda}H$

$^{9}Be\ (\pi^-,K^+)\ ^{9}_{\Lambda}He$

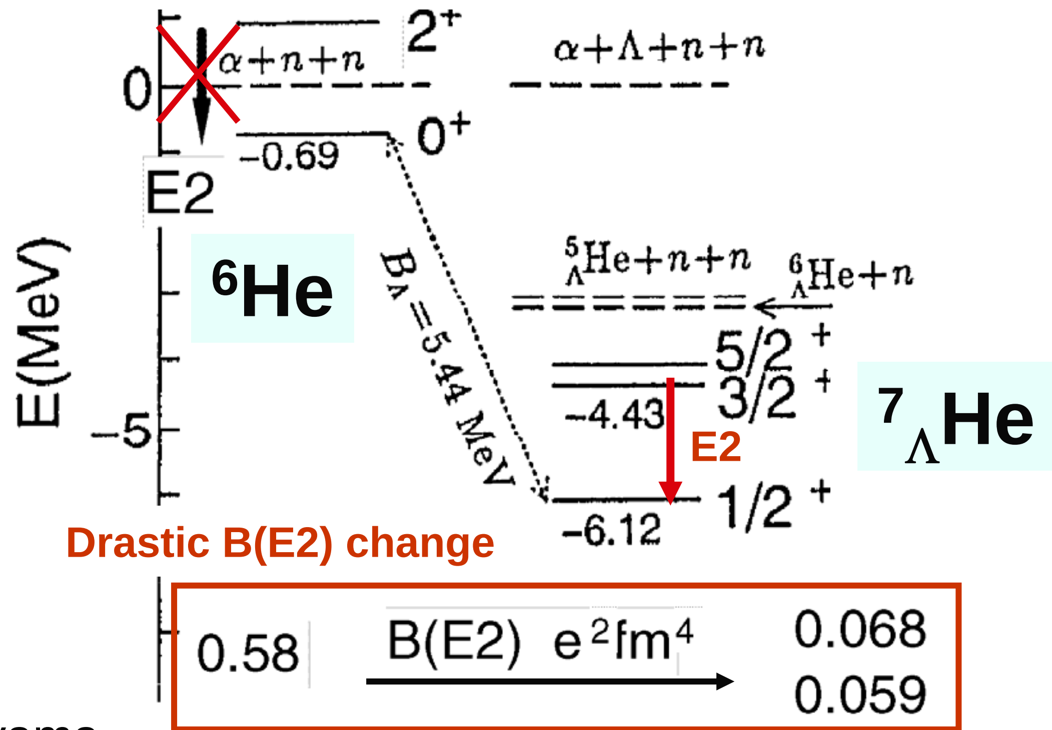
$^{10}B\ (\pi^-,K^+)\ ^{10}_{\Lambda}Li$ (again)

$^{12}C\ (\pi^-,K^+)\ ^{12}_{\Lambda}Be$

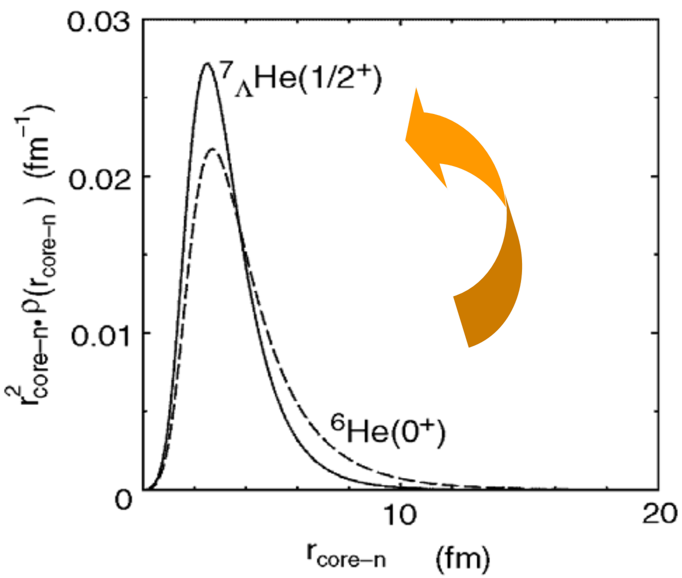
Future:

