KEK-PS review
Jan. 23, 2008

E566: Hypernuclear γ Spectroscopy on ^{12}C Target

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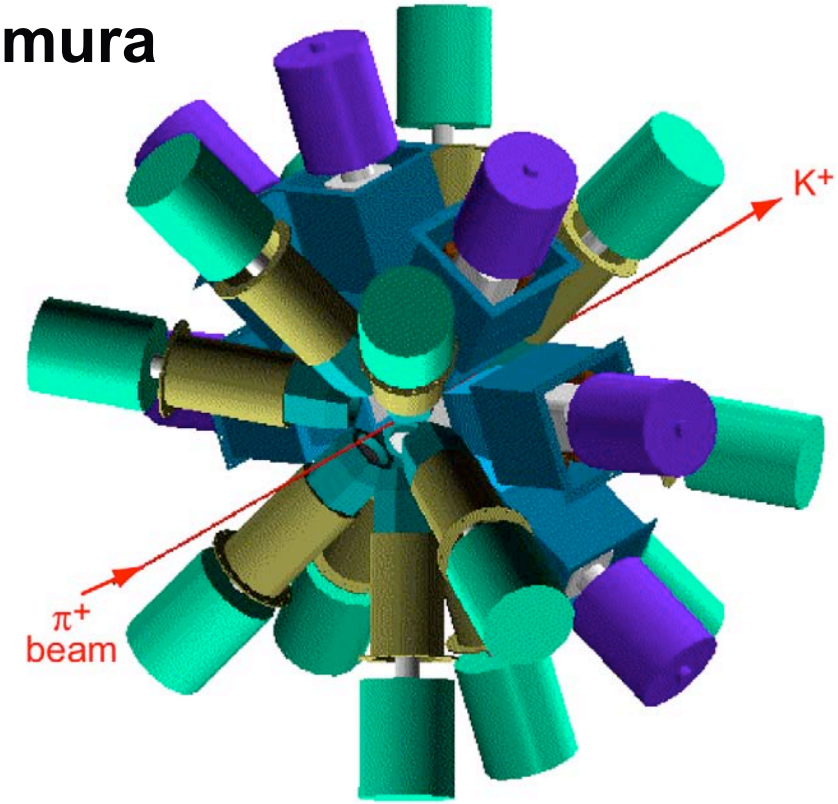

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Y. Ma et al., EPJ A33 (2007) 243

E566 Collaboration list

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Osaka Univ.	**S. Ajimura**
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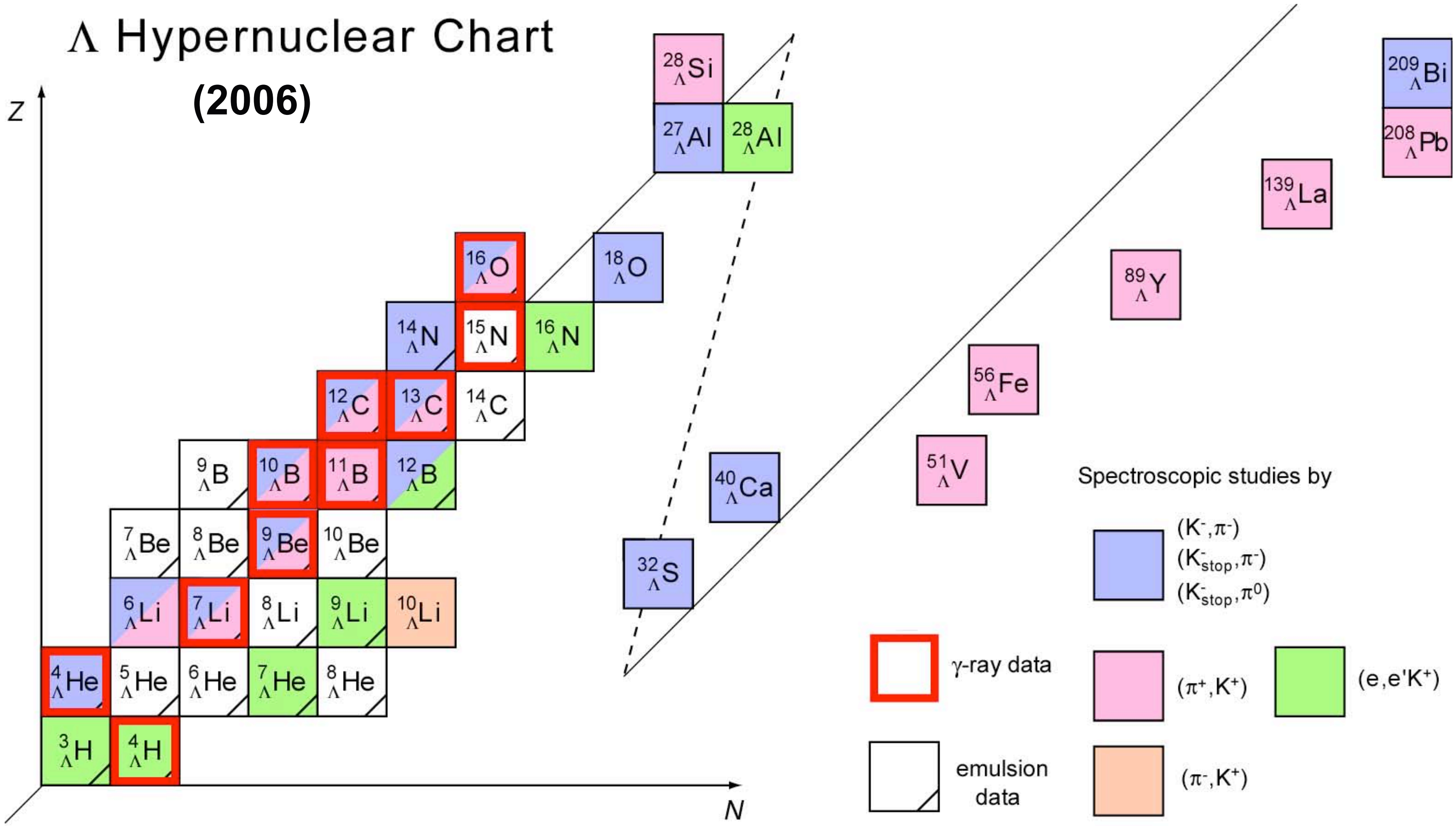
1. Introduction

Present Status of Λ Hypernuclear Spectroscopy



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

Hyperball (Tohoku/ Kyoto/ KEK, 1998)

- Large acceptance for small hypernuclear γ yields

  Ge (r.e. 60%) x 14

  Ω ~ 15%, ε ~ 3% at 1 MeV

- High-rate electronics for huge background

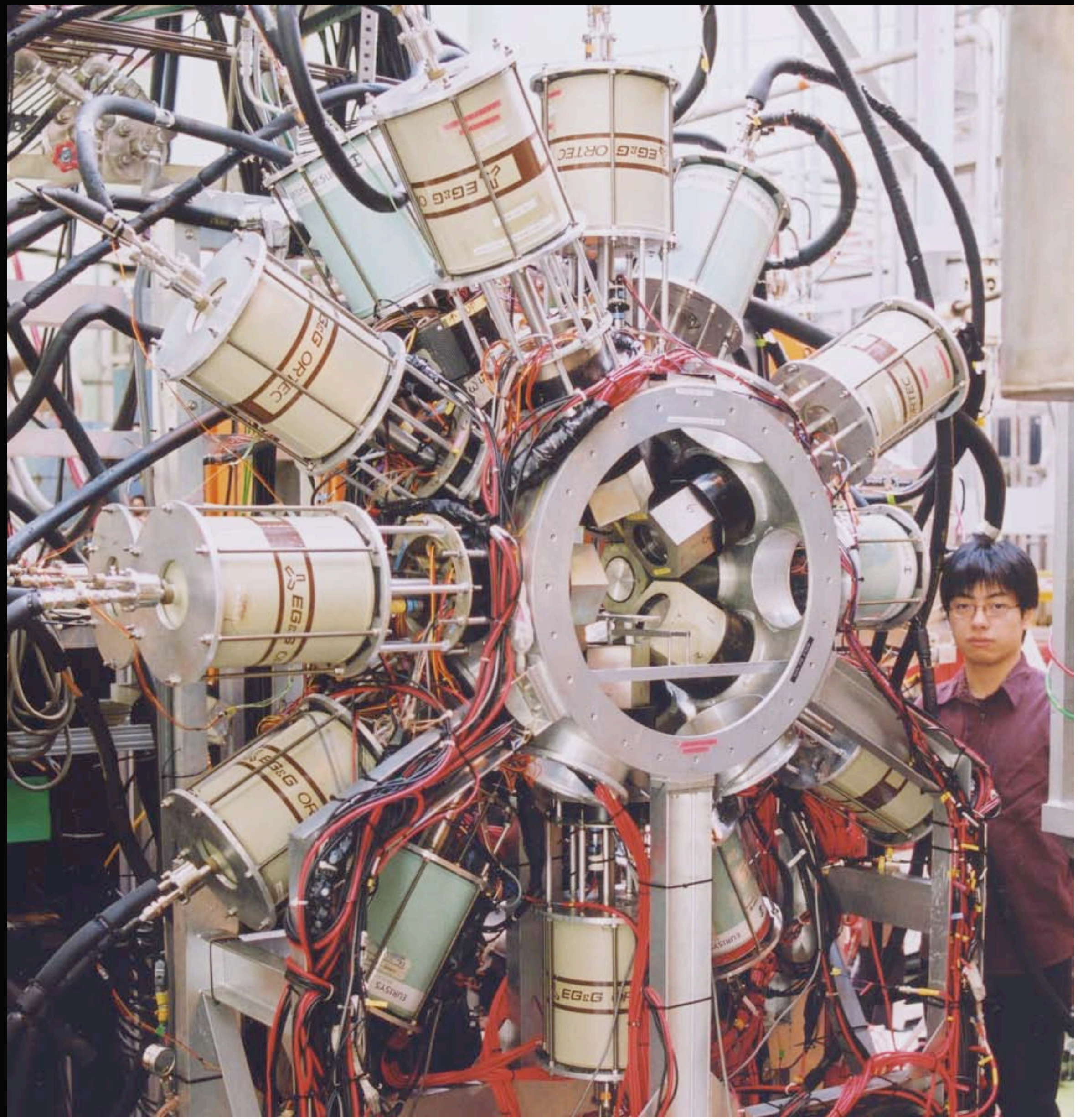
- BGO counters for π^0 and Compton suppression

Resolution of hypernuclear spectroscopy

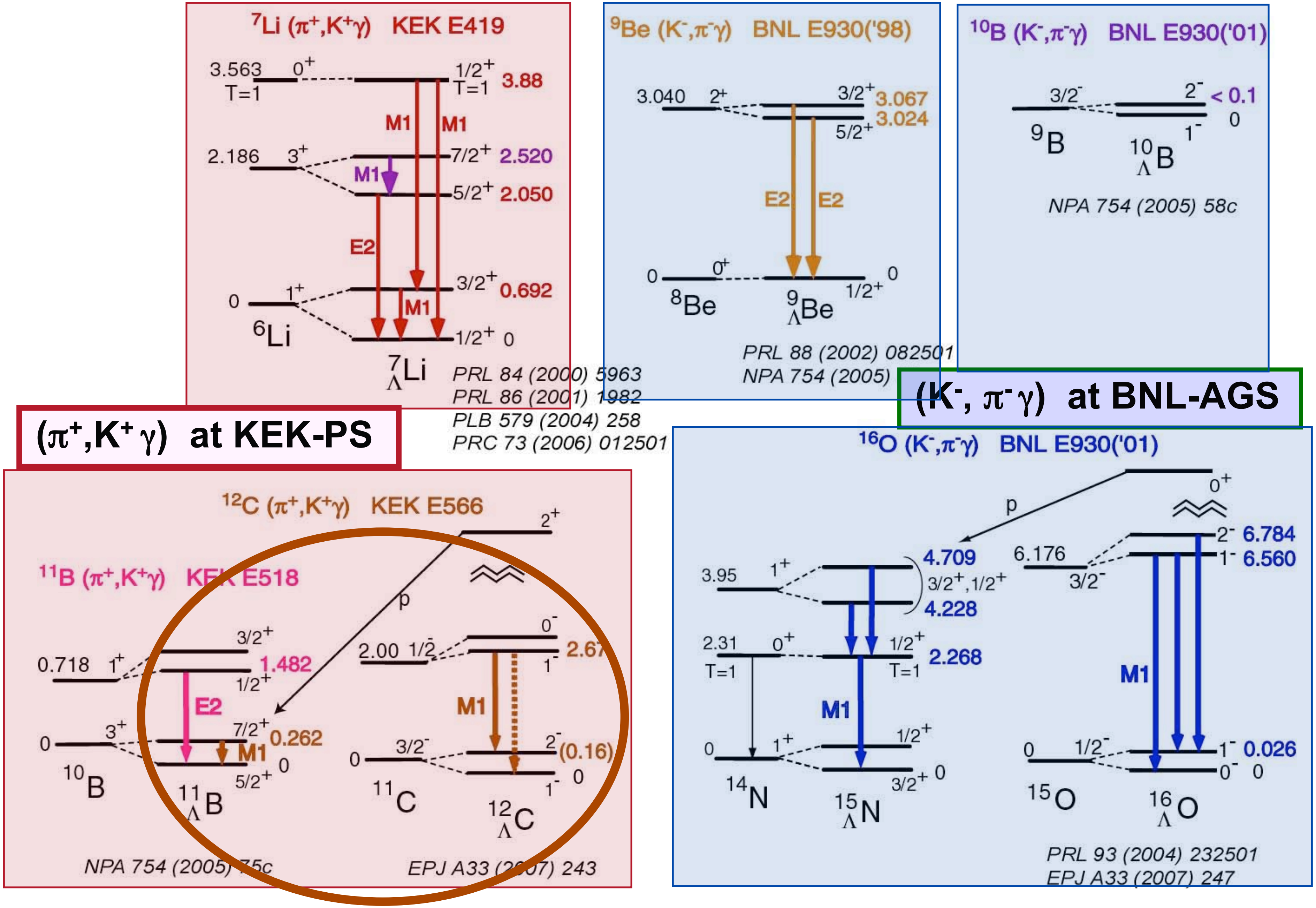
1 MeV -> 2 keV FWHM

First experiment (1998):

