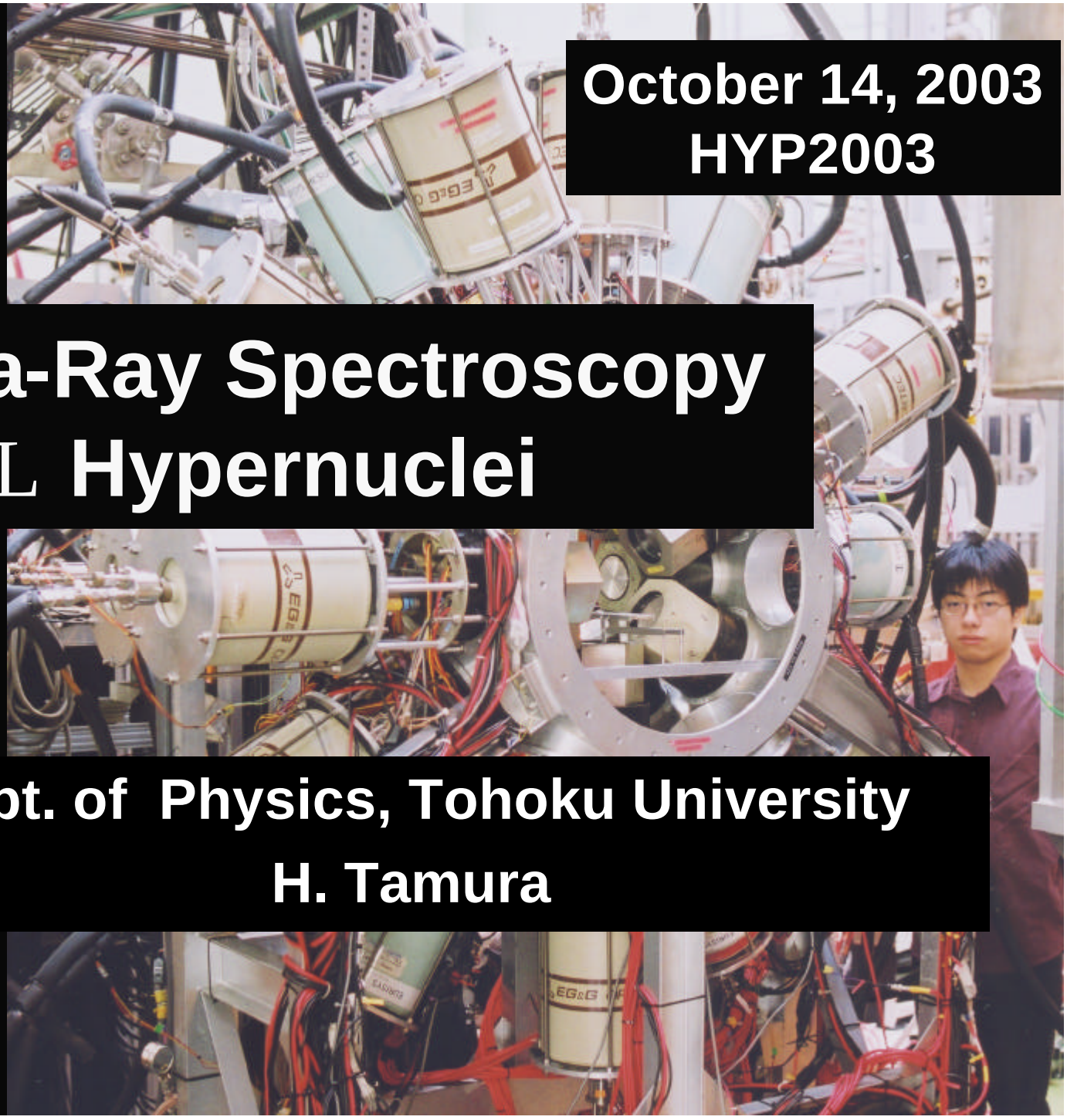
October 14, 2003
HYP2003

Gamma-Ray Spectroscopy in Λ Hypernuclei



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Hyperball collaboration (1998, 2001,2002)
E930, E509, E518