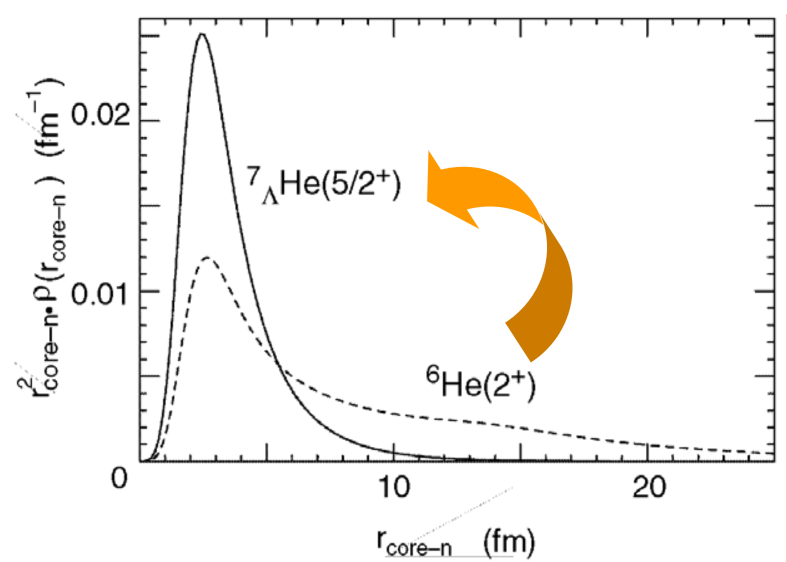
n-rich hypernuclei by $(K^-,\pi^0\gamma)$ reaction

--- Disappearence of n-halo in $^7_\Lambda$He ---



Calc. by Hiyama





5. Weak Decay

Weak Decays in Hypernuclei

$\Gamma_{tot}(=1/\tau)$

- Γ_m
  - $\Gamma_{\pi-}$ ($\Lambda \rightarrow p\pi^-$)
  - $\Gamma_{\pi o}$ ($\Lambda \rightarrow n\pi^o$)
- Γ_{nm}
  - Γ_p ($\Lambda p \rightarrow np$)
  - Γ_n ($\Lambda n \rightarrow nn$)
  - Γ_{2N} ($\Lambda NN \rightarrow nNN$)

Mesonic

q~ 100 MeV/c

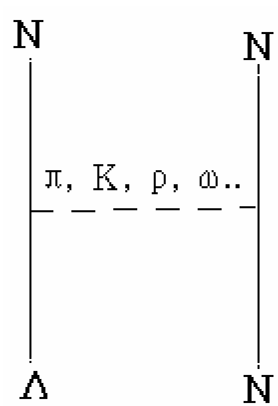
(1N)

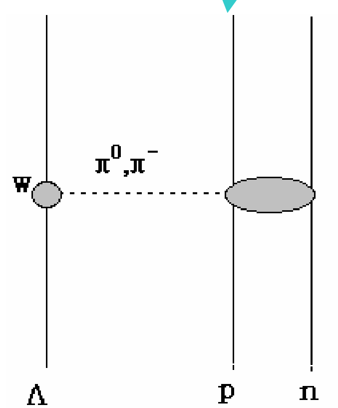
(2N)

