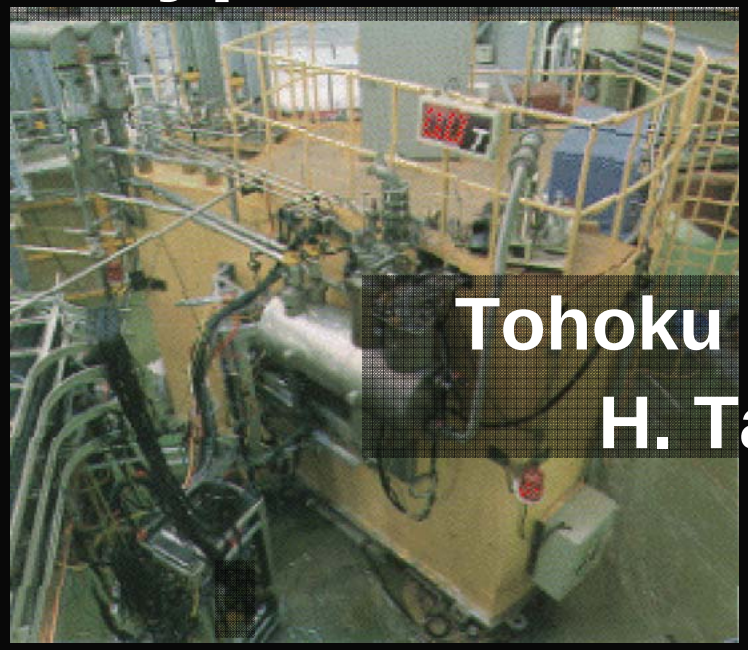
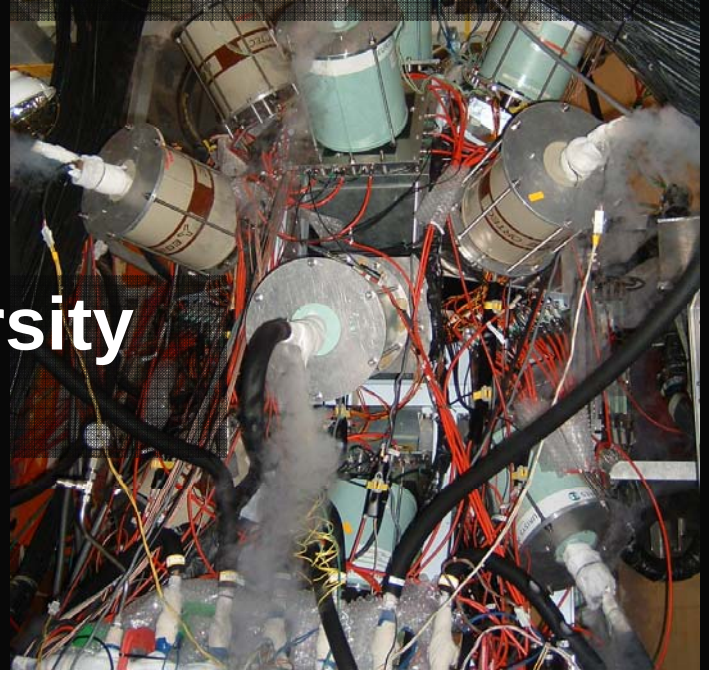
Hall C Meeting
August 10, 2007

Gamma-Ray Spectroscopy of Λ Hypernuclei at KEK, BNL and J-PARC





Tohoku University
H. Tamura

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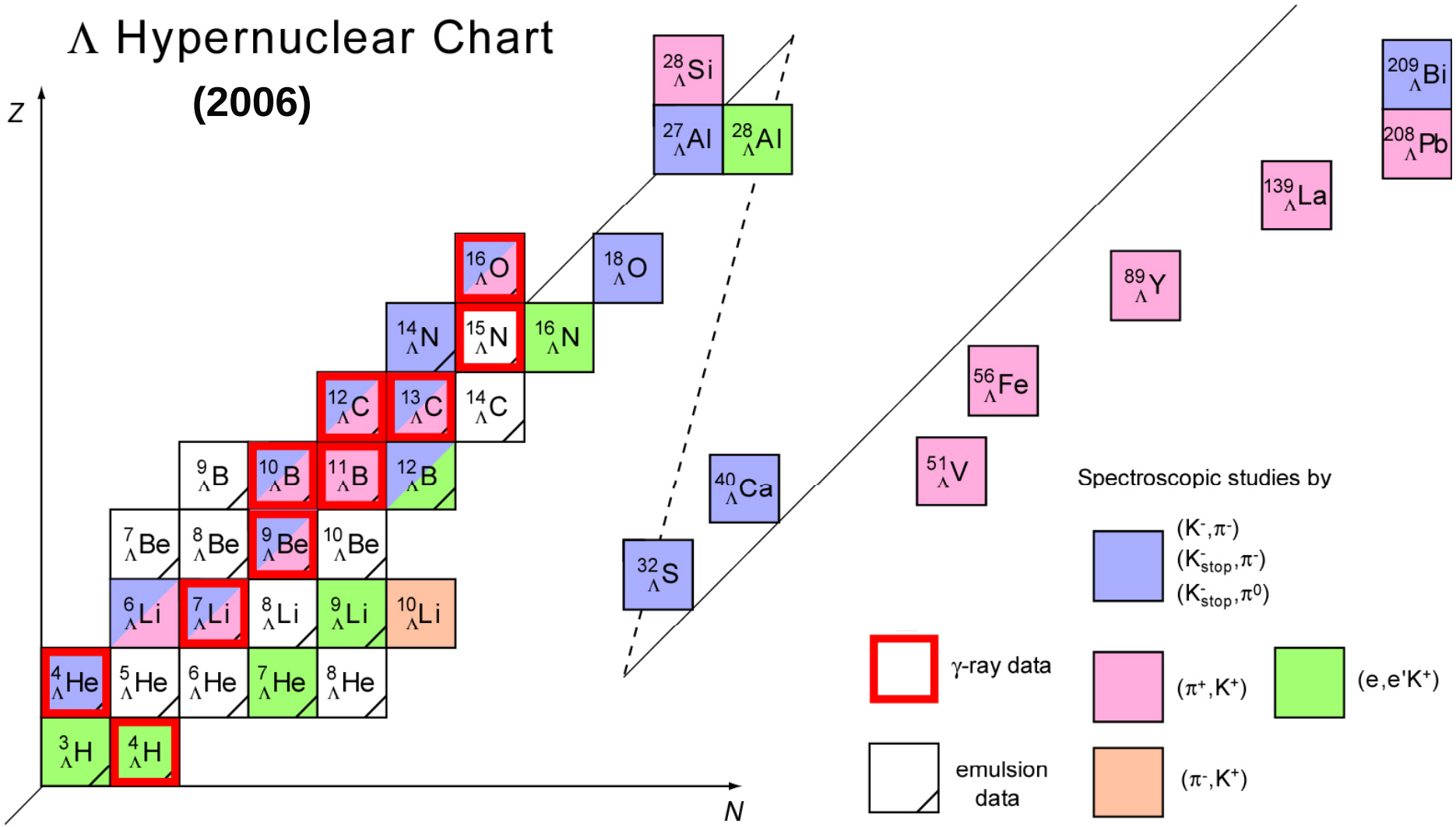
1. Introduction