KEK-E419 for $^{7}_{\Lambda}$Li

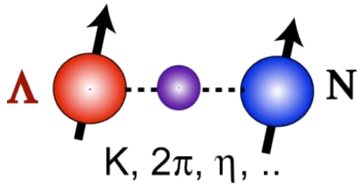


Present status of precision hypernuclear γ-ray spectroscopy

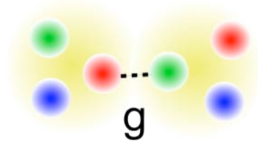


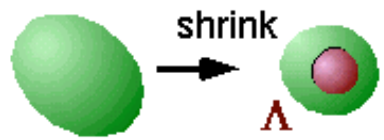
Motivation of Hypernuclear γ Spectroscopy

Precise measurement (ΔE = 1~2 MeV -> 2 keV FWHM)
of structures of hypernuclei



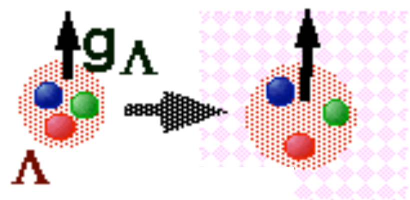
- **Baryon-Baryon interaction**
  - Unified picture of baryon-baryon interactions
  - Understand short-range nuclear forces in terms of quarks
  - Necessary to understand high density nuclear matter and strangeness mixing in neutron stars





- **Impurity effects** in nuclear structure
  - Changes of size/shape, symmetry, cluster/shell structure,..

- **Nuclear medium effects** of baryons
  - Probed by hyperons free from Pauli effect

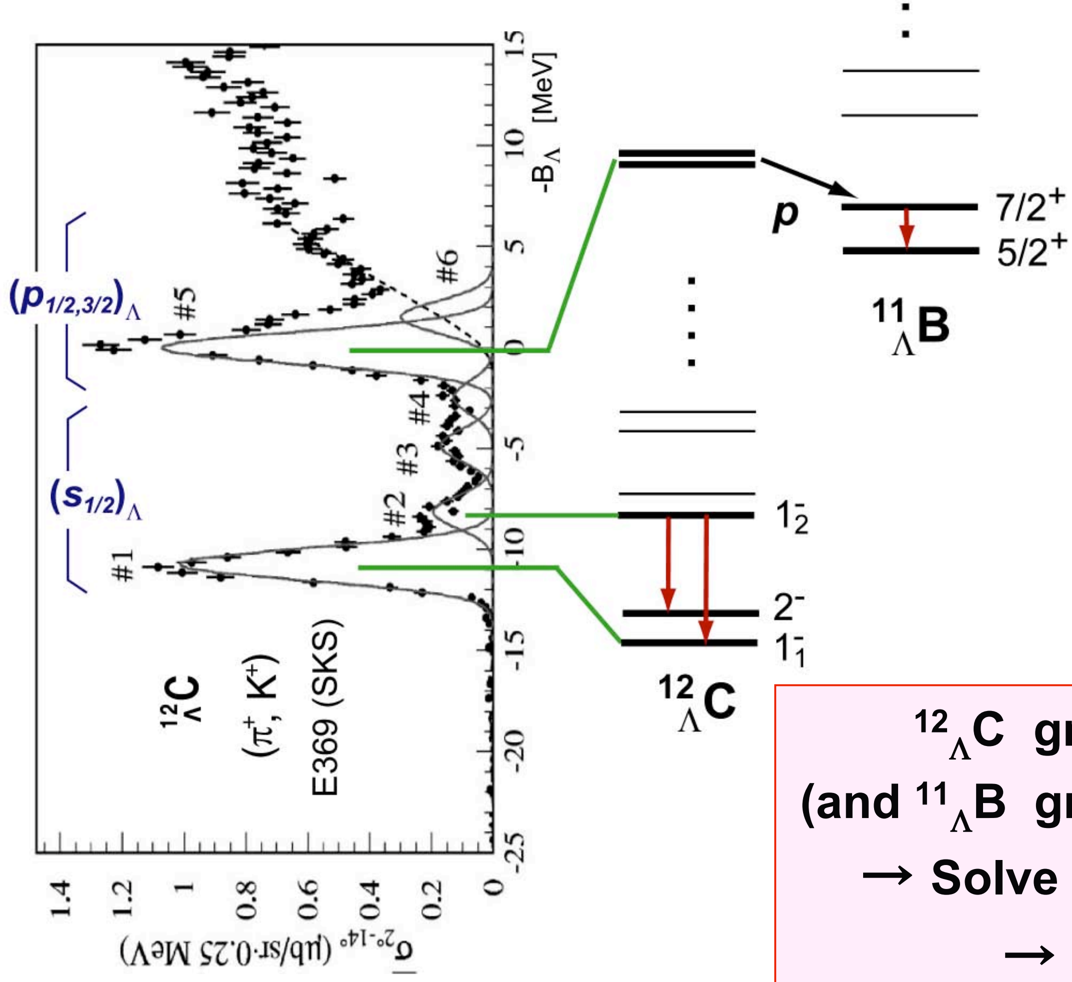


2. Purposes of E566

Purposes of the Experiment

^{12}C (π^+, $K^+ \gamma$) $^{12}{}_{\Lambda}C$ / $^{11}{}_{\Lambda}B$ with Hyperball2 + SKS at K6 line

80 (60+20) shifts



B(M1) of
spin-flip M1 ($^{11}{}_{\Lambda}B$: $7/2^+ \rightarrow 5/2^+$)
→ g_Λ in a nucleus
→ Medium effect of baryons

$^{12}{}_{\Lambda}C$ ground-doublet (2^-,1^-) spacing
(and $^{11}{}_{\Lambda}B$ ground-doublet ($5/2^+$,$7/2^+$) spacing)
→ Solve "$^{10}{}_{\Lambda}B$ puzzle" in ΛN interaction
→ Establish ΛN interaction

μ_Λ in nucleus

■ Why interesting?

Nuclear medium effect for baryons

Partial restoration of chiral symmetry….Reduction of mass ? Swelling?

-> μ_N changes? $\mu_q = \dfrac{e\hbar}{2m_q c}$

m_q **: Constituent quark mass**

Can be investigated using a Λ (free from Pauli) in 0s orbit

+ Quark exchange current (Pauli effect between quarks)
+ Meson exchange current

Calculated.
Small (a few %) for Λ.

■ How to measure it?

Direct measurement of μ -- extremely difficult. "Dream Experiment"

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

100% **Doppler Shift Attenuation Method**

$$\Gamma_\gamma = Br / \tau = (16\pi/9\hbar)\,(E_\gamma / \hbar c)^3\ B(M1)$$

$$= 1.76\times10^{13}\ E_{\gamma\,[\mathrm{MeV}]}^{3}\ B(M1)\,[\mu_N^2]$$

$\psi_{\Lambda\uparrow}\,\psi_c$

$\psi_{\Lambda\downarrow}\,\psi_c$

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

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

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

$$\propto (g_\Lambda - g_c)^2$$

ΛN Spin-dependent interactions and γ spectroscopy

- Two-body ΛN effective interaction

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

$\bar{V}$ Δ S_Λ S_N T

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

Well known (U_Λ = - 30 MeV)

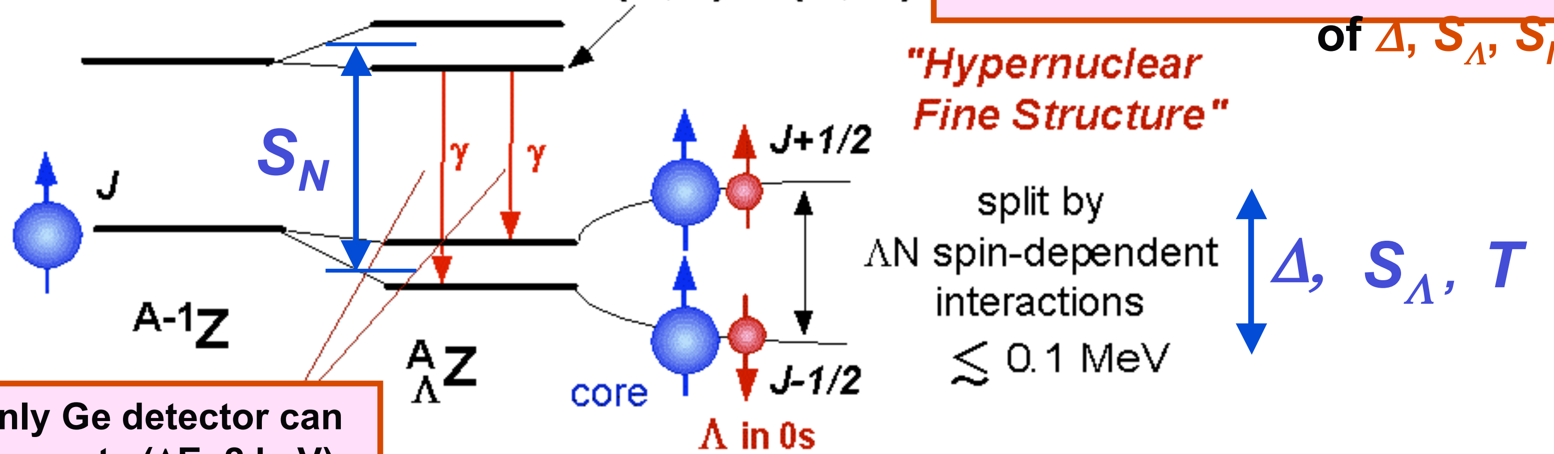
$$\Delta = \int V_\sigma(r)\, |u(r)|^2\, r^2 dr, \quad r = r_{s_\Lambda} - r_{p_N}$$

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

- Low-lying levels of Λ hypernucleus

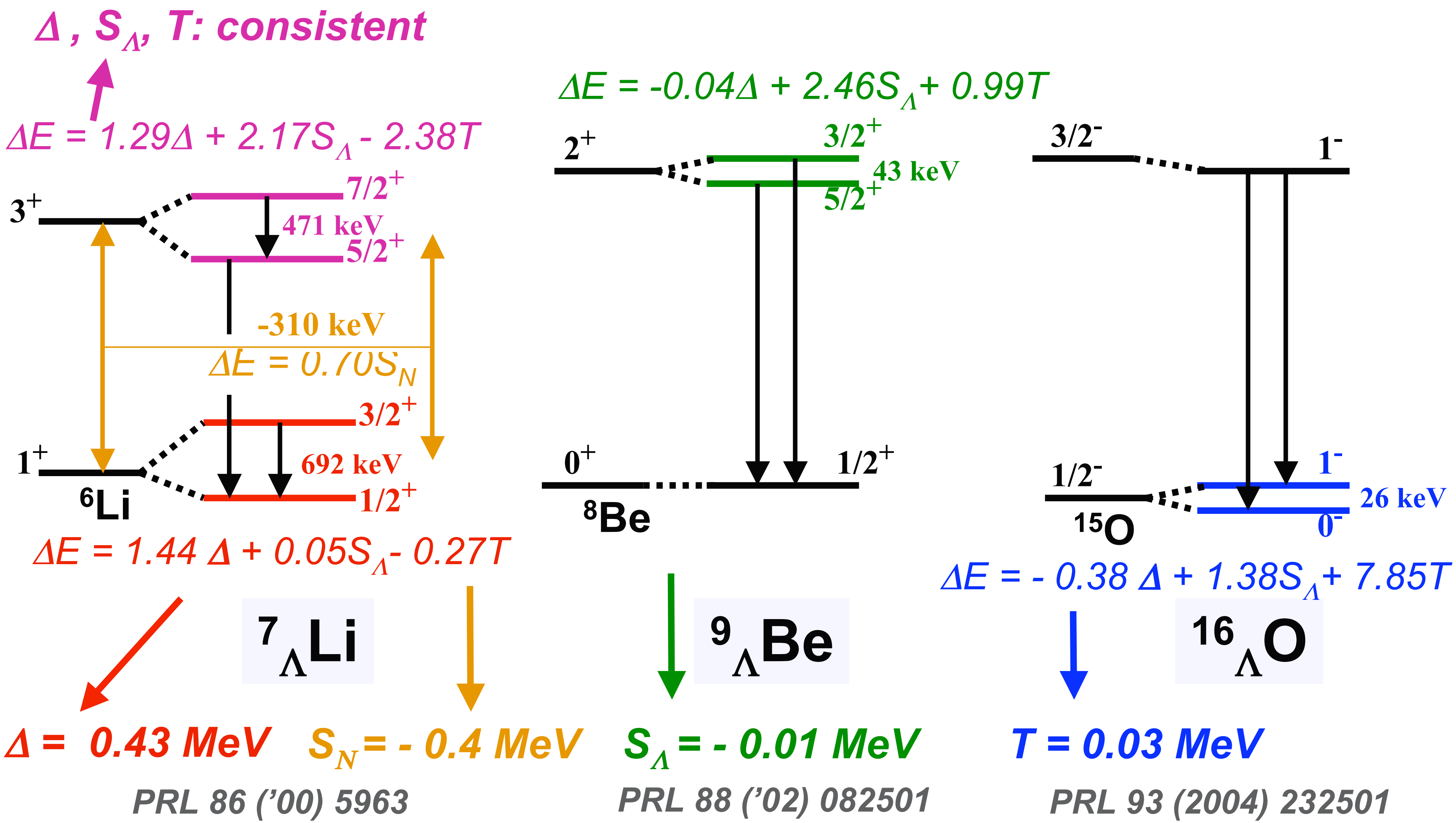
Level spacing: linear combination of Δ, S_Λ, S_N, T