Nonmesonic

q~ 400 MeV/c

Sensitive to short range part of BB interaction





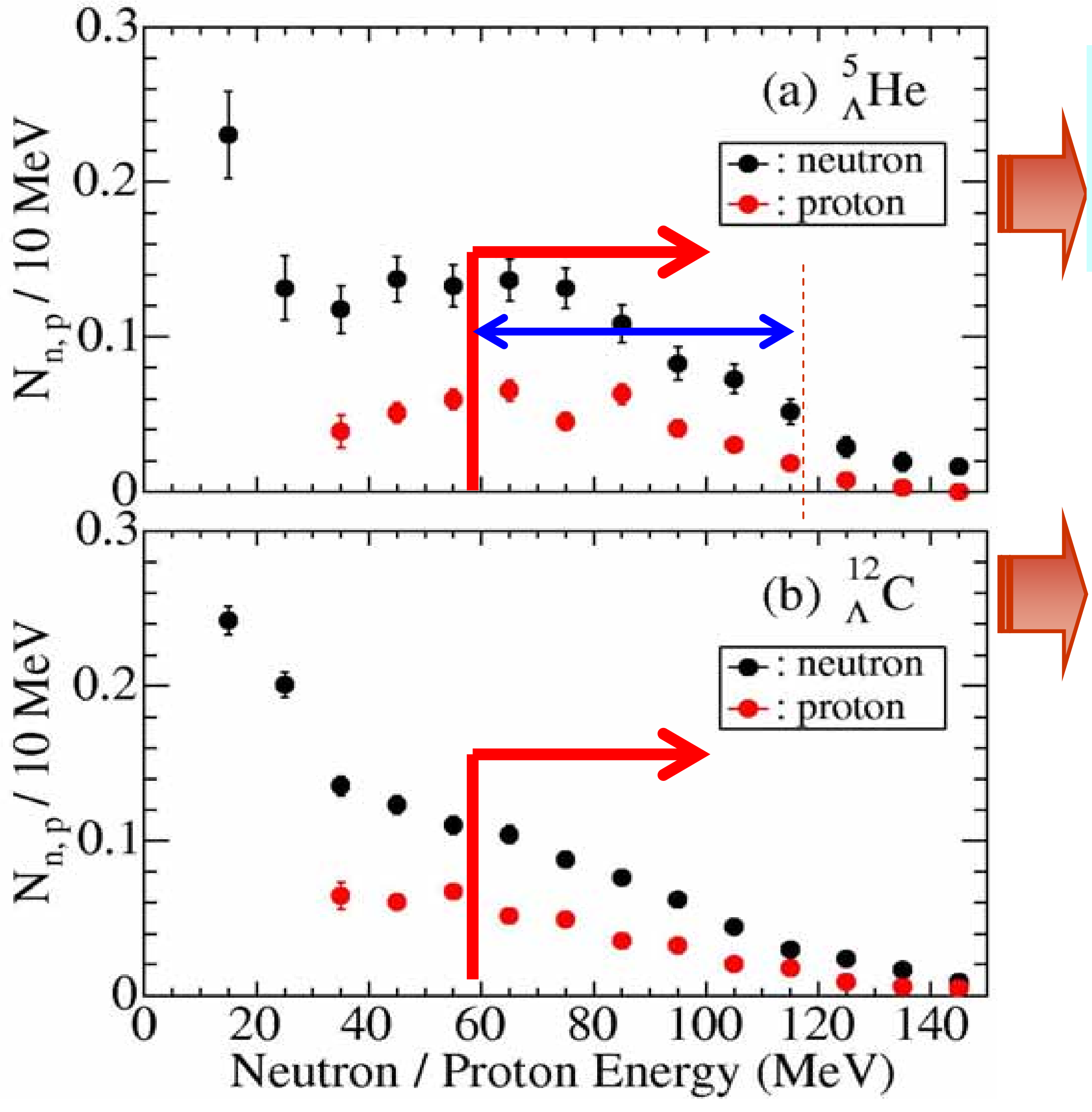
(3-Body)

Γ_n / Γ_p (≡np ratio) puzzle:

Large statistical and systematic errors
(FSI, n-detection, proton energy loss,..)
Inconsistent with theories