Present Status of
Λ Hypernuclear Spectroscopy



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

Comparison between γ and (e,e'K$^+$) Spectroscopy

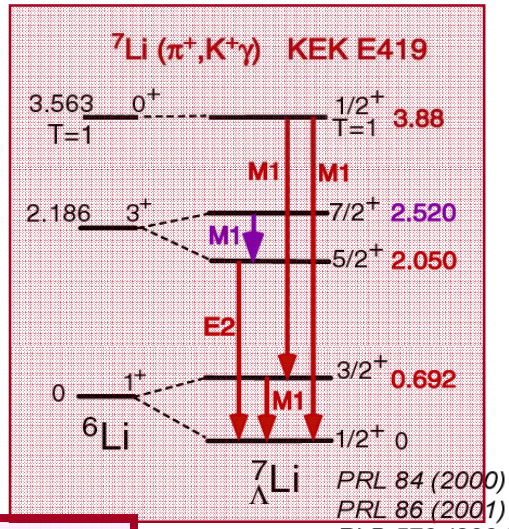
γ spectroscopy	(e,e'K$^+$) spectroscopy
Resolution: ~3 keV (FWHM)	~300 keV (FWHM) …best in reaction method
Only bound states (E_X < 5 MeV)	Bound and unbound states
Only E_X	Absolute values of mass (B_Λ)
Level assignment from:	
$d\sigma/d\Omega$ of (K,π) reaction (strong) $\gamma\gamma$ coin., angular correlation	$d\sigma/d\Omega$ of (e,eK) reaction (weak)
Lifetime (from Doppler shift), B.R. -> transition prob. (B(M1), B(E2),..)	Lifetime (from width)
Thick target	Thin target -> various enriched target

Both should be pursued.

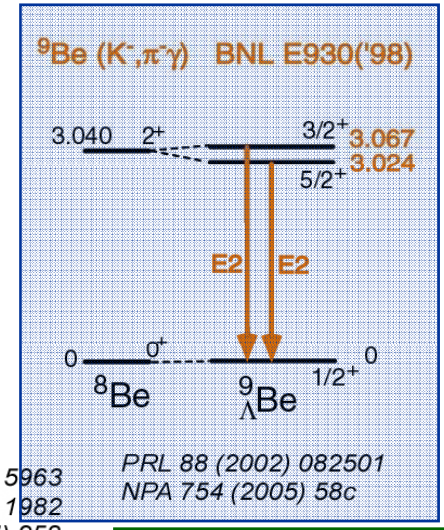
2. Present Status of γ-ray spectroscopy

Hypernuclear γ-ray data since 1998

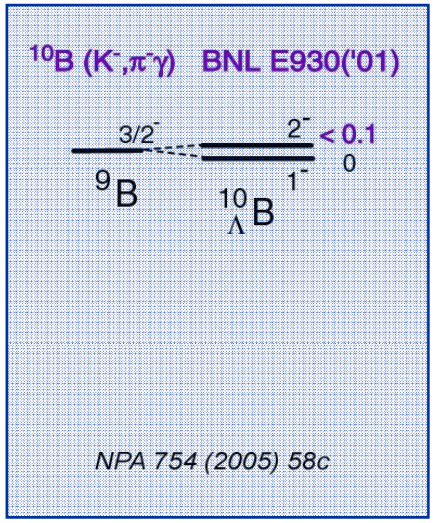
"Table of Hyper-Isotopes"