"Hypernuclear Fine Structure"



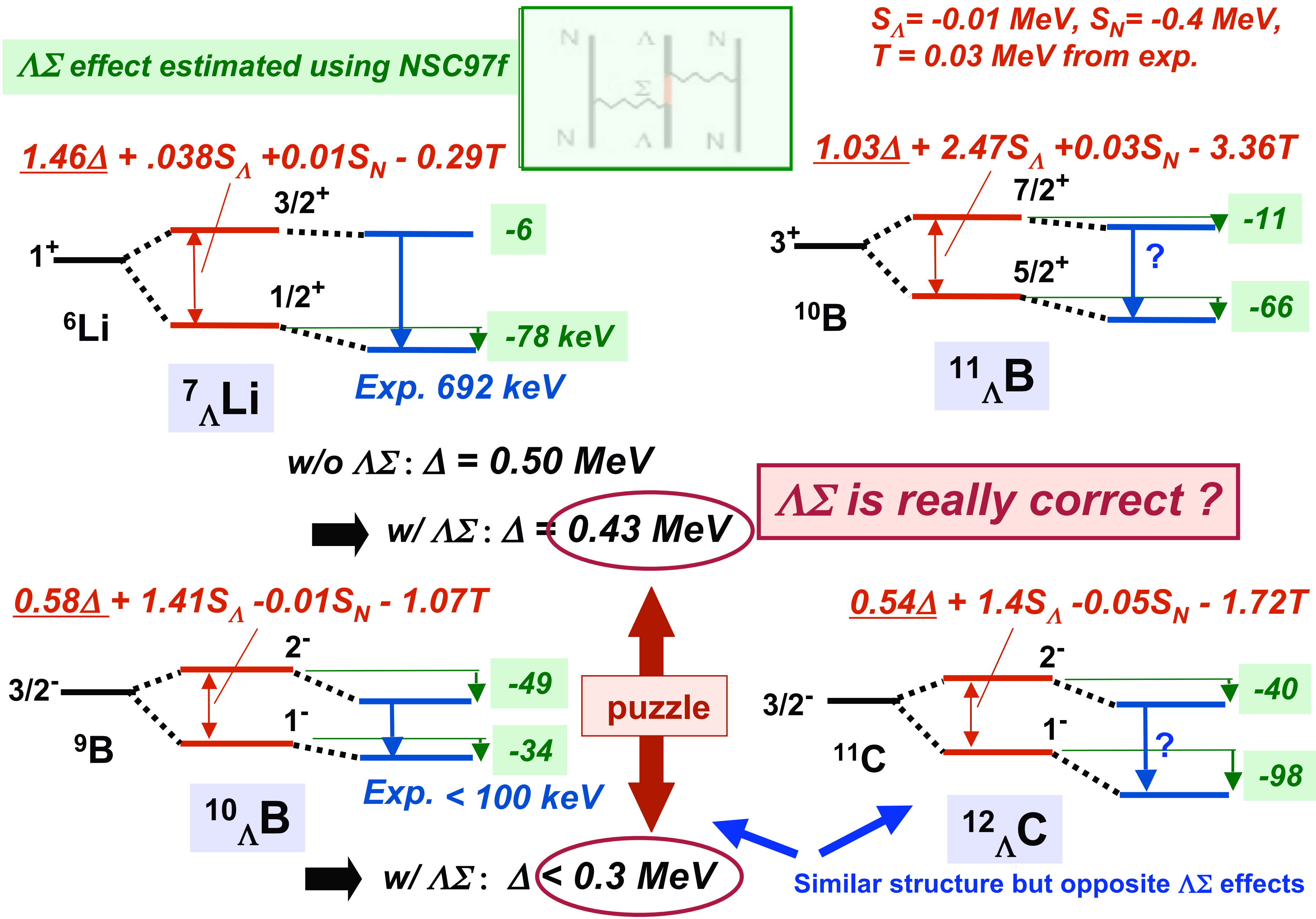
Only Ge detector can separate (ΔE~2 keV)

Determination of the spin-dependent force parameters (KEK E419, BNL E930)



All the spin-dependent force parameters determined !
but consistency test is necessary

Spin-spin strength (Δ) and Λ-Σ coupling (Millener)



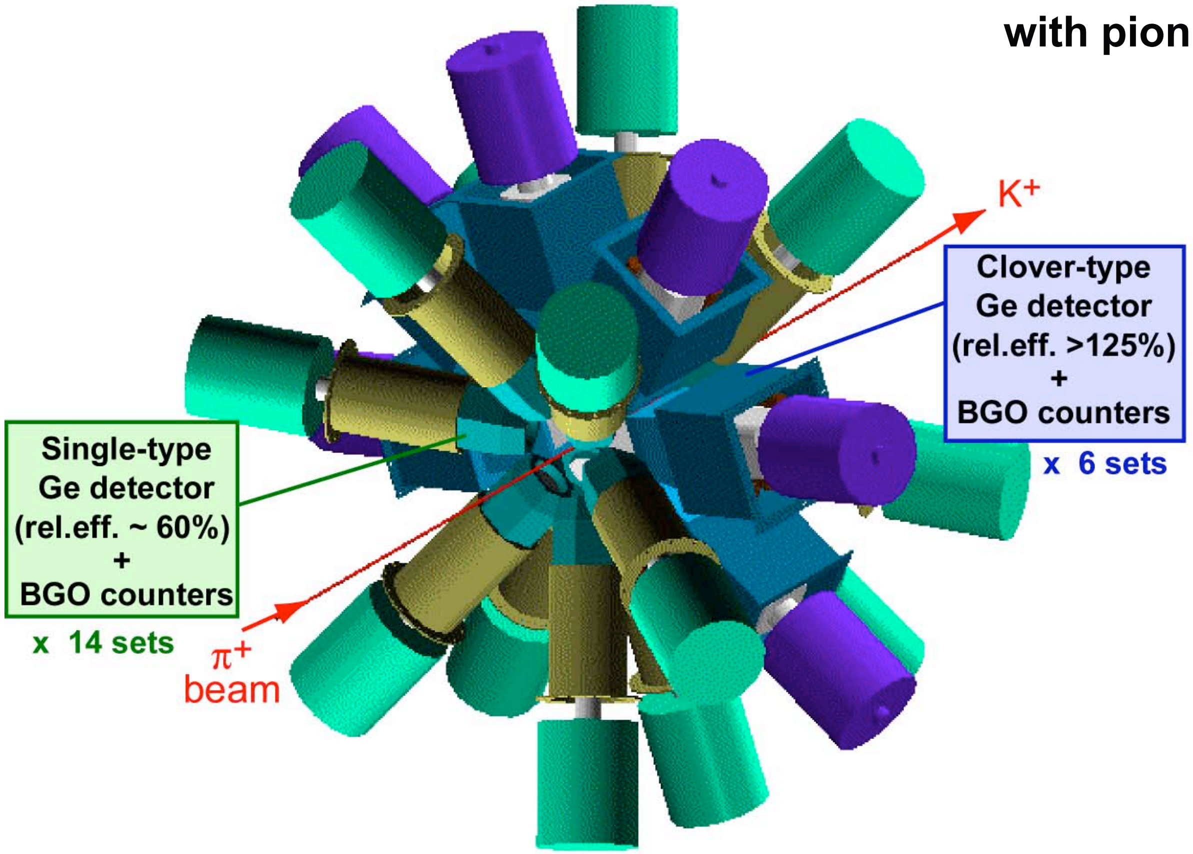
3. Setup and Hyperball2

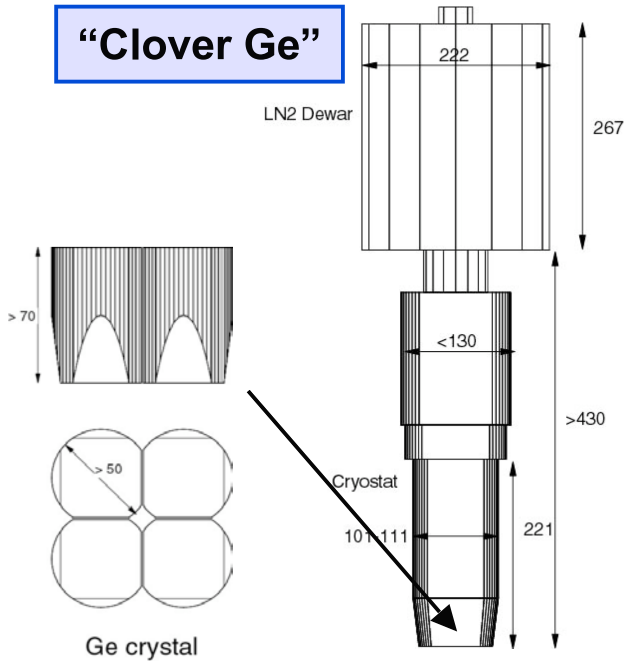
Hyperball-2

- Reset-type "Clover Ge" (r.e.>125%) newly developed at Eurisys Measures
- BGO counters (from China)