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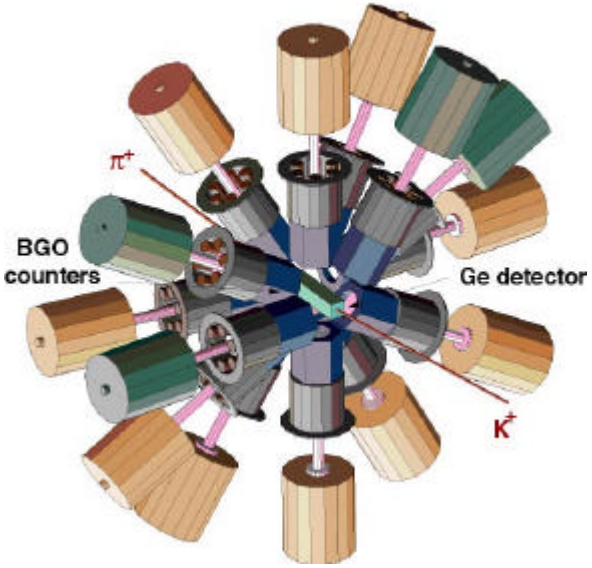


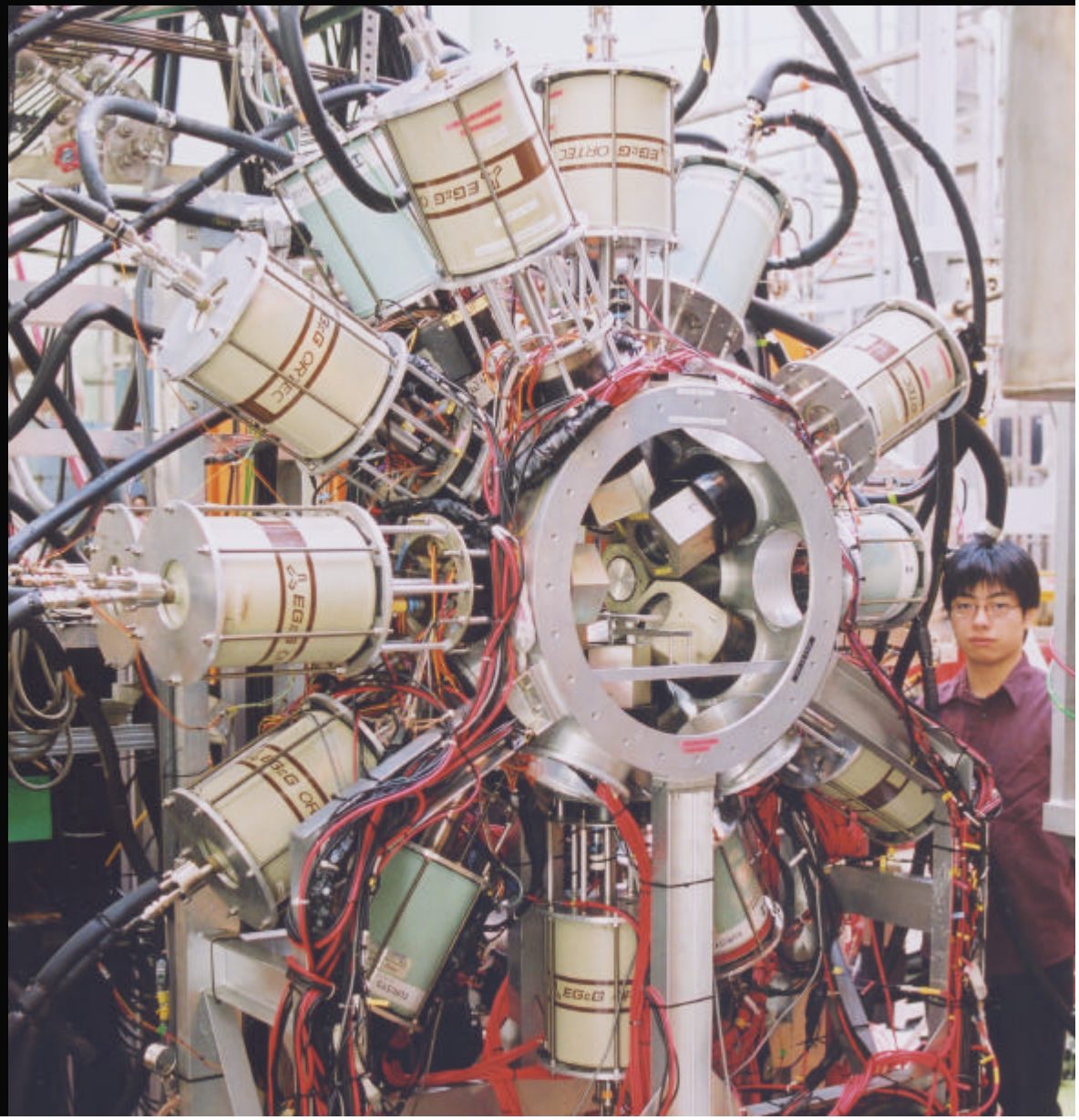
Introduction

- Hyperball
- Motivation - ΛN spin dependent forces
- Status

Hyperball (Tohoku/ Kyoto/ KEK, 1998)

- Large acceptance for small hypernuclear γ yields