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

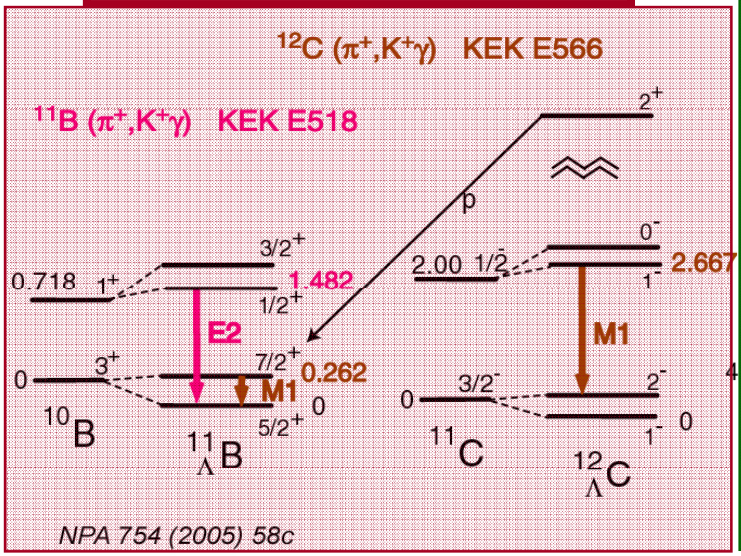


PRL 88 (2002) 082501
NPA 754 (2005) 58c



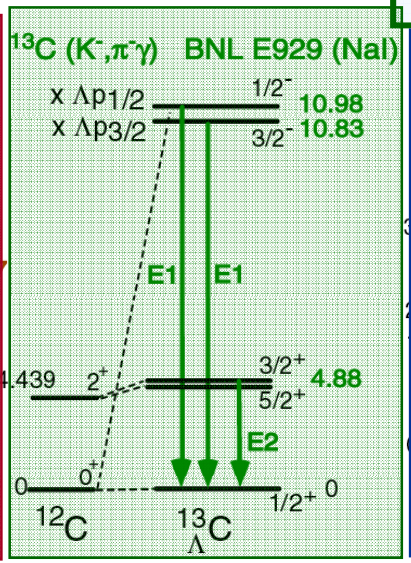
NPA 754 (2005) 58c

(π^+,K$^+\gamma$) at KEK-PS

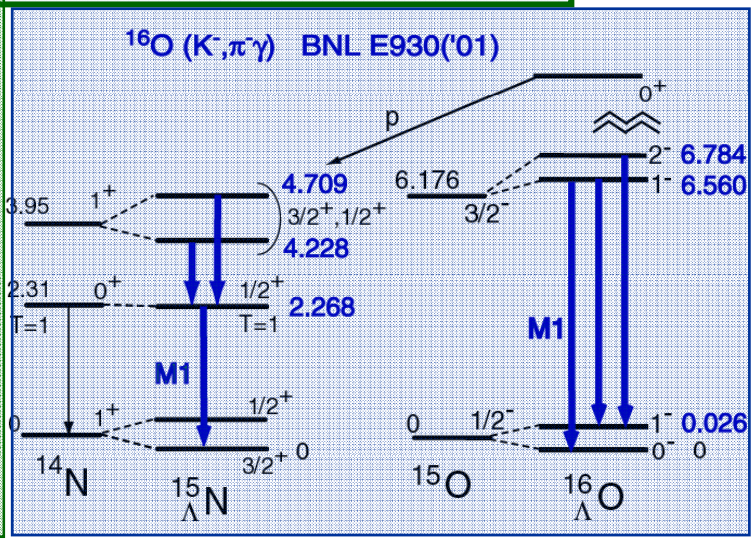


NPA 754 (2005) 58c

(K$^-$, $\pi^-\gamma$) at BNL-AGS

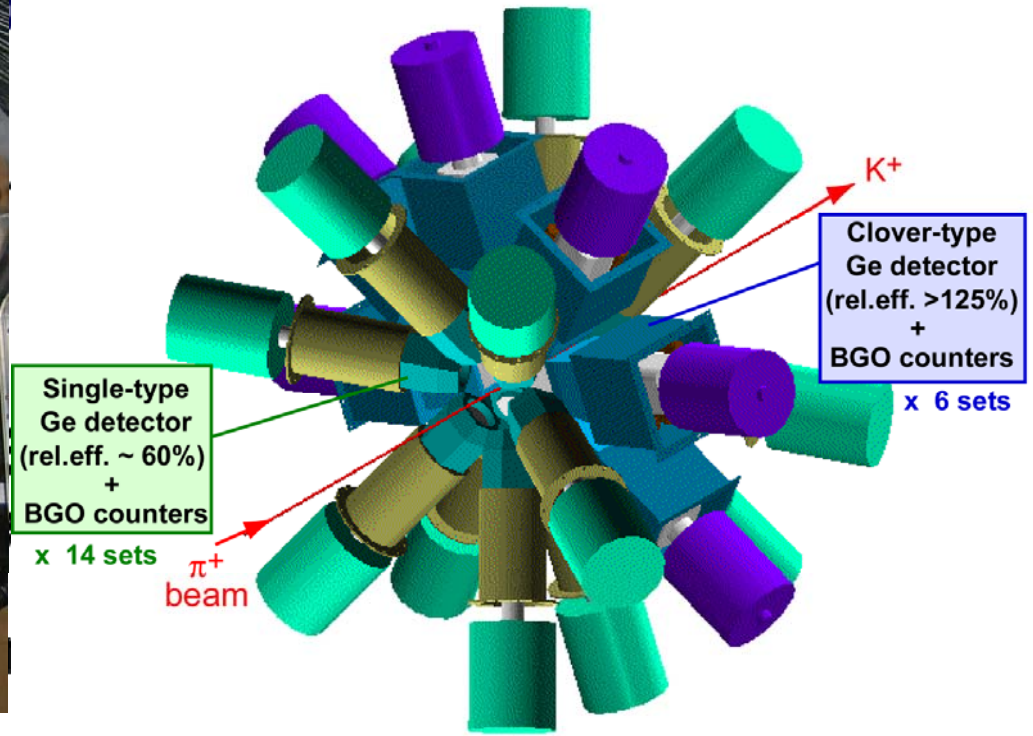


PRL 86 (2001) 4255
PRC 65 (2002) 034607



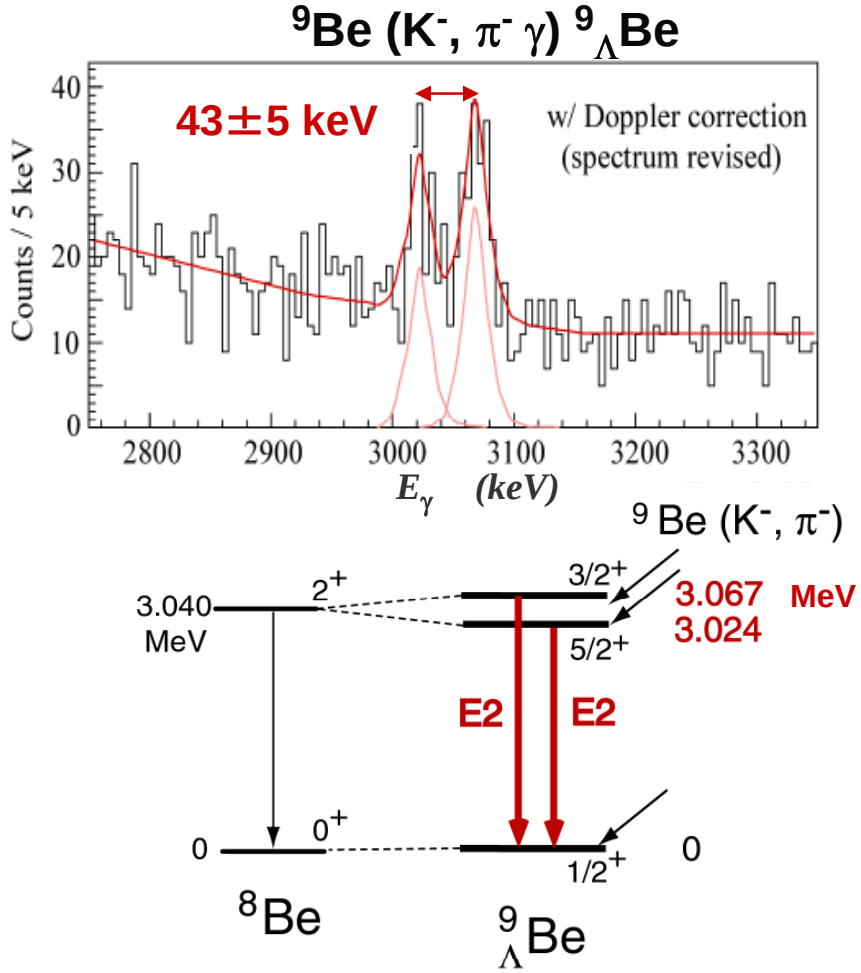
PRL 93 (2004) 232501

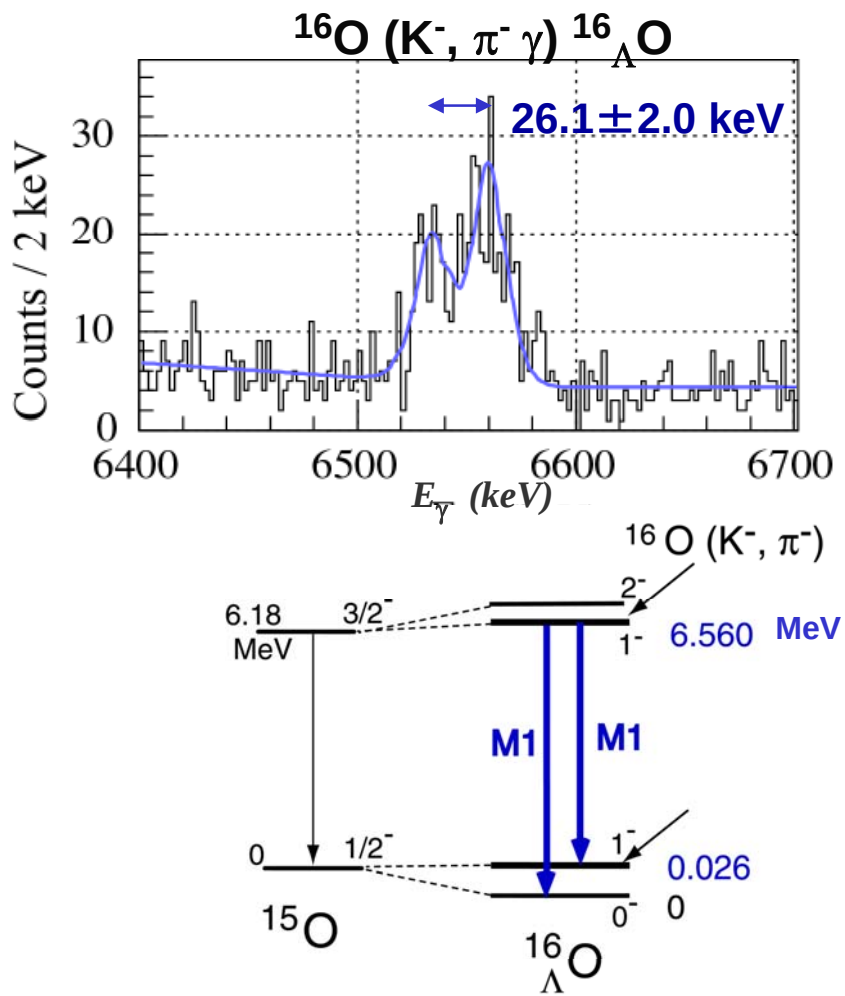
Setup for ^{A}Z (π^{+}



Observation of Hypernuclear Fine Structure

BNL E930 (AGS D6 line + Hyperball)