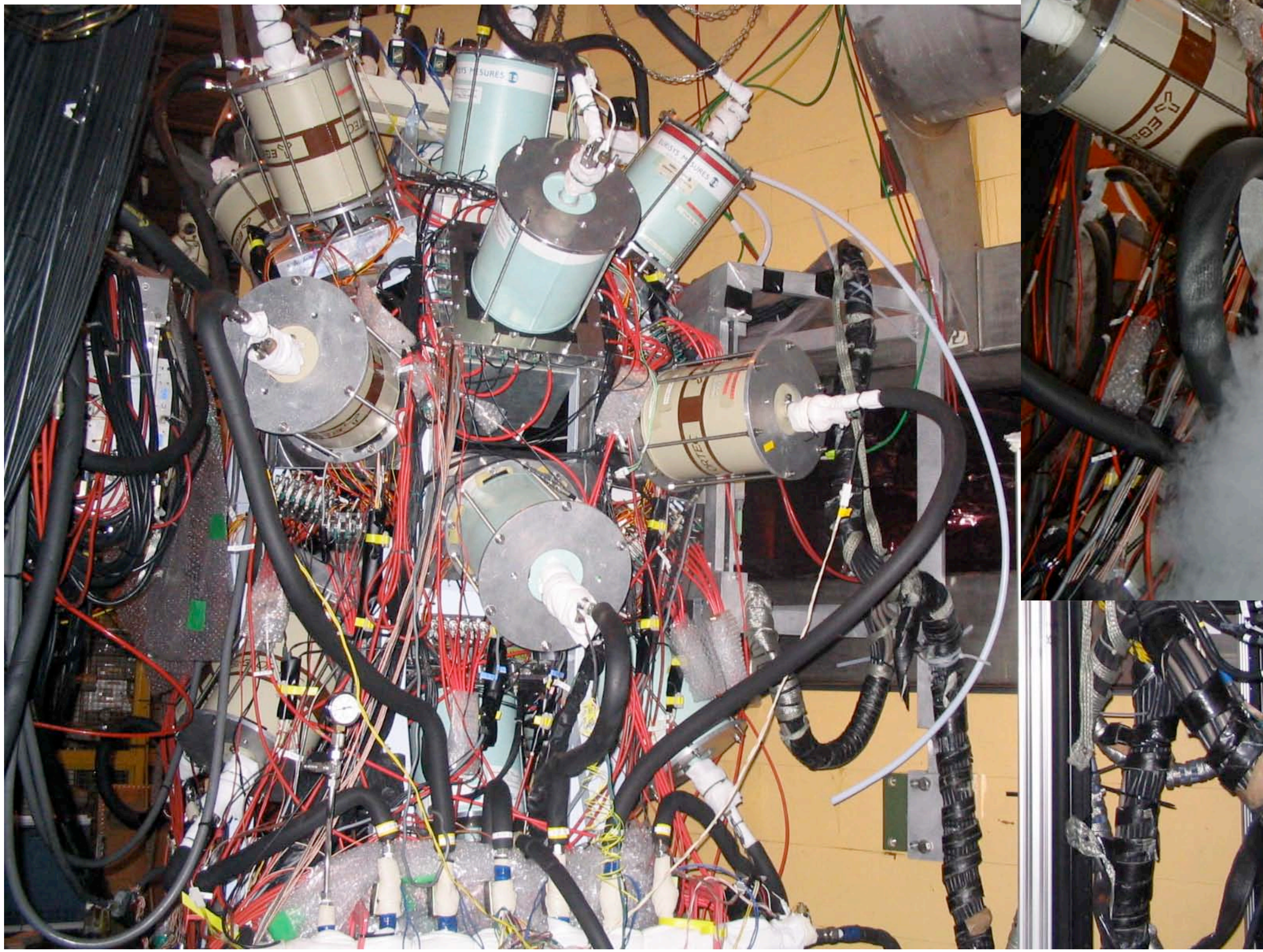
x 6 sets added to Hyperball

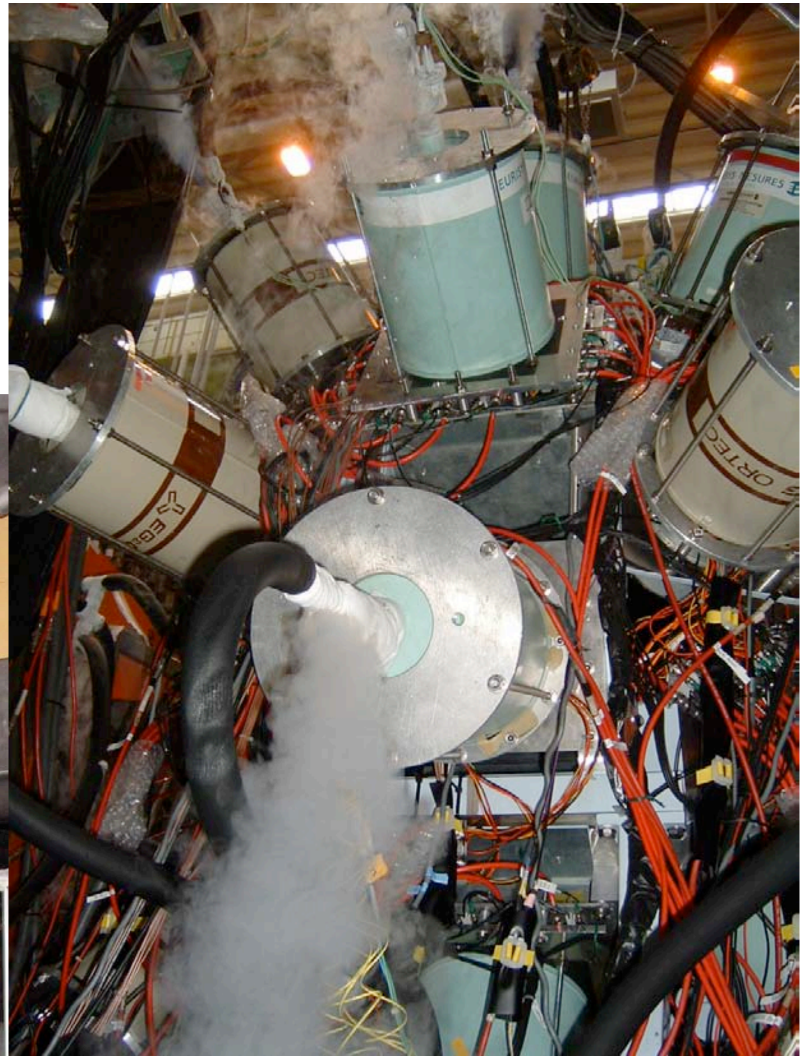
- Photo-peak efficiency x2
  ~ 2.5% -> 5% at 1 MeV
- High-rate performances same as Hyperball
- VME-based fast readout
- Clover's already tested with pion beam at K6 (T536) -- almost OK (slightly lower eff. than single Ge)



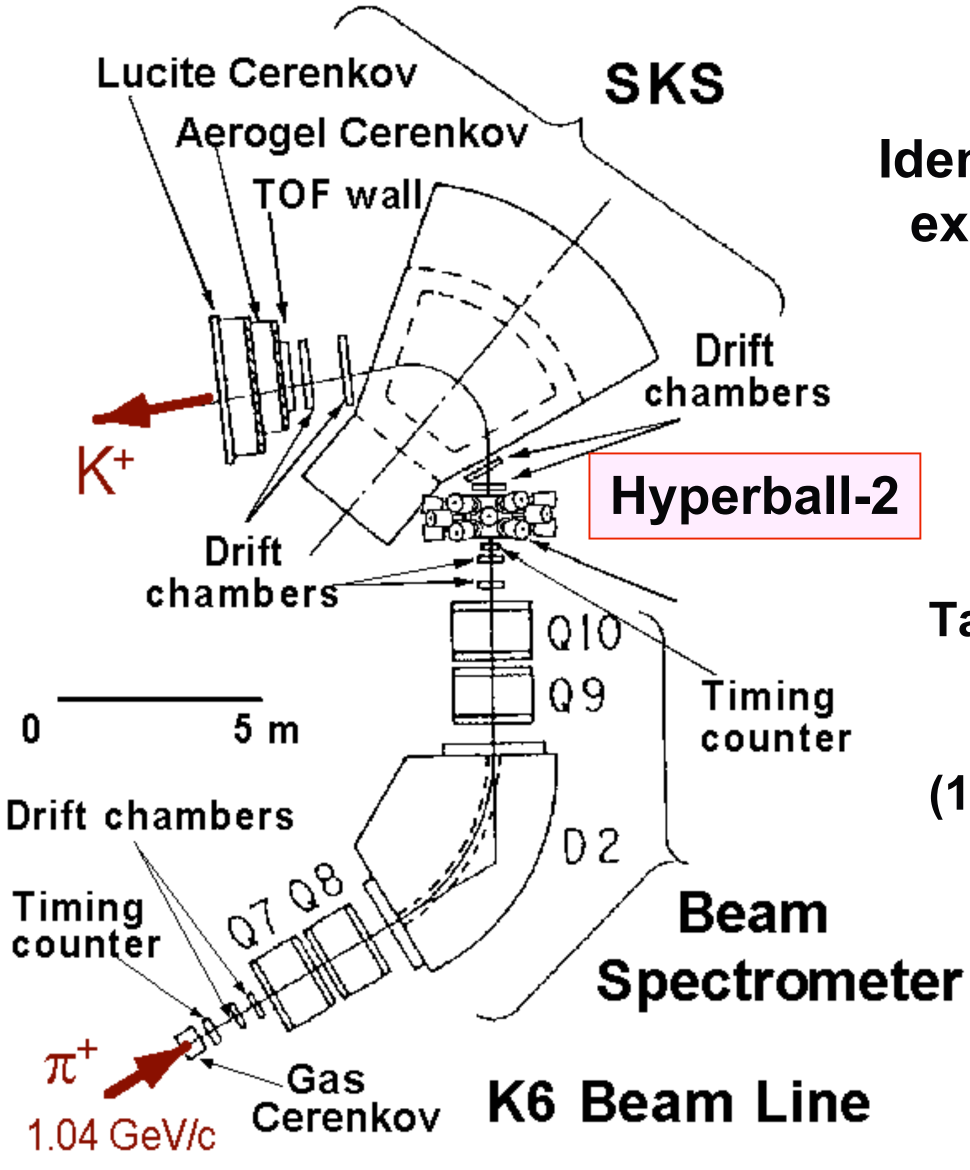


Hyperball2 at K6





Setup and beam status



Identical to E419, E518 except for Hyperall2

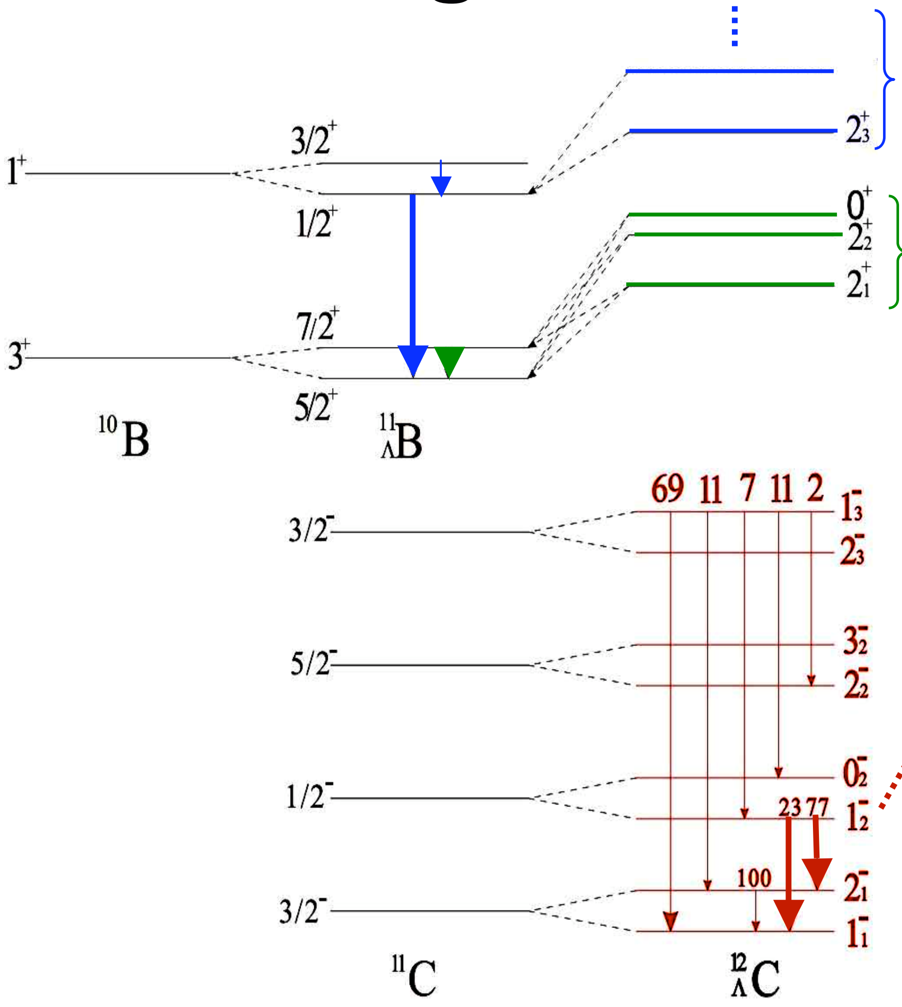
Target: polyethylene

18.8 g/cm^2

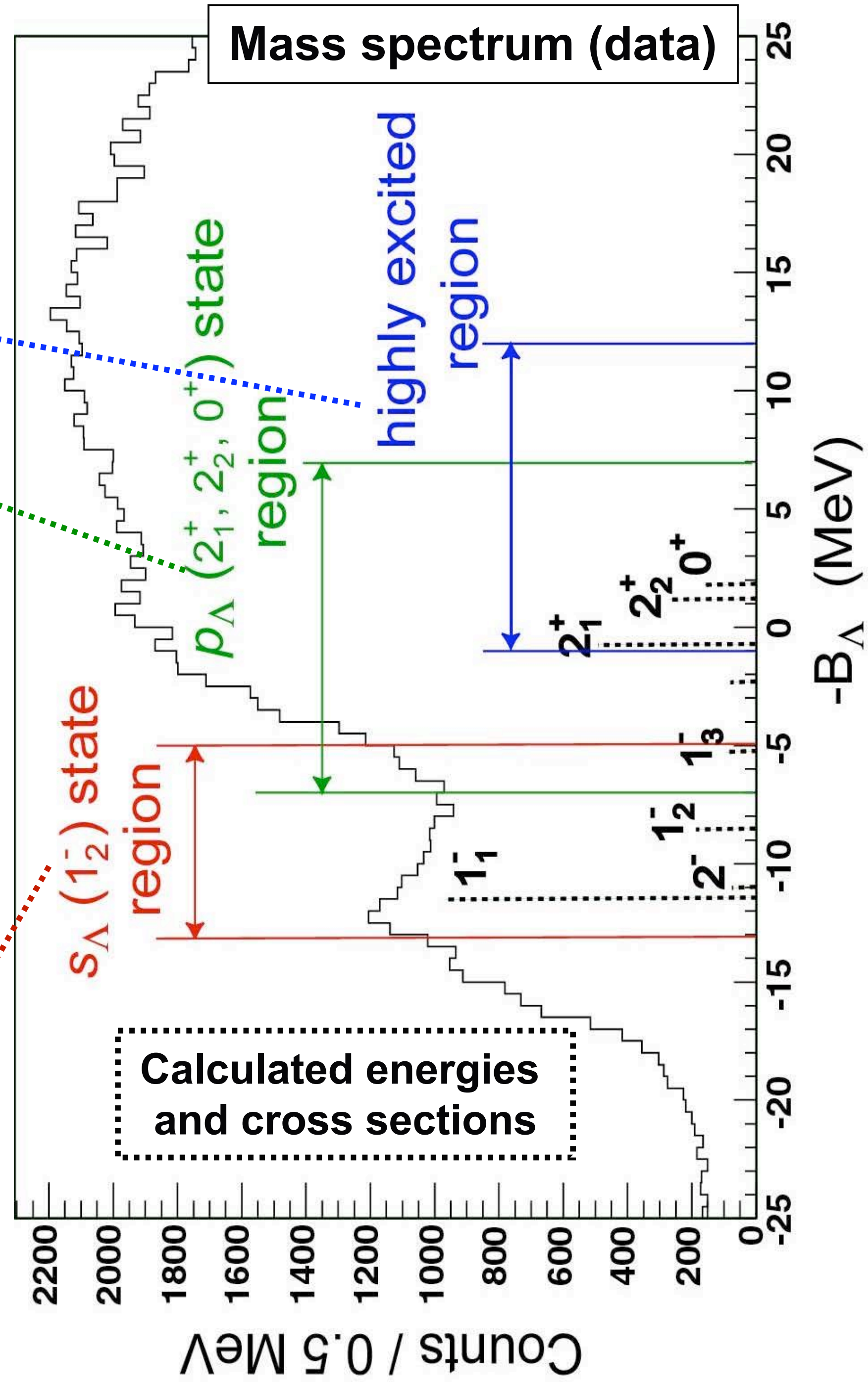
(16.1 g/cm^2 for ^{12}C)