  - Ge (r.e. 60%) x 14
    - $\Omega \sim 15\%$
    - $\varepsilon_{peak} \sim 3\%$ at 1 MeV
- High-rate electronics for huge background
- BGO counters for π^0 and Compton suppression

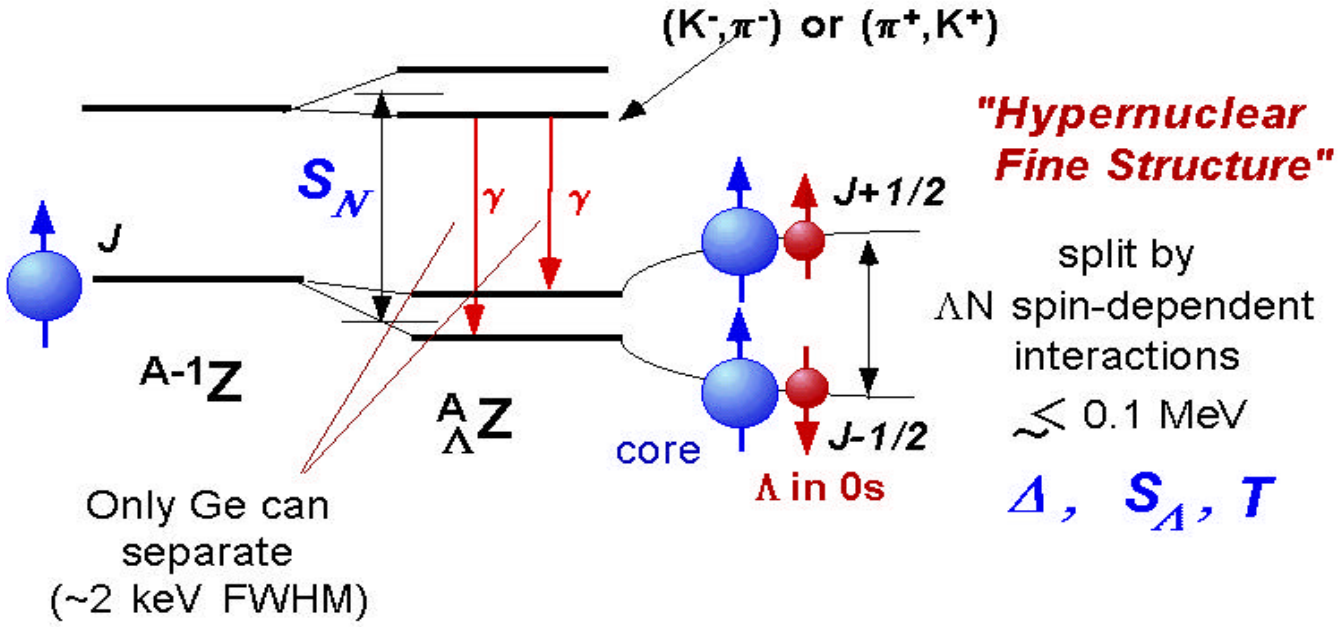
Resolution of hypernuclear spectroscopy
1 MeV -> 2 keV FWHM