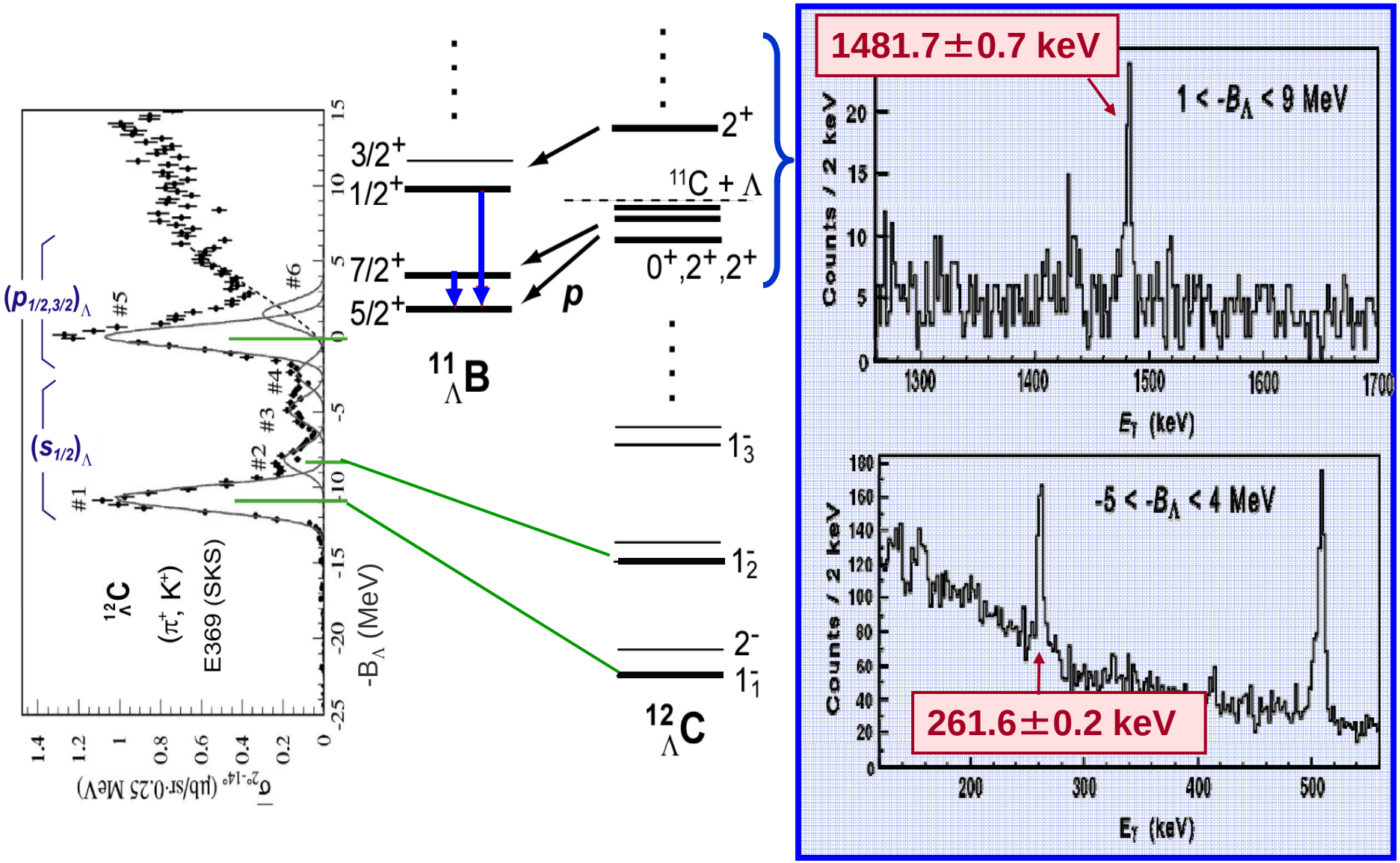


Akikawa et al., PRL 88 (2002) 082501

Ukai et al., PRL 93 (2004) 232501

$^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C γ rays from ^{12}C(π^+,K$^+$) *preliminary*

KEK E566: Hyperball2 + SKS



$^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C γ rays from ^{12}C(π^+,K$^+$) *preliminary*

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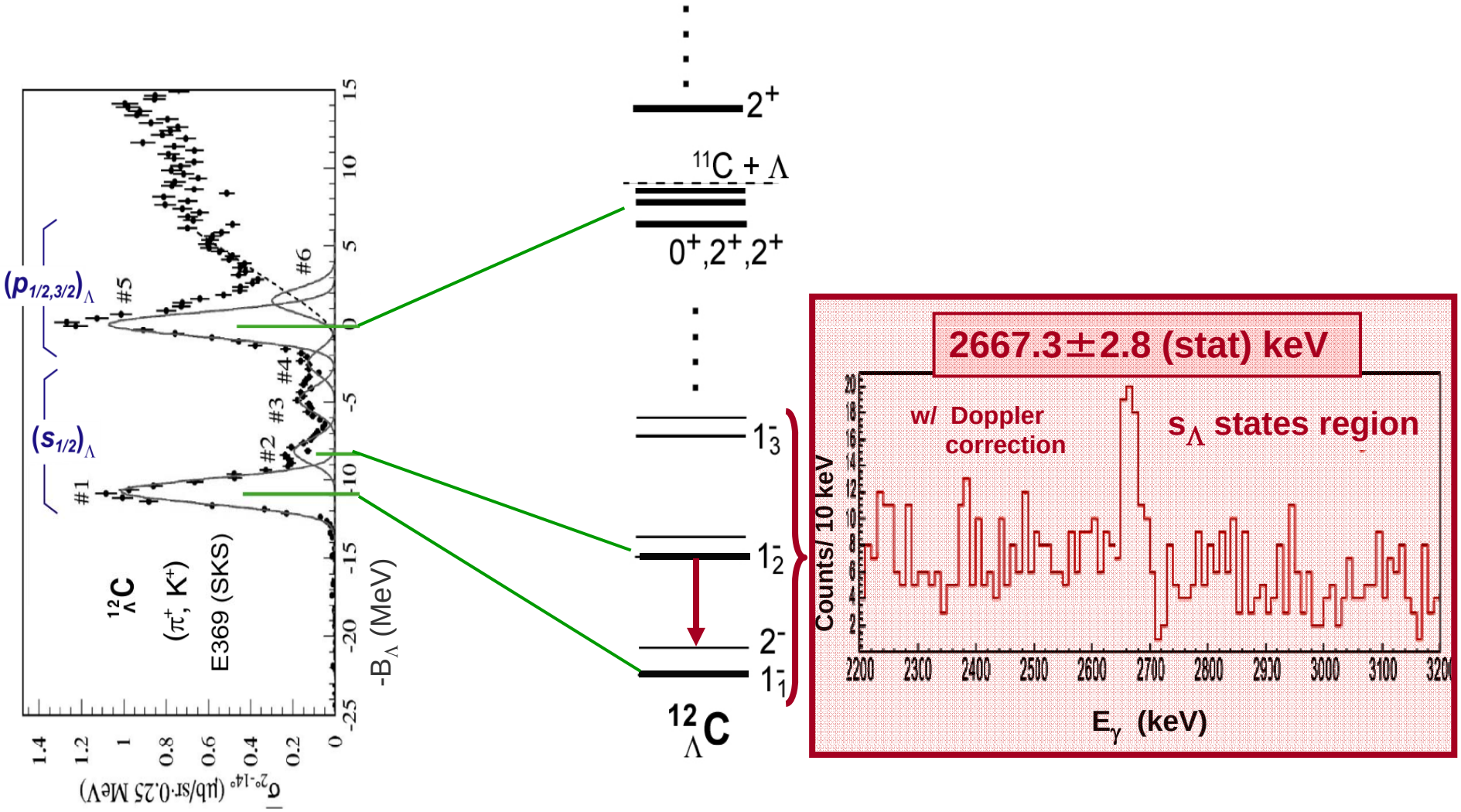