4. Results and discussion

Mass spectrum and gates



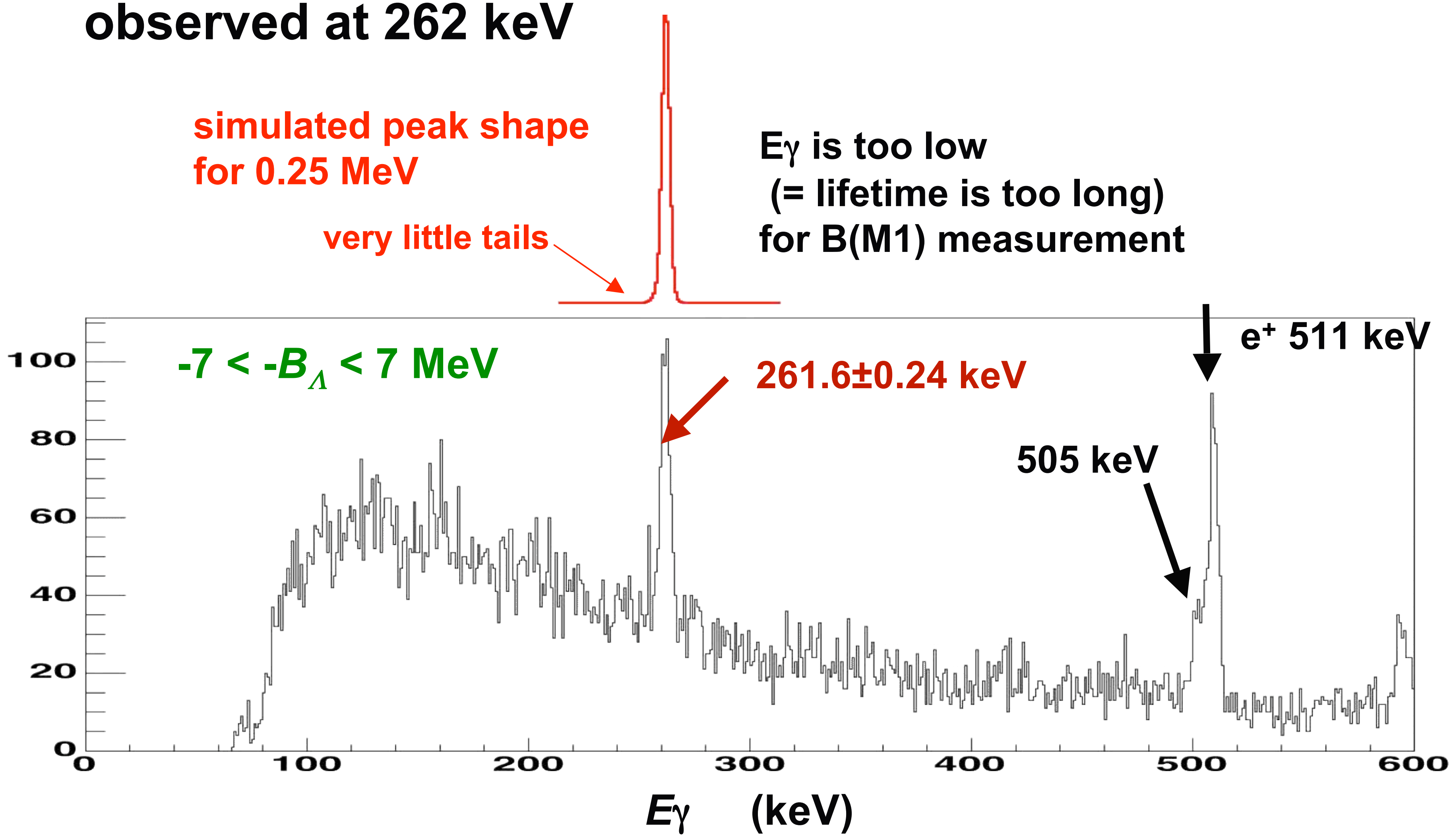
Expected level scheme and transitions



p_Λ state region

Δ= 0.43 MeV from $^{7}_{\Lambda}$Li
->
1.036Δ

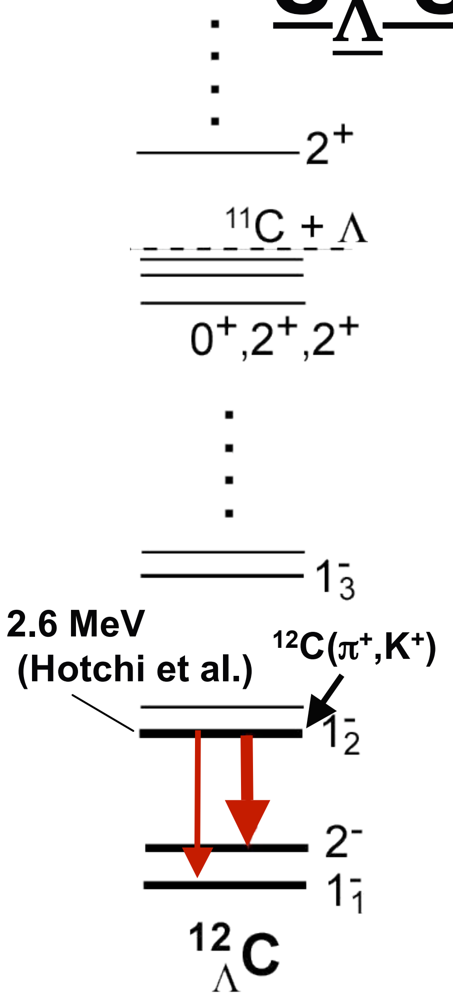
$^{11}_{\Lambda}$B(7/2^{+}->5/2^{+}) peak
observed at 262 keV