Motivation

ΛN spin-dependent interactions

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



- **2-body ΛN effective interaction**

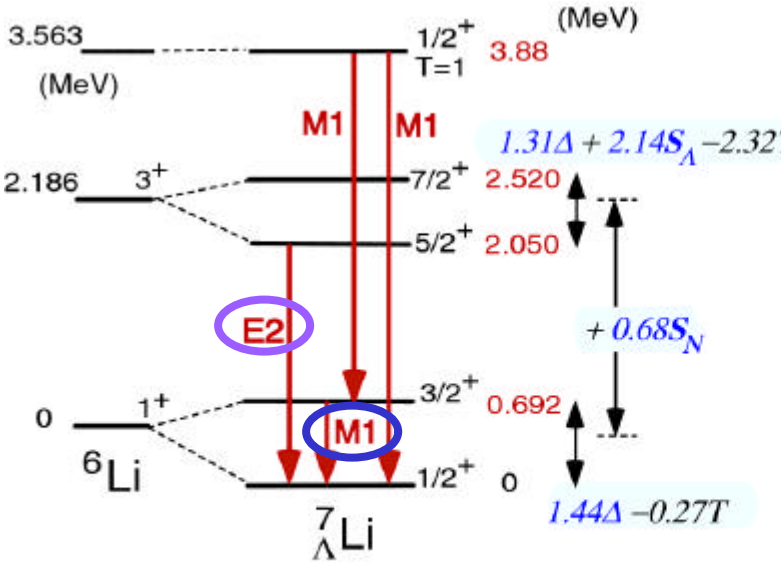
Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

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

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

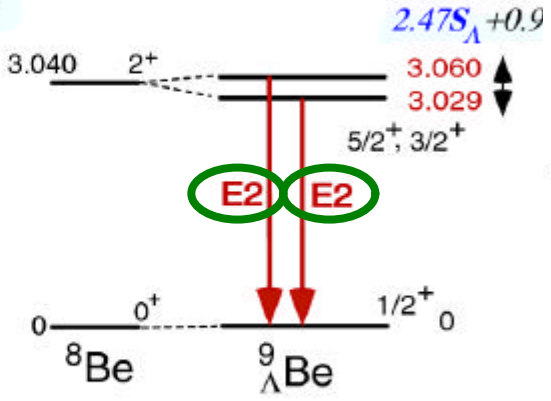
observed

Status as of HYP00



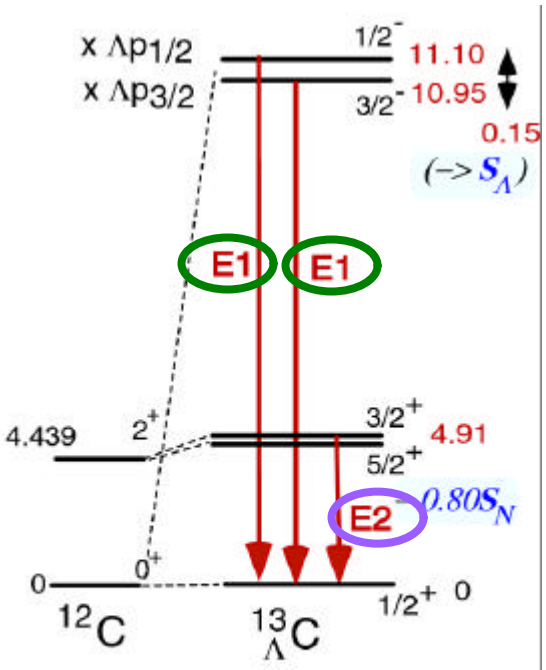
KEK E419

PRL 86 (2001) 1982
PRL 84 (2000) 5963



BNL E930

PRL 88 (2002) 082501



BNL E929 (NaI)

PRL 86 (2001) 4255

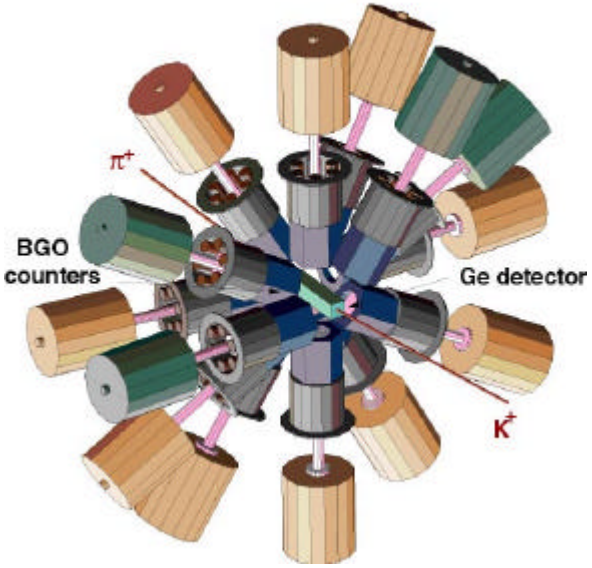
-> D = 0.50 MeV

S_N = -0.4 MeV

-> B(E2) = 3.6±0.5±0.5 e^2fm^4
Shrinkage of 19±4%

-> $|S_L| < 0.03$ MeV -> $p_{1/2} - p_{3/2} \sim 0.15$MeV
very small LS force

T: no experimental data



ΛN spin-depdendent forces (E930)