3. Spin dependence of ΛN interaction

ΛN Spin-dependent interactions and γ spectroscopy

- **Two-body ΛN effective interaction**

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

$\bar{V}$ $\quad\Delta\quad$ S_Λ $\quad S_N\quad$ T

Well known (U_Λ = - 30 MeV)

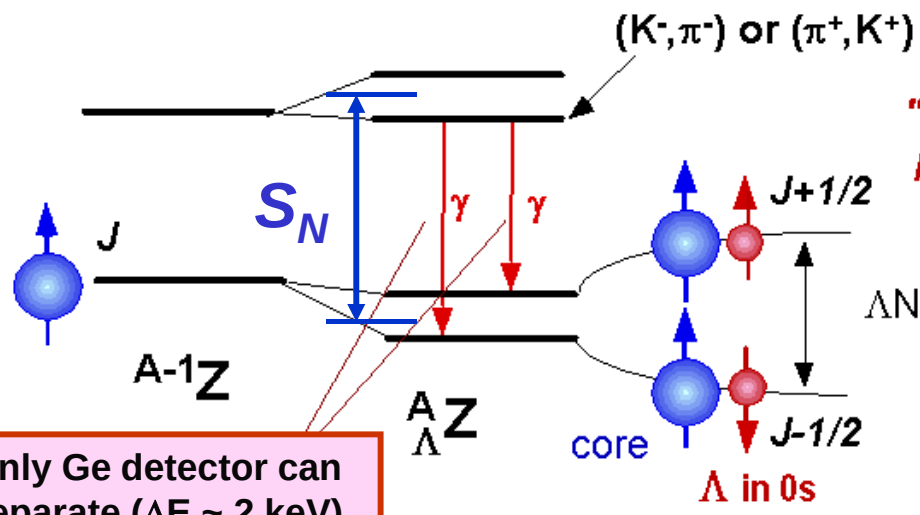
p-shell: 5 radial integrals for $p_N s_\Lambda$ w.f.

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

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

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

Level spacing: linear combination of Δ, S_Λ, S_N, T



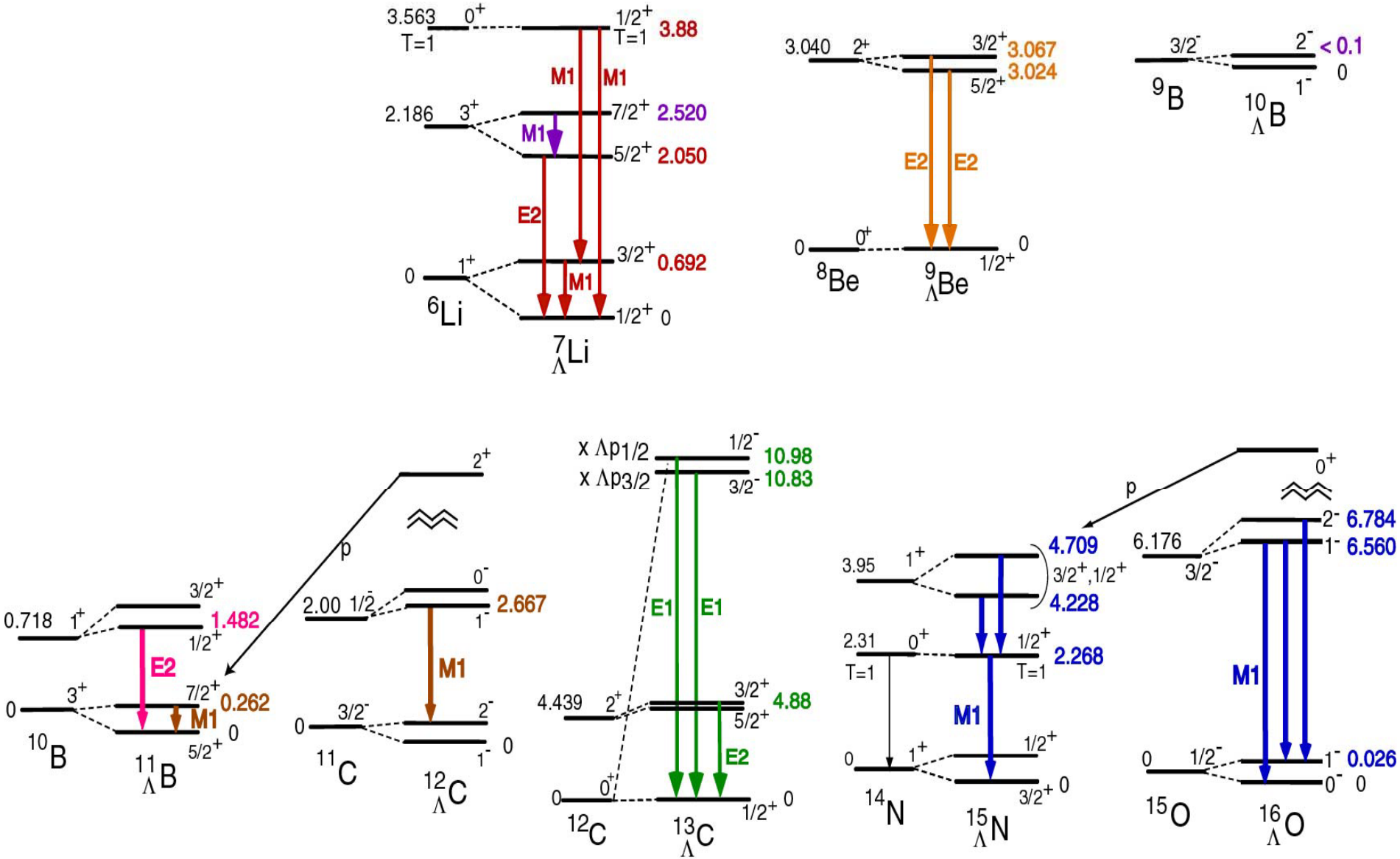
"Hypernuclear Fine Structure"

split by ΛN spin-dependent interactions $\lesssim$ 0.1 MeV

Δ, S_Λ, T

Only Ge detector can separate (ΔE ~ 2 keV)

Interaction Parameters (Millener)



Interaction Parameters (Millener)

$\Delta E = -0.04\Delta + 2.46S_\Lambda + 0.99T$

S_N: consistent

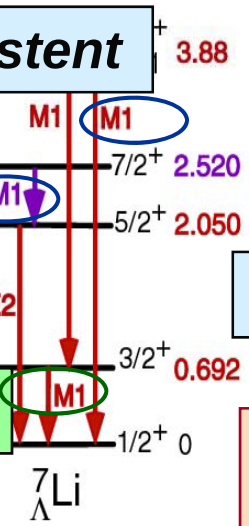
Δ, S_Λ, T: consistent

$S_N = -0.4$ MeV

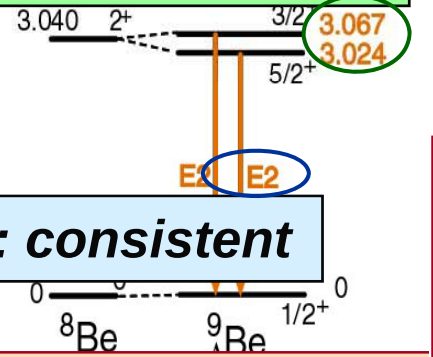
$\Delta E = 0.70S_N$

$\Delta = 0.43$ MeV

$\Delta E = 1.44\,\Delta + 0.05S_\Lambda - 0.27T$

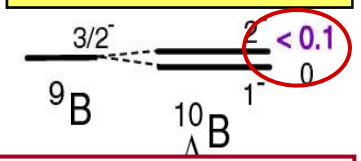


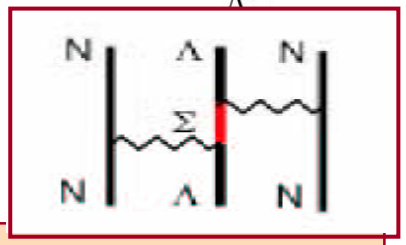
$S_\Lambda = -0.01$ MeV



S_N: consistent

$\Delta < 0.3$ MeV





Effect of ΣN-ΛN coupling force?
Accuracy of core wave function?