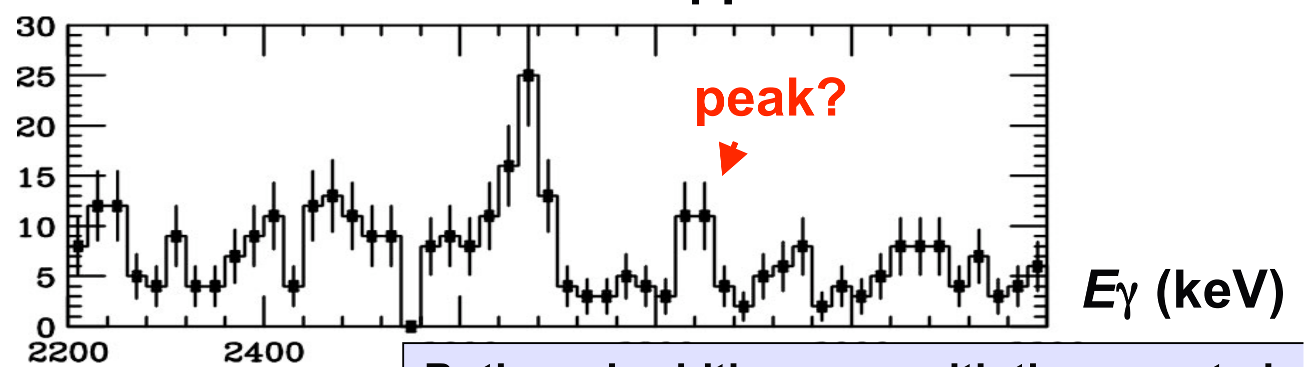


s_Λ state region

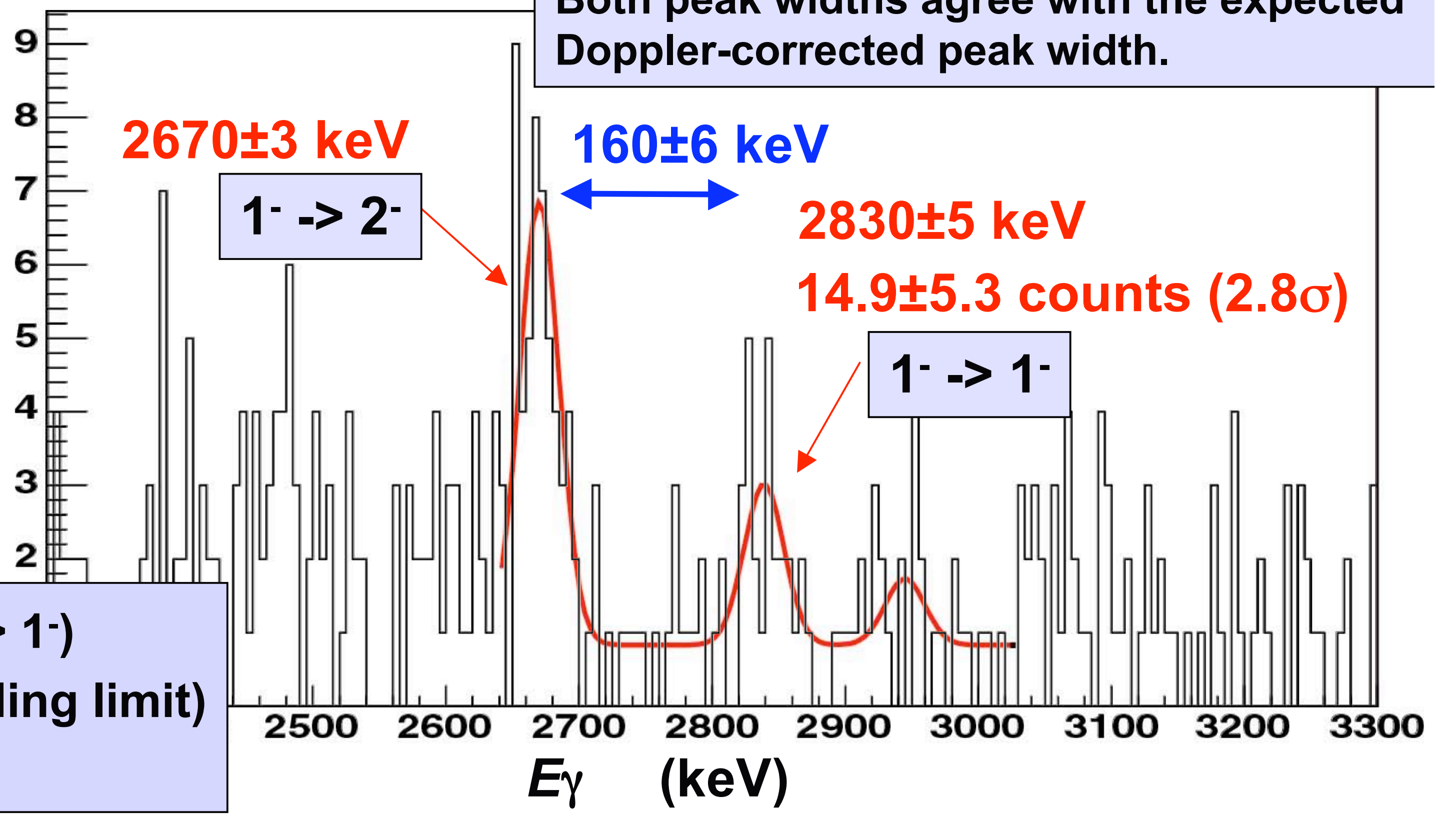
$-13 < -B_\Lambda < -5$ MeV

After Doppler shift corrected



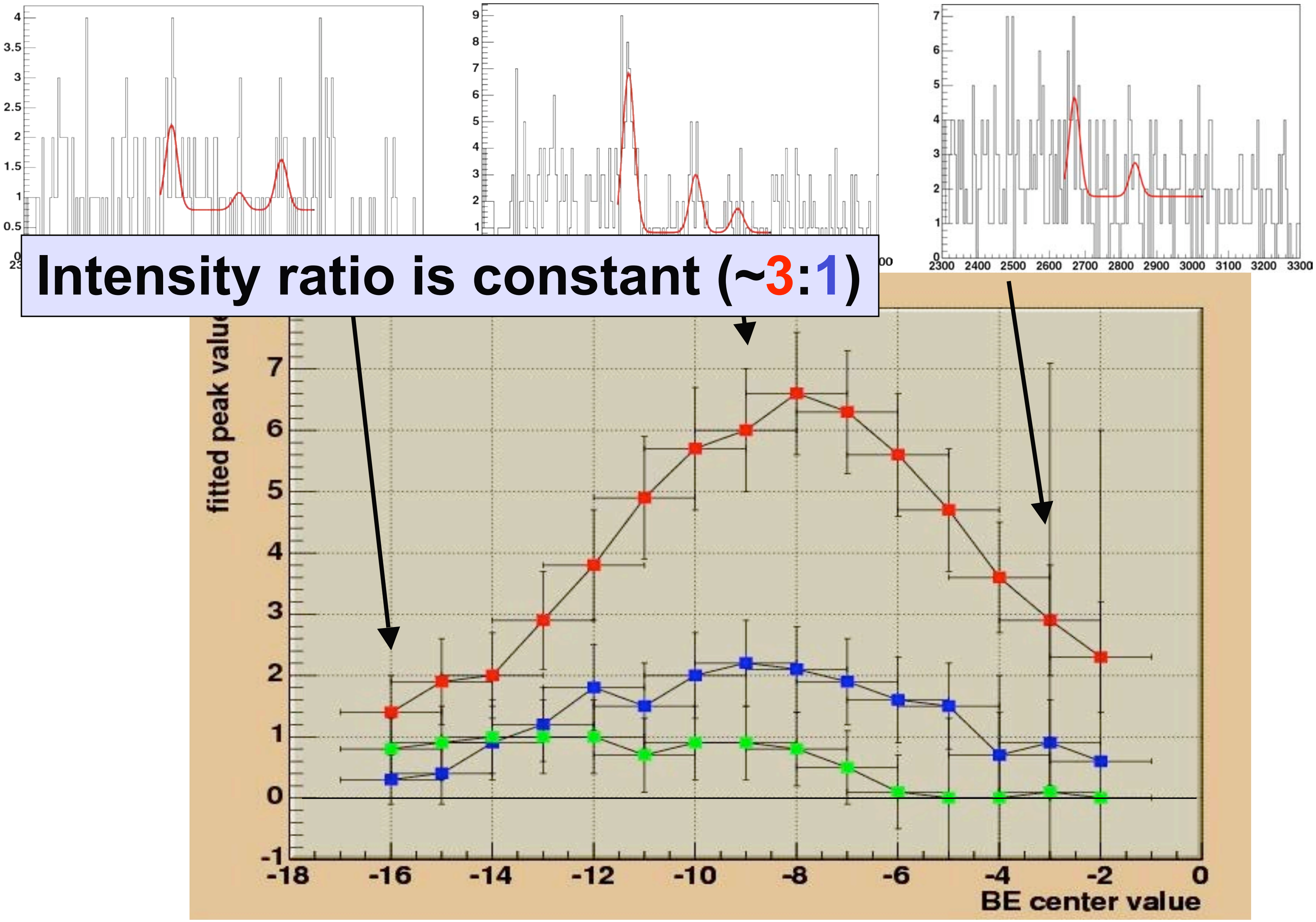


Both peak widths agree with the expected Doppler-corrected peak width.



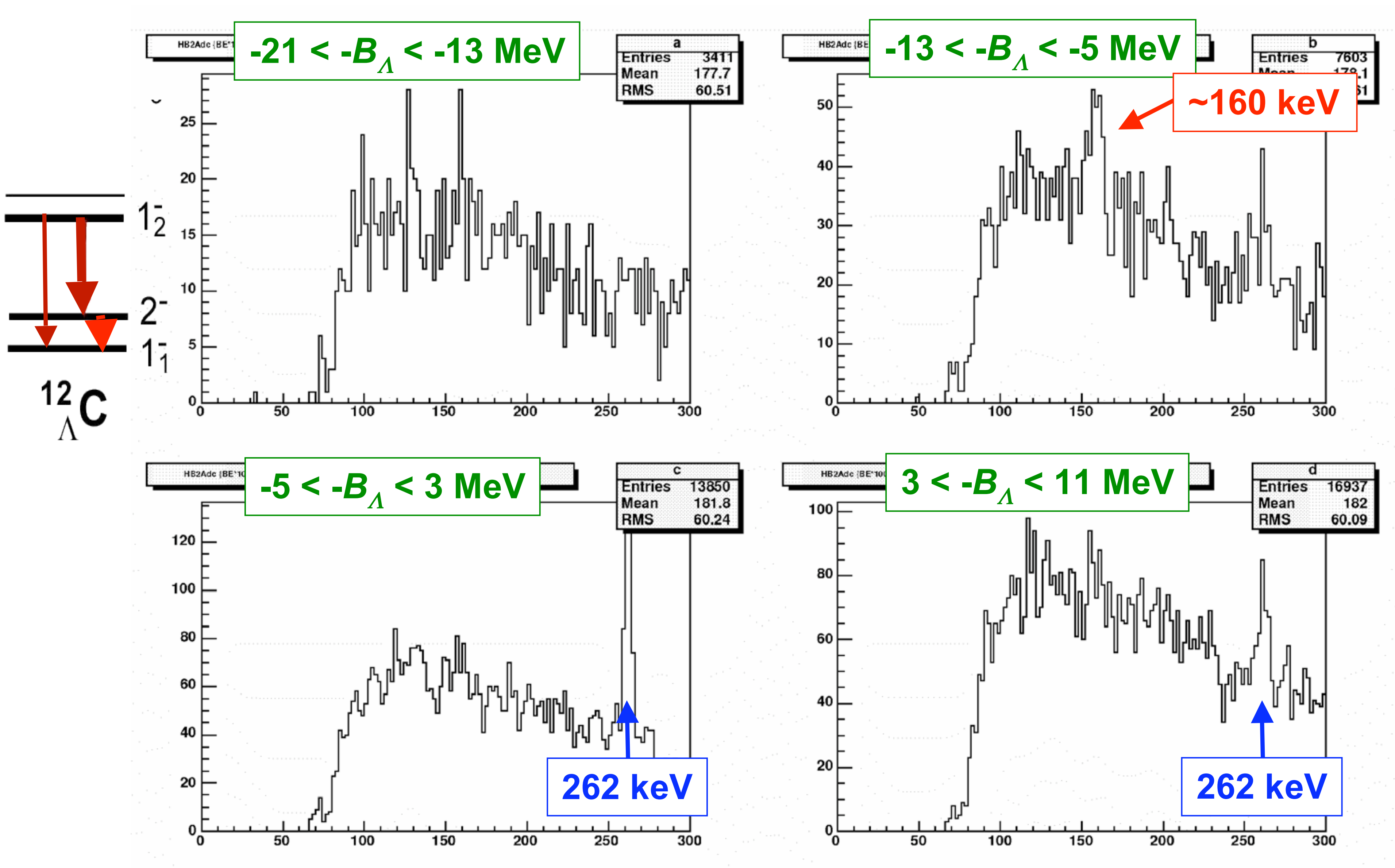
Br(1⁻ -> 2⁻): Br(1⁻ -> 1⁻)
= 5 :1 (weak coupling limit)
~ 3 :1 (Millener)

Dependence on the mass gate position

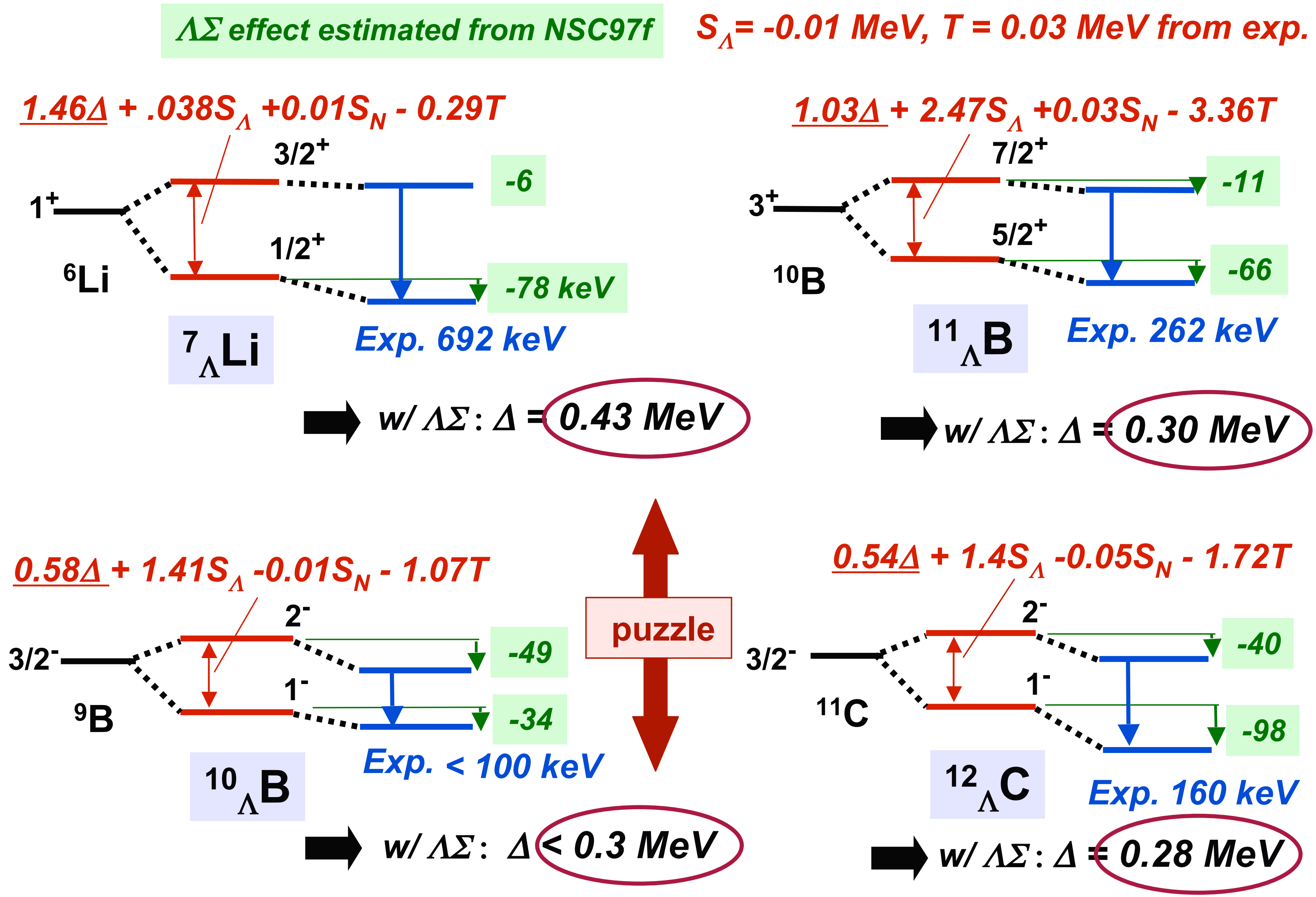


Intensity ratio is constant (~3:1)

Another evidence



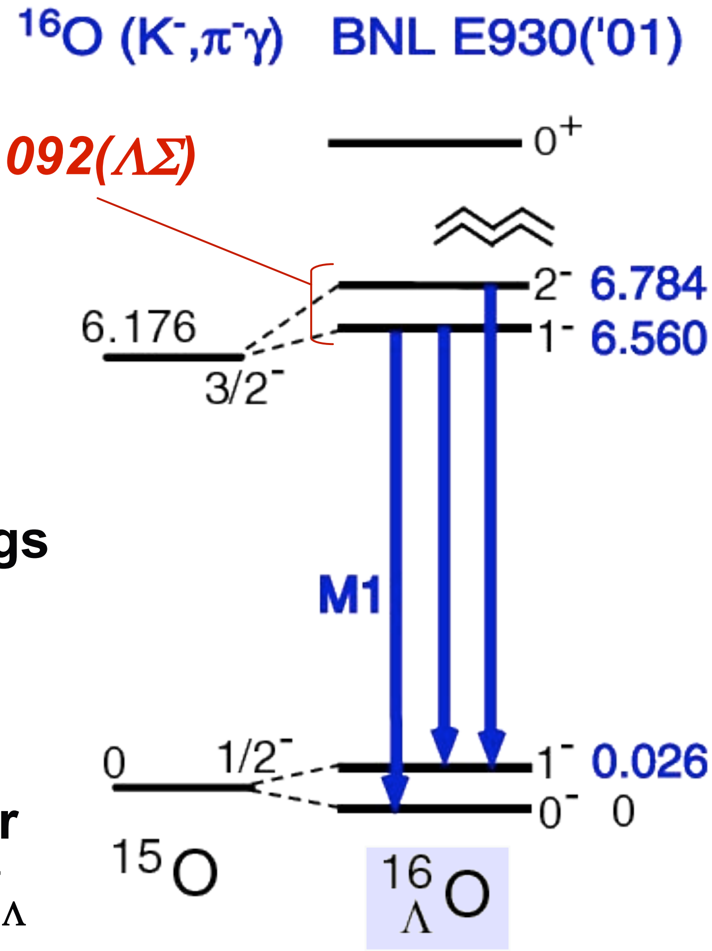
Spin-spin strength (Δ) and Λ-Σ coupling (Millener)