- $^{9}_{\Lambda}$Be (E930-1)
- $^{16}_{\Lambda}$O, $^{15}_{\Lambda}$N (E930-2)

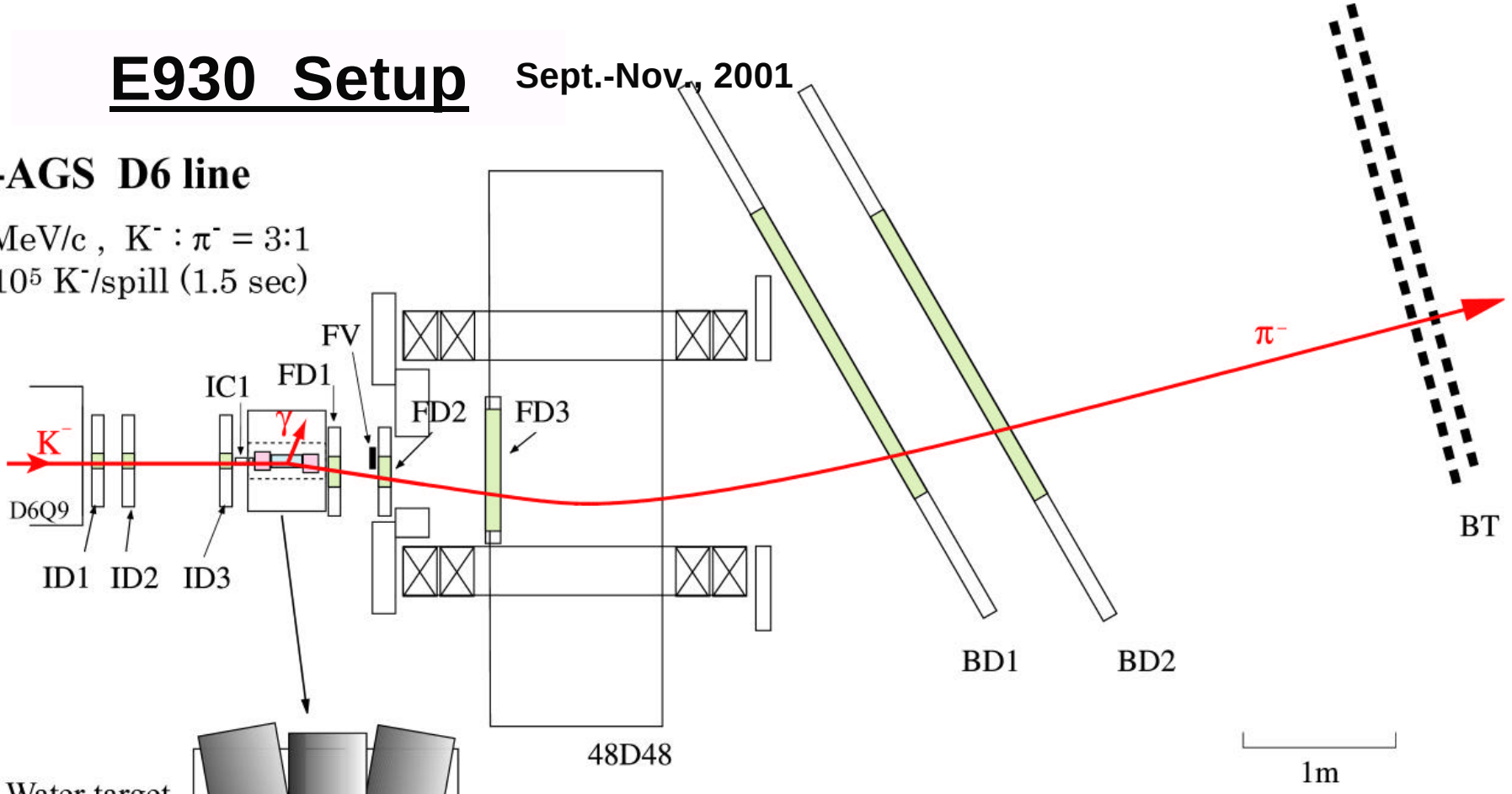
E930 Setup

Sept.-Nov., 2001

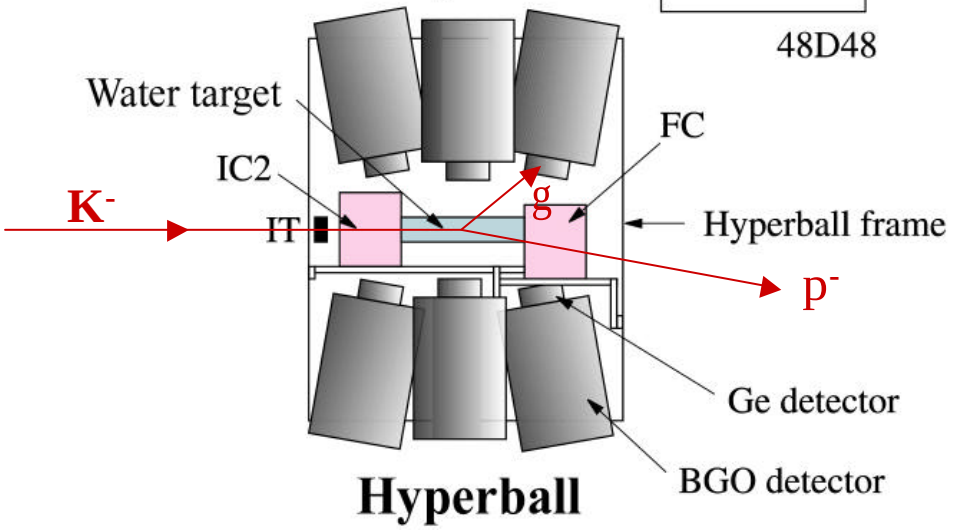
BNL-AGS D6 line

930 MeV/c , $K^- : \pi^- = 3:1$

2.3×10^5 K^-/spill (1.5 sec)