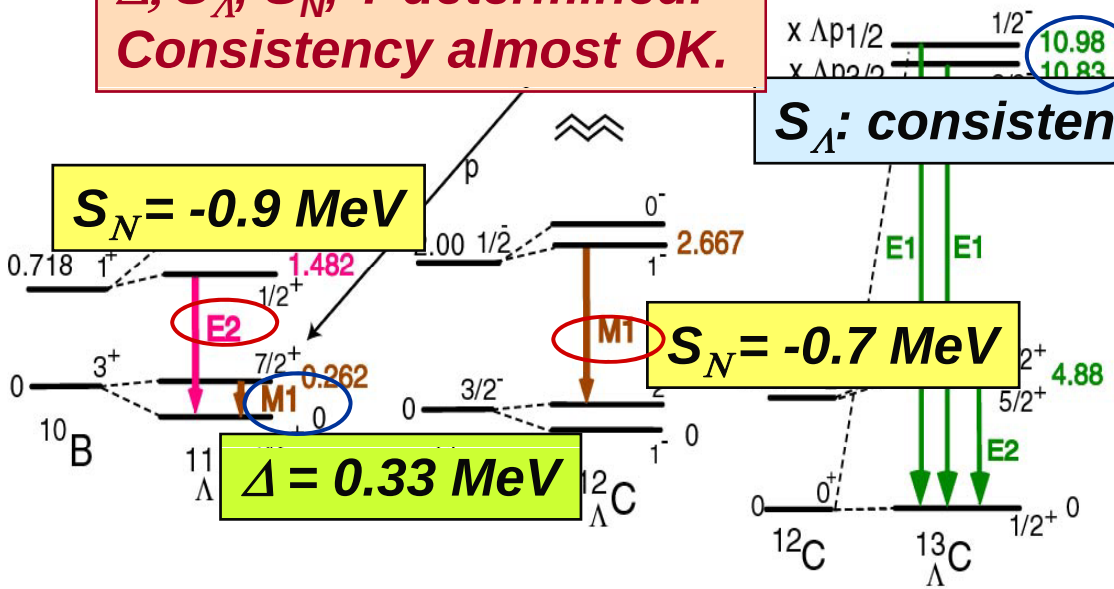
Δ, S_Λ, S_N, T determined.
Consistency almost OK.

S_Λ: consistent

$S_N = -0.9$ MeV

$S_N = -0.7$ MeV

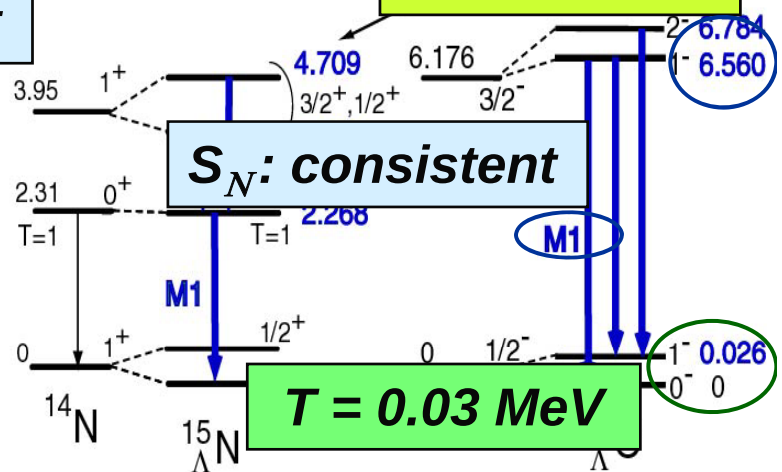
$\Delta = 0.33$ MeV



$\Delta = 0.33$ MeV

S_N: consistent

$T = 0.03$ MeV



$\Delta E = -0.38\,\Delta + 1.38S_\Lambda + 7.85T$

Feedback to YN interaction models

Nijmegen meson-exchange models

	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	0.754	-0.140	-0.257	0.054
("Quark"		0.0	-0.4	)
Exp.	0.4	-0.01	-0.4	0.03

G-matrix calc. by Yamamoto

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

spin-spin:

Δ = 0.33--0.43 MeV => ***NSC97f selected*** **(consistent with $^4_\Lambda$H(1^+,0^+))**

(+ slight adjustment favorable)

spin-orbit:

S_Λ = -0.01 MeV
(SLS+ALS)

S_N = -0.4 MeV
(SLS-ALS)

=> ***All Nijmegen models fail***

Quark models OK

$^9_\Lambda$Be = $\alpha\alpha\Lambda$ model

Hiyama et al., PRL 85 (2000) 270

Fujiwara et al. Prog.Part.Nucl.Phys.58 (2007) 439.

tensor:

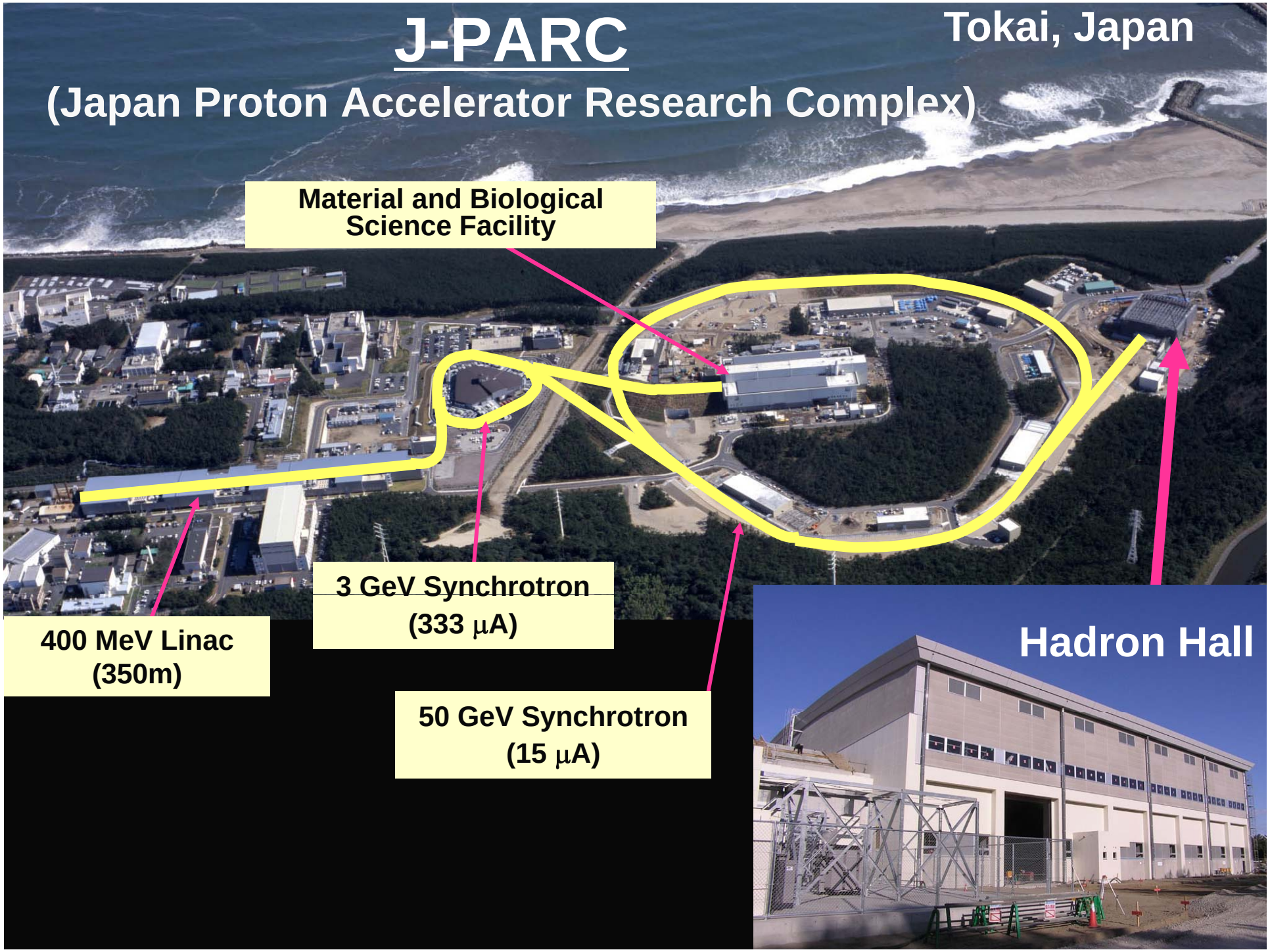
T = 0.03 MeV => ***Nijmegen models OK***