More consistency test on Δ

$0.627\Delta + 1.37S_\Lambda - 0.003S_N - 1.75T + 0.092(\Lambda\Sigma)$

➡ *w/ ΛΣ*: $\Delta = 0.33$ *MeV*

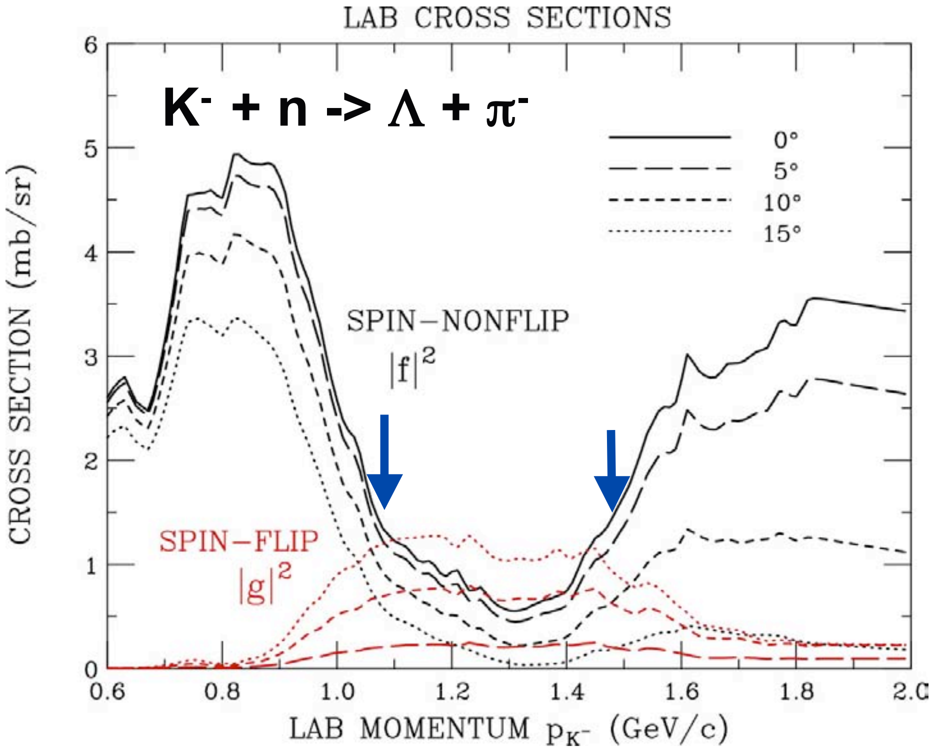


Δ~ 0.30 MeV explains
all the Δ-dominating doublet spacings
($^{10}_{\Lambda}$B, $^{11}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{16}_{\Lambda}$O) except for $^{7}_{\Lambda}$Li

Why is Δ for $^{7}_{\Lambda}$Li large (~0.43 MeV)?
Size effect ? But Δ should be smaller for loosely-bound nucleus such as $^{7}_{\Lambda}$Li.

5. Further experiments at J-PARC

Best K^- beam momentum



Both spin-flip and nonflip states should be produced.

-> p_K = 1.1 or 1.5 GeV/c

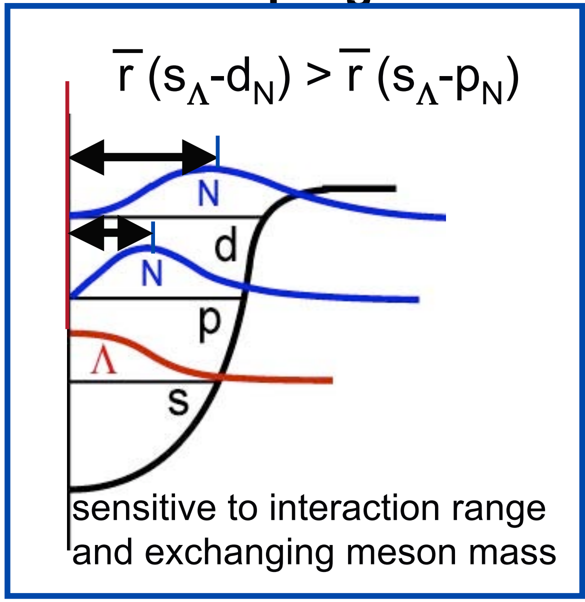
p_K = 1.1 GeV/c : K1.1 + “SKS” (ideal)
p_K = 1.5 GeV/c : K1.8 + SKS (realistic)

High K/π ratio to minimize radiation damage to Ge detectors
-> Double-stage separation. K1.8BR is not good.

Proposed DAY-1 experiment

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

DAY1 program: Feasible even with low intensity beam (~2μA)



asurement and g_Λ in a nucleus

guities exist and most reliable. (500 hrs)

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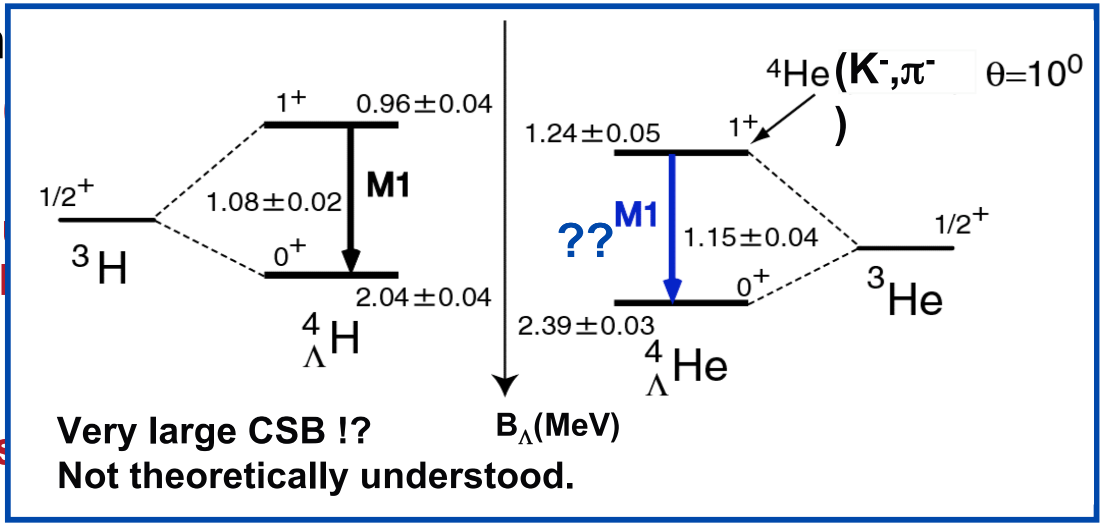


(3) Radial dependence of

$^{19}{}_\Lambda$F : Easiest in sd-s

(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)

Proposed B(M1) measurement

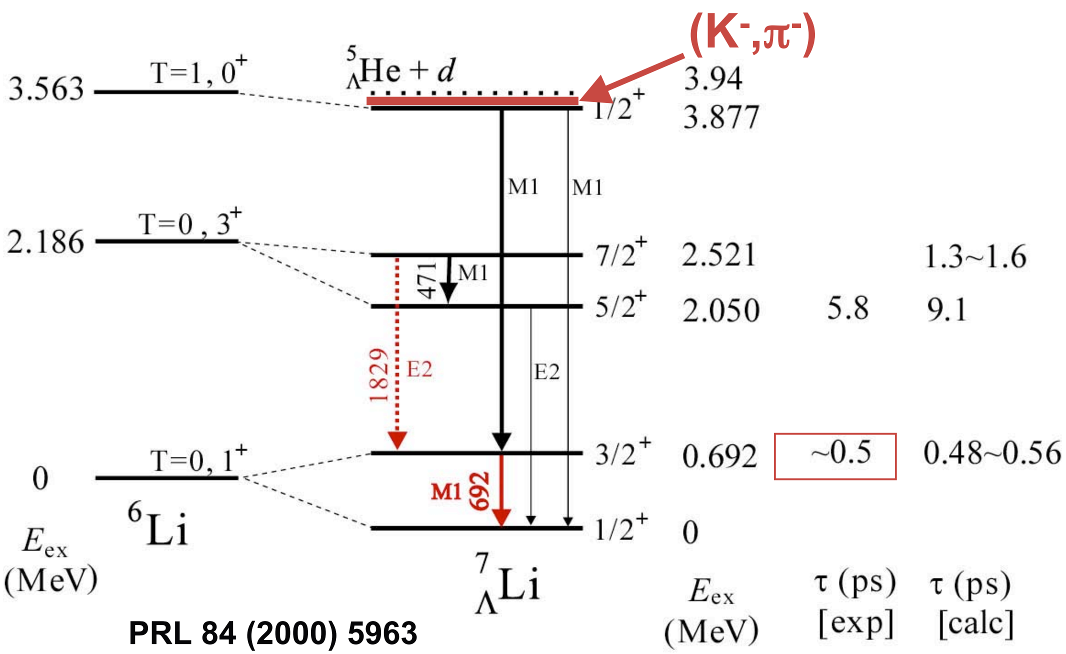
Difficulties in B(M1) measurement

- Doppler Shift Attenuation Method works only when $\tau \lesssim t_{stop}$
- τ is very sensitive to E_γ because B(M1) $\propto 1/\tau \propto E_\gamma^{3}$. But E_γ is unknown.
- Cross sections and background cannot be accurately estimated.

Previous attempts: ${}^{10}_{\Lambda}B$, ${}^{11}_{\Lambda}B$ (E_γ too small -> $\tau >> t_{stop}$), ${}^{7}_{\Lambda}Li$ (byproduct: indirect population)

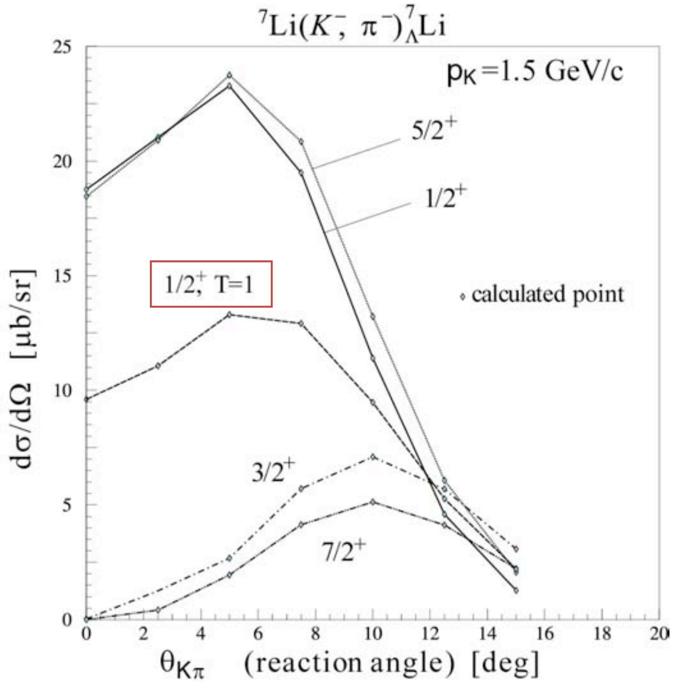
To avoid ambiguities, we use the best-known hypernucleus, ${}^{7}_{\Lambda}Li$.