Slide from H.C. Bhang

Singles spectra in NMWD



Okada et al., PLB 597 (2004) 249

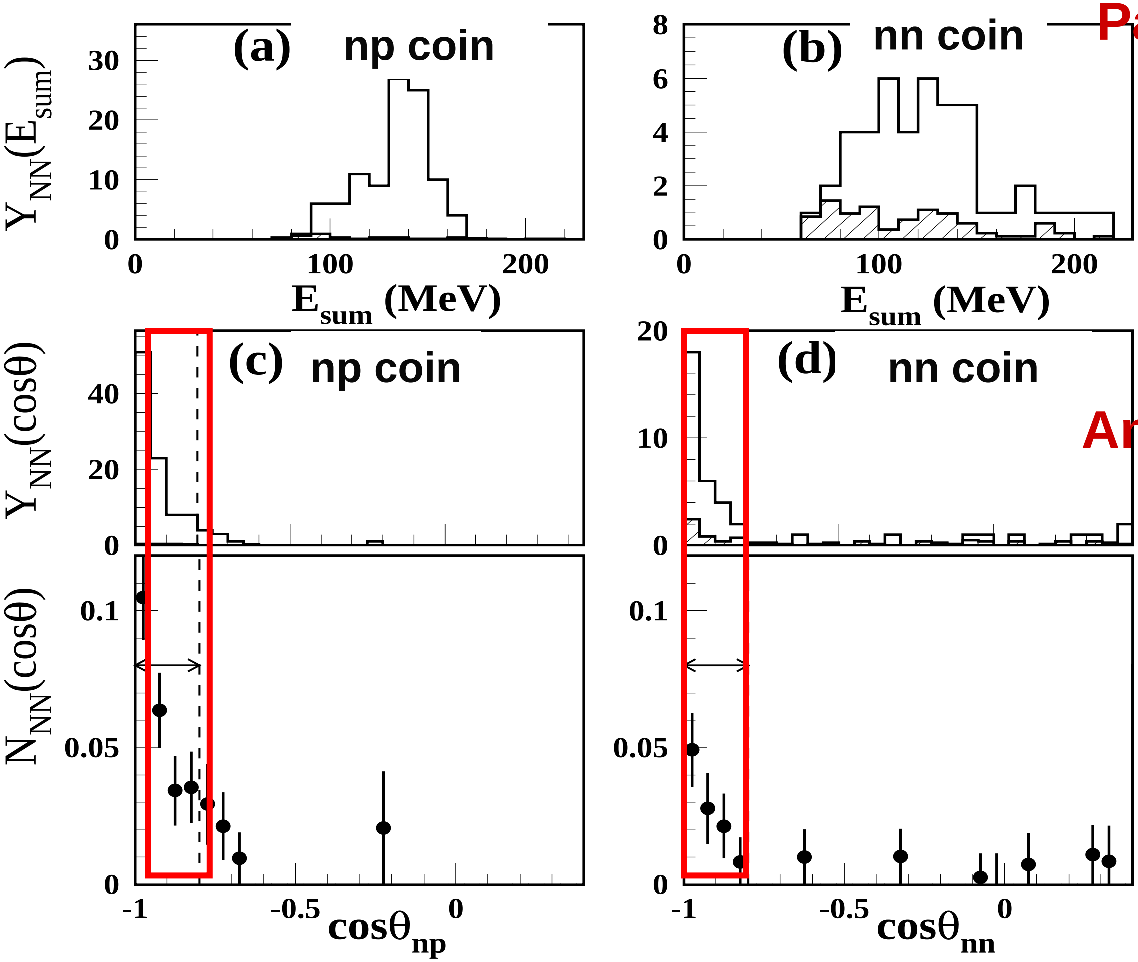
N_n / N_p (60 < E < 110 MeV)
~2.17±0.15±0.16
→ Γ_n/Γ_p= 0.61±0.08±0.08

N_n / N_p (E > 60 MeV)
~2.00±0.09±0.14
→ Γ_n/Γ_p= 0.58±0.06±0.08

Γ_{2N} =0 was assumed to derive these values.

Slide from H.C. Bhang

Coincidence Yields (NN correlations) ; ${}^{5}_{\Lambda}He$



Pair Energy Sum Spectum

Sharp peak in Y_{np}(He)
at Q value(Λp→np).
→ FSI not severe in He.