4. Experiments at J-PARC

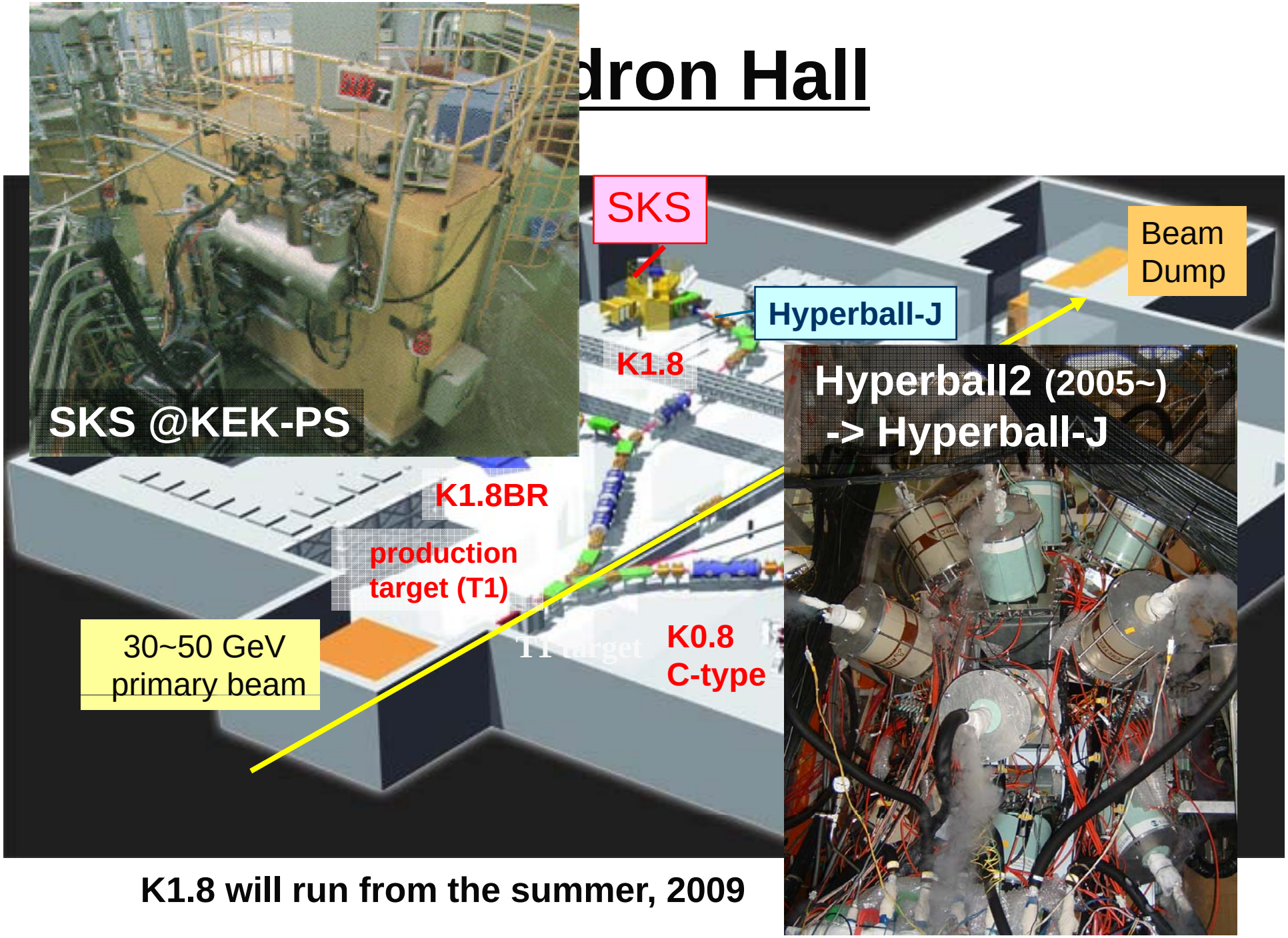
J-PARC

(Japan Proton Accelerator Research Complex)