- 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



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

Calc. by Motoba



Expected yield and sensitivity

Yield estimate

N_K = 0.5 x 10^6 /spill

Target (^{7}Li in Li_2O) = 20cm x 2.0g/cm^3 x 14/30 x 0.934 / 7 x 6.02x10^{23}

$\int d\sigma/d\Omega(1/2;1)\,\Delta\Omega$ x BR($1/2^+$;1->$3/2^+$) = 0.84 μb x 0.5

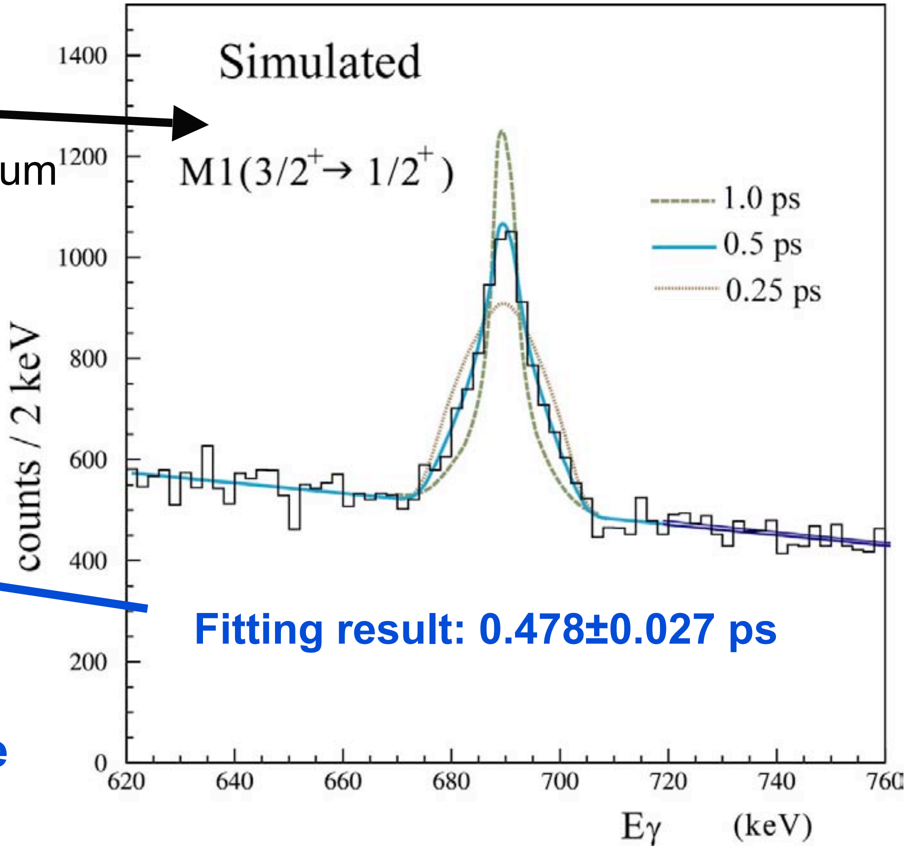
ε(Ge) x ε (tracking) = 0.7 x 0.6

=>

Yield ($3/2^+$->$1/2^+$) = 7.3 /hr(1000 spill)

= 3600 / 500 hrs

Background estimated from E419 $^7{}_\Lambda$Li spectrum



Fitting result: 0.478±0.027 ps

■**Stat. error $\Delta\tau/\tau$ = 5.4%**

=> $\dfrac{\Delta|g_\Lambda - g_c|}{|g_\Lambda - g_c|}$ ~ 3%

■**Syst. error < 5%**
mainly from stopping time

Beam and Setup

SMF: Muon filter to suppress $K^- \rightarrow \mu^- \nu$

- **Spectrometer: SKS (modified)**
  Δp ~ 4 MeV (FWHM)
  Ω ~ 110 msr

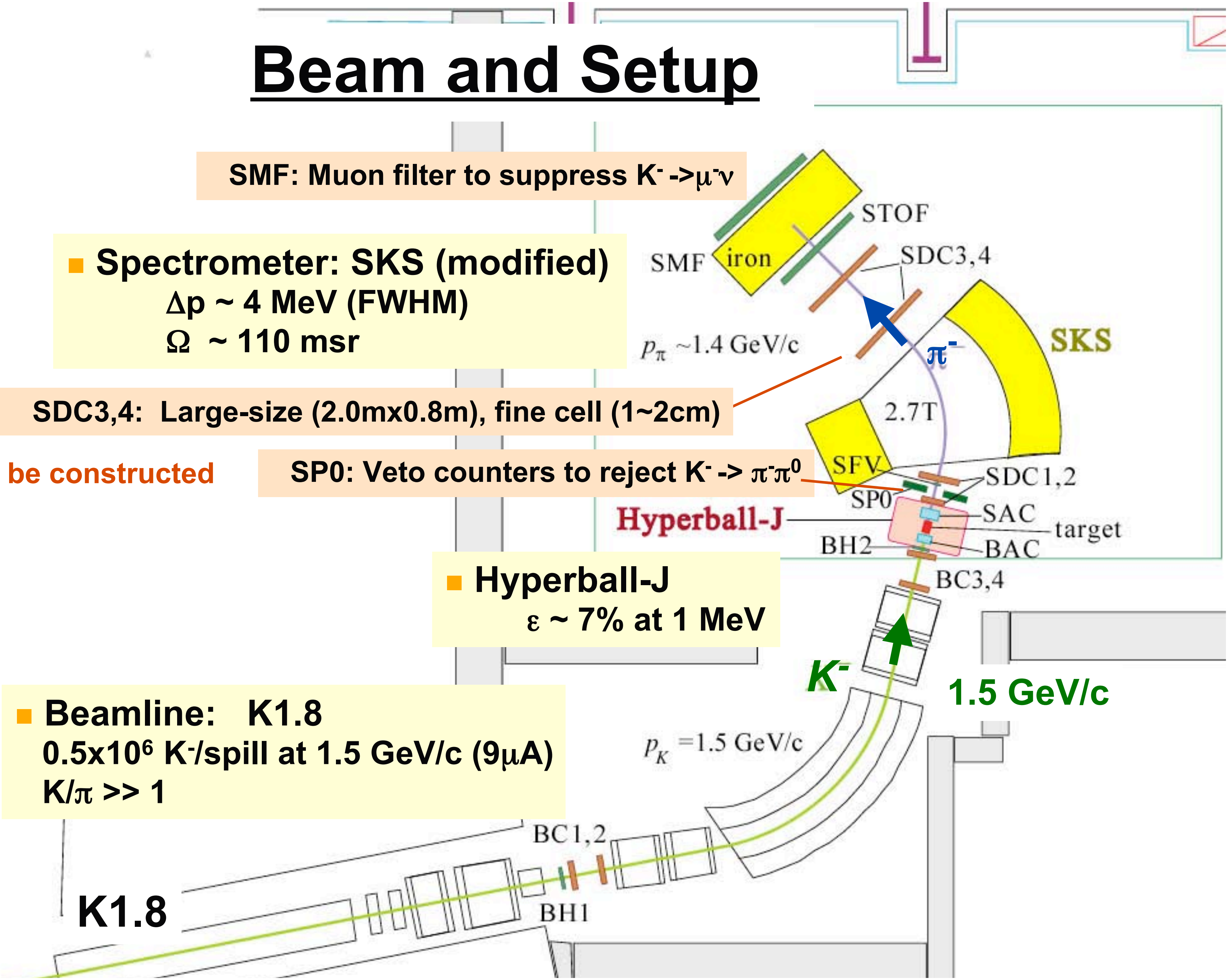
SDC3,4: Large-size (2.0mx0.8m), fine cell (1~2cm)

To be constructed

SP0: Veto counters to reject $K^- \rightarrow \pi^- \pi^0$

- **Hyperball-J**
  ε ~ 7% at 1 MeV

- **Beamline: K1.8**
  0.5×10^6 K^-/spill at 1.5 GeV/c (9μA)
  $K/\pi >> 1$



Hyperball-J

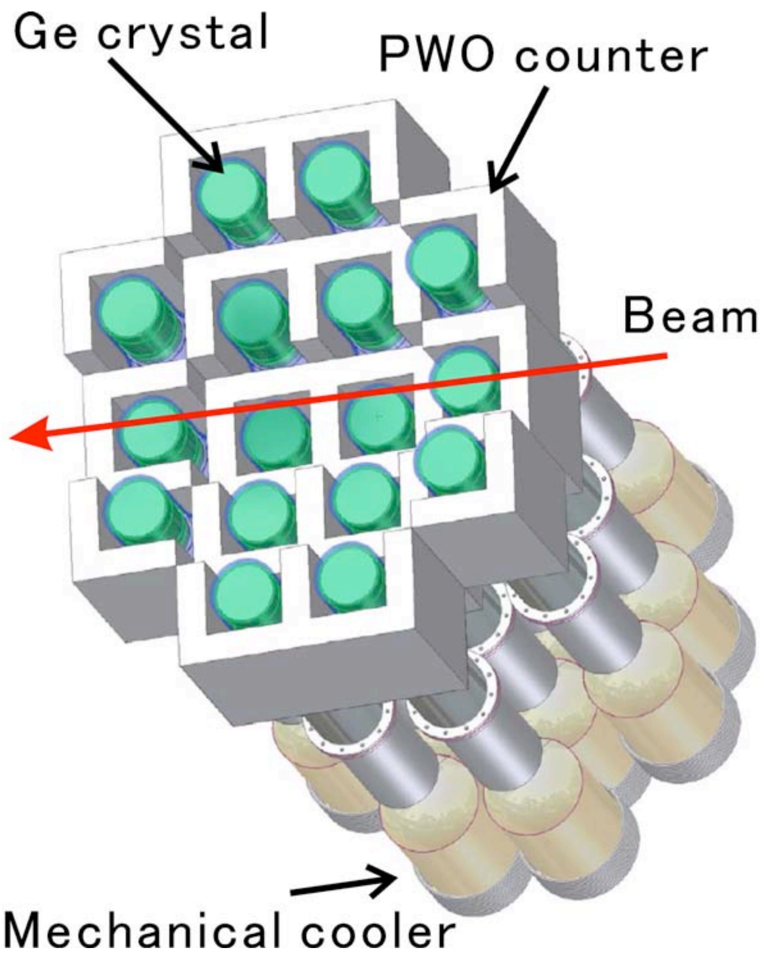
Under construction

- Ge (single, r.e.~60%) x ~32
  → peak efficiency ~6% at 1 MeV
  (x ~3 of Hyperball)

- Mechanical cooling
  -- Lower temp. for less radiation damage
  -- Save space for flexible arrangement

- PWO background suppression counters replaced from BGO for higher rate

- Waveform readout (under development)
  => Rate limit ~2x10^7 particles /s
  (x5 of Hyperball)



Lower half

Further plans of γ spectroscopy K1.8-> K1.1

Reaction / p (GeV/c) ; Beamline ; Features

(1) *Complete study of light (A<30) hypernuclei* …, $^{20}_{\Lambda}$Ne, $^{23}_{\Lambda}$Na, $^{27}_{\Lambda}$Al / $^{28}_{\Lambda}$Si

(K^-,π^-) p= 1.1 and 0.8 ; K1.1 ; $\gamma\gamma$ coin, angular corr. , B(E2),..

"Table of Hyper-Isotopes" ΛN interaction (ΛN–ΣN, p-wave, ..) Shrinkage, collective motion, ... **Partly in E13**

(2) *Systematic study of medium and heavy hypernuclei* $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La, $^{208}_{\Lambda}$Pb

(K^-,π^-) p=0.8-1.8 ; K1.1 and K1.8 ; p-wave ΛN interaction

(3) *Hyperfragments* $^{8}_{\Lambda}$Li, $^{8}_{\Lambda}$Be, $^{9}_{\Lambda}$B,…

K^--in-beam (stopped K^-) p=0.8 ; K1.1 ; p/n-rich hypernuclei,

(4) *n-rich and mirror hypernuclei* $^{7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{12}_{\Lambda}$B...

(K^-,π^0) p= 1.1 and 0.8 ; K1.1 ; charge sym.break., shrinkage of n-halo,

(5) *B(M1) using Doppler shift* $^{7}_{\Lambda}$Li and heavier **Partly in E13**

(K^-,π^-) p= 1.1 and (π^+,K^+) p= 1.05 ; K1.1 ; μ_Λ in nucleus

(6) *B(M1) using γ-weak coincidence*

(K^-,π^-) p= 1.1 and 0.8 ; K1.1 ; ρ, T dependence of μ_Λ in nucleus

S=-2

Reaction / p (GeV/c) ; Beamline ; Features

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(7) *Ξ atom X rays*

in E03, E07

(K^-, K^+) p=1.8 GeV/c; K1.8 ; ΞN interaction

(8) *ΛΛ-hypernuclei*

(K^-, K^+) p=1.8 GeV/c; K1.8 ; ΛΛ, ΞN-ΛΛ interactions

Summary

- $^{12}C(\pi^+,K^+\gamma)^{11}{}_\Lambda B, ^{12}{}_\Lambda C$ experiment was performed at K6/SKS and Hyperball2. Hyperball2 (upgraded Hyperball) worked well.
- We observed five transitions:
  - $^{12}{}_\Lambda C(1^- \to 2^-)$ at 2.67 MeV (new)
  - $^{12}{}_\Lambda C(1^- \to 1^-)$ at 2.83 MeV (new, 2.8σ significance)
  - $^{11}{}_\Lambda B(7/2^+ \to 5/2^+)$ at 0.262 MeV (also observed in E518 w/o assignment)
  - $^{11}{}_\Lambda B(1/2^+ \to 5/2^+)$ at 1.48 MeV (also observed in E518)
  - $^{11}{}_\Lambda B(3/2^+ \to 1/2^+ ?)$ at 0.505 MeV (also observed in E518 w/o assignment)
- $^{11}{}_\Lambda B(7/2^+,5/2^+)$, $^{12}{}_\Lambda C(1^-,1^-)$, $^{16}{}_\Lambda O(1^-,2^-)$ can be explained by $\Delta \sim 0.3$ MeV, and $^{10}{}_\Lambda B(3^+,2^+)$ is also consistent. "$^{10}{}_\Lambda$B puzzle" is now "$^{7}{}_\Lambda$Li puzzle". The calculated ΣN-ΛN coupling effect looks OK.
- $^{11}{}_\Lambda B(7/2^+ \to 5/2^+)$ energy is too small for B(M1) measurement.
- J-PARC E13 (γ spectroscopy of light Λ hypernuclei) is approved as one of the Day-1 experiment at K1.8.
- It aims at B(M1) measurement ($^{7}{}_\Lambda$Li),
  more p-shell data for ΛN interaction ($^{10}{}_\Lambda$B, $^{11}{}_\Lambda$B),
  charge symmetry breaking ($^{4}{}_\Lambda$He),
  radial dependence of ΛN interaction ($^{19}{}_\Lambda$F)
- Hyperball-J and SksMinus detectors are under preparation.