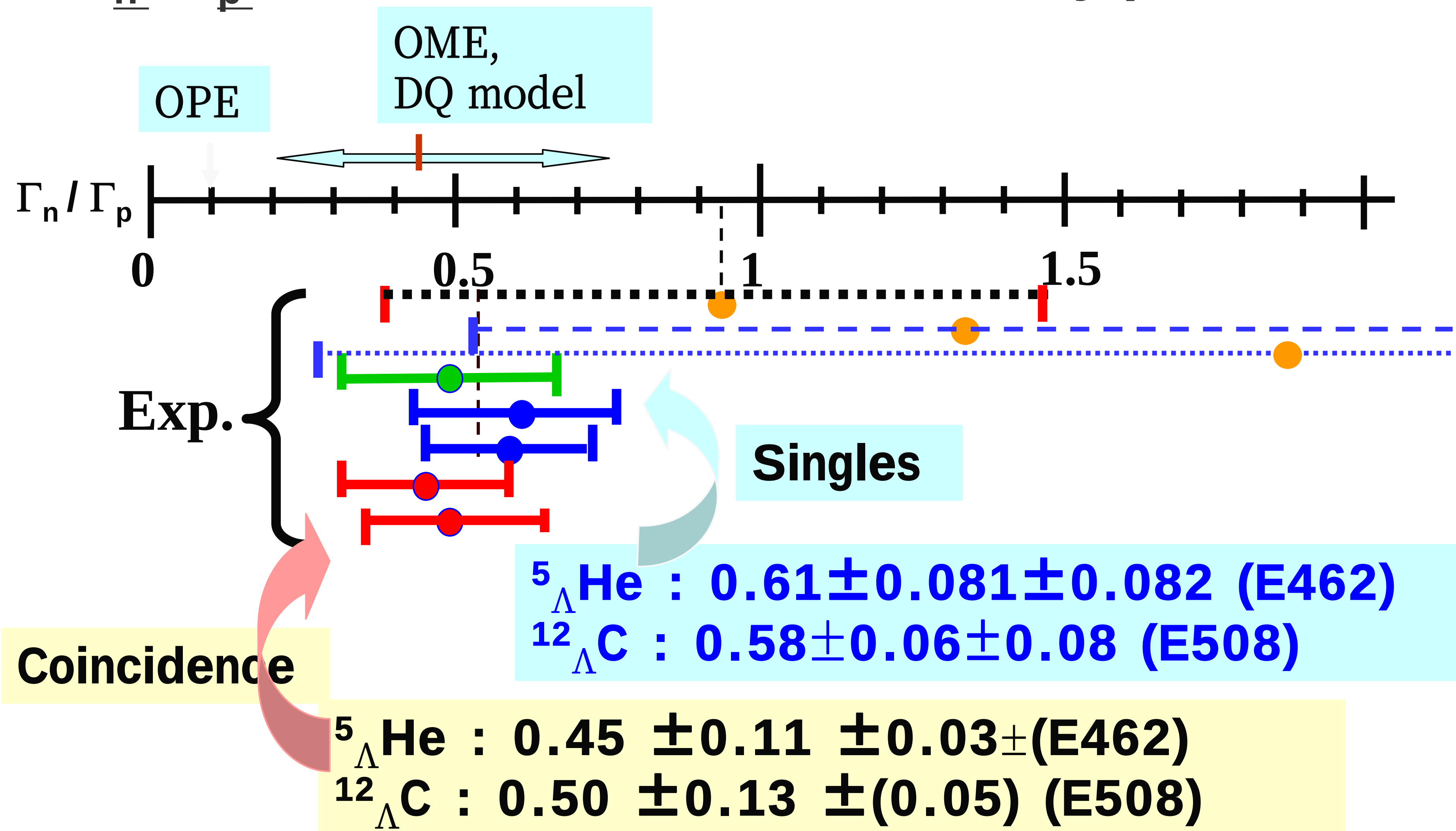
Angular correlation

$\Gamma_n/\Gamma_p \sim N_{nn} / N_{np} = 0.45 \pm 0.11 \pm 0.03$

B.Kang et al., PRL 96 ('06)

Slide from H.C. Bhang

Γ_n / Γ_p results and hint for three body process



The difference can be understood if there were Γ_{2N}

(J-PARC proposal by Bhang et al.)

Present questions in weak decay

- **Three body decay (Γ_{2N}) exists?**
  -> 3N coincidence data, more accurate Γ_n , Γ_p
  (Proposed by Bhang)

- **A_y not understood yet**
  Maruta et al. by pn coin.: $\alpha_p^{NM} = 0.31 \pm 0.22$ <-> theory: $\alpha_p^{NM} \sim -0.6$
  -> Theoretical challenge

- **$\Delta I = 1/2$ not experimentally examined yet**
  -> precise measurement of ${}^4_\Lambda$He (Λn ->nn) or ${}^4_\Lambda$H (Λp ->np)
  (Proposed by Ajimura/Sakaguchi)

6. Summary

- **New experimental techniques for Λ hypernuclear studies.**
  High-precision γ spectroscopy
  $(e,e'K^+)$ spectroscopy at Jlab
  (π^-,K^+) spectroscopy for n-rich hypernuclei
  pn, nn coincidence measurement in NMWD

- **γ spectroscopy has done for most of the p-shell Λ hypernuclei.**
  All the ΛN spin-dependent force strengths were determined, and consistency seems almost OK.
  Planning a precise B(M1) measurement for g_Λ.

- **$(e,e'K^+)$ spectroscopy at JLab achieved < 1 MeV FWHM resolution.**
  Hall A and C are studying various hypernuclei with improved (~0.4 MeV) resolutions .
  Future plans for heavier hypernuclei with a new apparatus.

- **First observation of n-rich hypernuclei $^{10}_{\Lambda}$Li and future plans for others by (π^-,K^+) reaction**

- **In the weak decays, the n-p ratio puzzle was solved but A_y, Γ_{2N}, $\Delta I=1/2$ rule are to be studied.**

- **J-PARC as well as JLab will start data collection from 2008 with improved beam and apparatus.**