Tokai, Japan



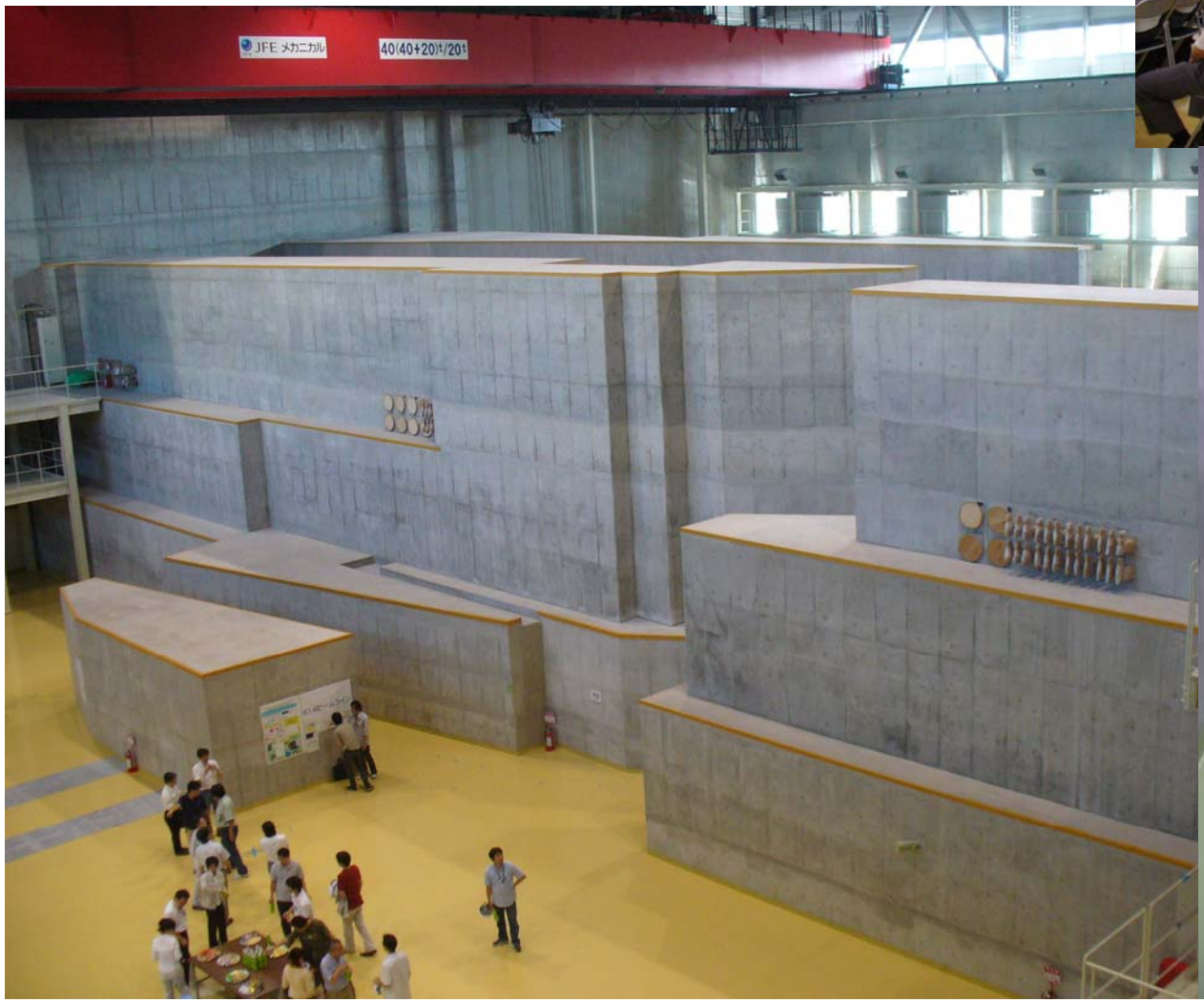
dron Hall



K1.8 will run from the summer, 2009

Present status of Hadron Hall

Ready to install magnets
Operation from Dec. 2009



Ceremony on July 27th

Primary line cave

E13: Approved DAY-1 experiment

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

$^{7}_{\Lambda}$Li

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

$^{4}_{\Lambda}$He

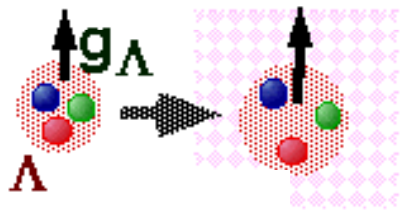
(3) Further ΛN interaction study from p-shell hypernuclei

$^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B

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

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

g factor of Λ in nucleus



- **Motivation**

  μ_Λ in nucleus -> medium effect of baryons

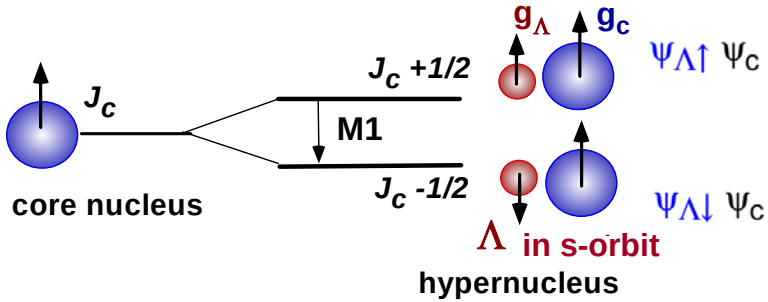
  Can be investigated using a Λ in 0s orbit

Reduction of constituent q mass?
Swelling?

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

- **B(M1) of Λ-spin-flip M1 transition -> g_Λ**

$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$
$$= (2J_{up}+1)^{-1} |\langle \psi_{\Lambda\downarrow}\, \psi_c \| \mu \| \psi_{\Lambda\uparrow}\, \psi_c \rangle|^2$$
$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c) J_\Lambda$$
$$= \frac{3}{8\pi}\frac{2J_{low}+1}{2J_c+1}(g_\Lambda - g_c)^2 \quad [\mu_N^2]$$



- **How to measure**

Doppler-shift attenuation method : **applied to "hypernuclear shrinkage" in $^7{}_\Lambda$Li (5/2⁺->1/2⁺) from B(E2)**
PRL 86 ('01)1982

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

- **Preliminary data (statistical error only)**
  from $^7{}_\Lambda$Li (3/2⁺->1/2⁺) (BNL E930)

$$g_\Lambda = -1.1^{+0.6}_{-0.4}\ \mu_N \Leftrightarrow g_\Lambda(\text{free}) = -1.226\ \mu_N$$

-> < 5% accuracy at J-APRC

E13: Approved DAY-1 experiment

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

$^{7}_{\Lambda}$Li

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

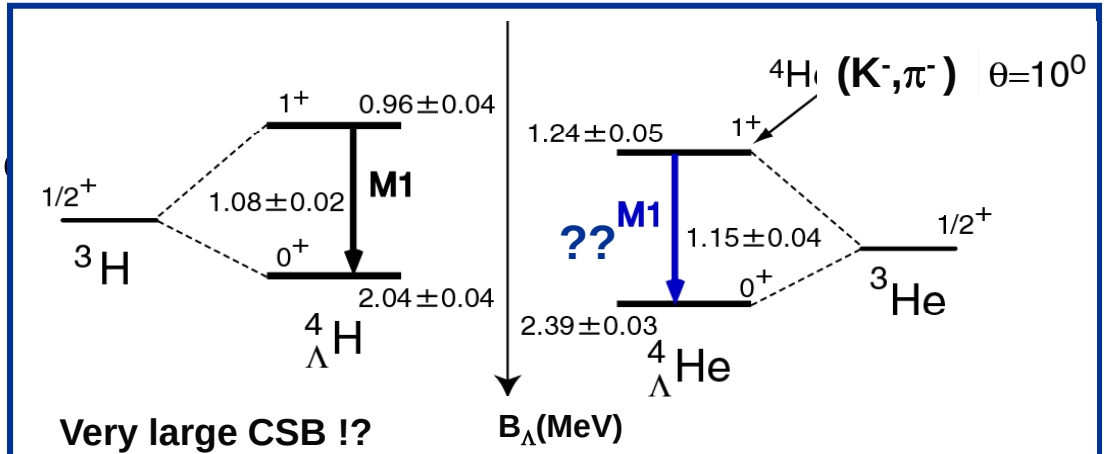
$^{4}_{\Lambda}$He

(3) Further ΛN interacti

$^{10}_{\Lambda}$B and $^{11}_{\Lambda}$B

(4) Radial dependence

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



Very large CSB !?
Not theoretically understood.

5. Summary

- **Most of p-shell hypernuclei have been investigated via γ-spectroscopy technique at KEK-PS and BNL-AGS**
  - **Hypernuclear fine structure in $^{9}_{\Lambda}$Be and $^{16}_{\Lambda}$O**
  - **New data on $^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C by ^{12}C (π^+,K$^+$)**
- **Spin dependence of ΛN interaction:**
  - **All the spin-dependent interaction strengths have been determined.**
  - **Consistency OK except for some inconsistency in A=10~12.**
- **J-PARC Hadron Hall will be ready soon.**
  - **Approved experiment (E13): g_{Λ} in nucleus, CSB in ΛN int., etc.**