side view



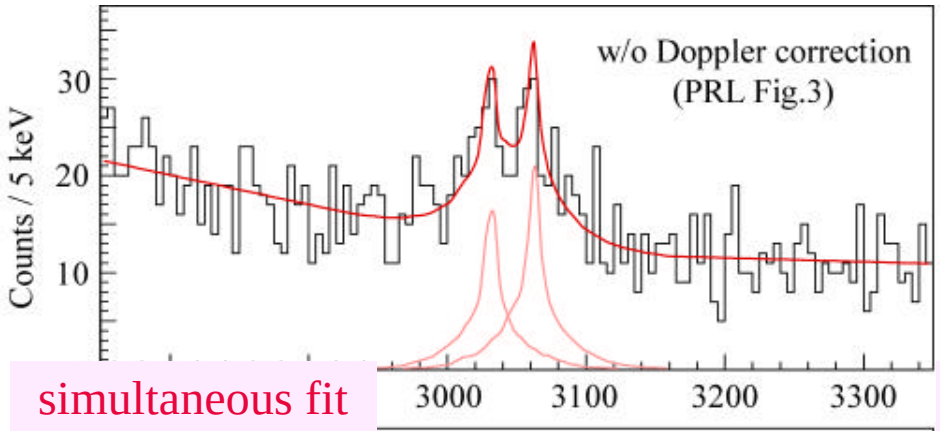
drift chambers

Cerenkov counters

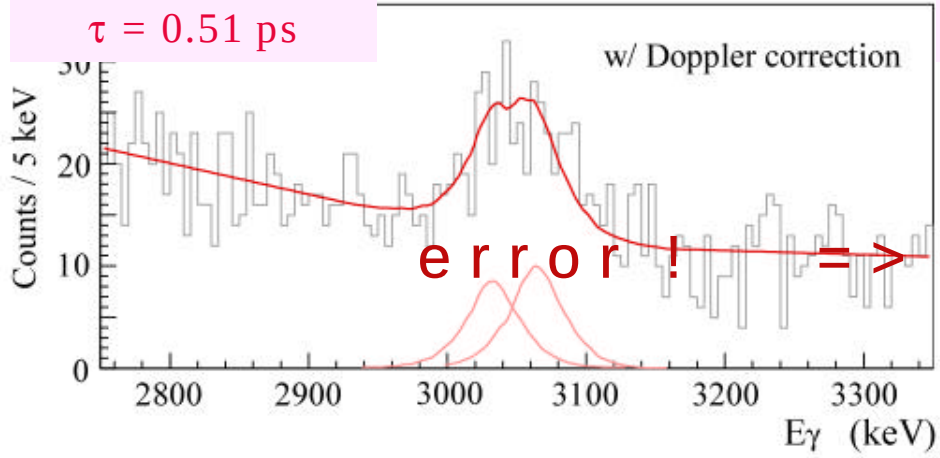
plastic counters

$^{9}_{\Lambda}$Be (E930-1) revised results

Akikawa et al., PRL 88 (2002) 082501



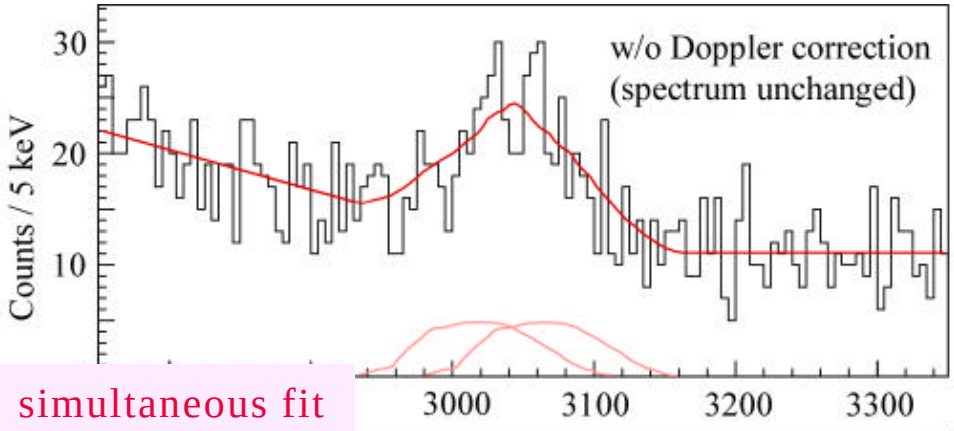
simultaneous fit
τ = 0.51 ps



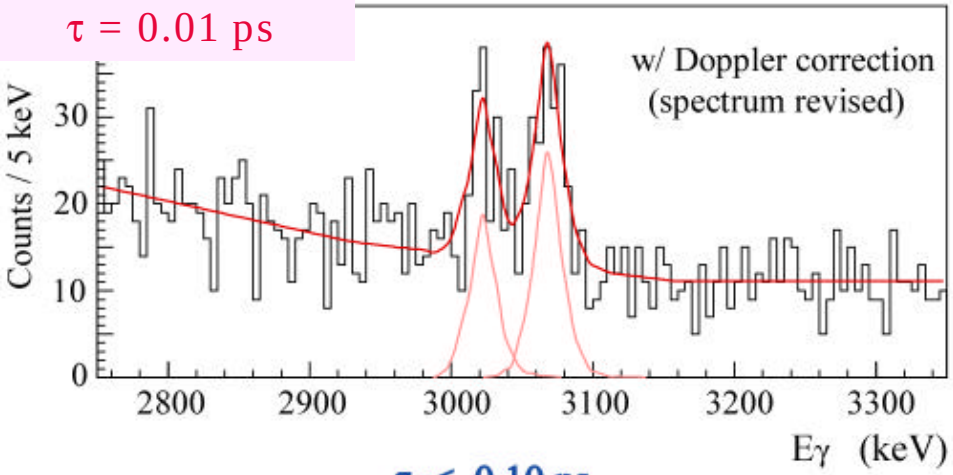
e r r o r ! =>

~~Results $\tau = 0.51^{+0.28}_{-0.14}$ ps~~
~~$\Delta E = 31.4^{+2.}_{-3.6}$ keV~~
~~$E = 302.$ ±2±1, 3060±2±1 keV~~
~~χ^2/dof = 0.9~~

Revised



simultaneous fit
τ = 0.01 ps



Revised Results
$\tau < 0.10$ ps
$\Delta E = 43 \pm 5$ keV
$E = 3024 \pm 3 \pm 1$, $3067 \pm 3 \pm 1$ keV
χ^2/dof = 1.22

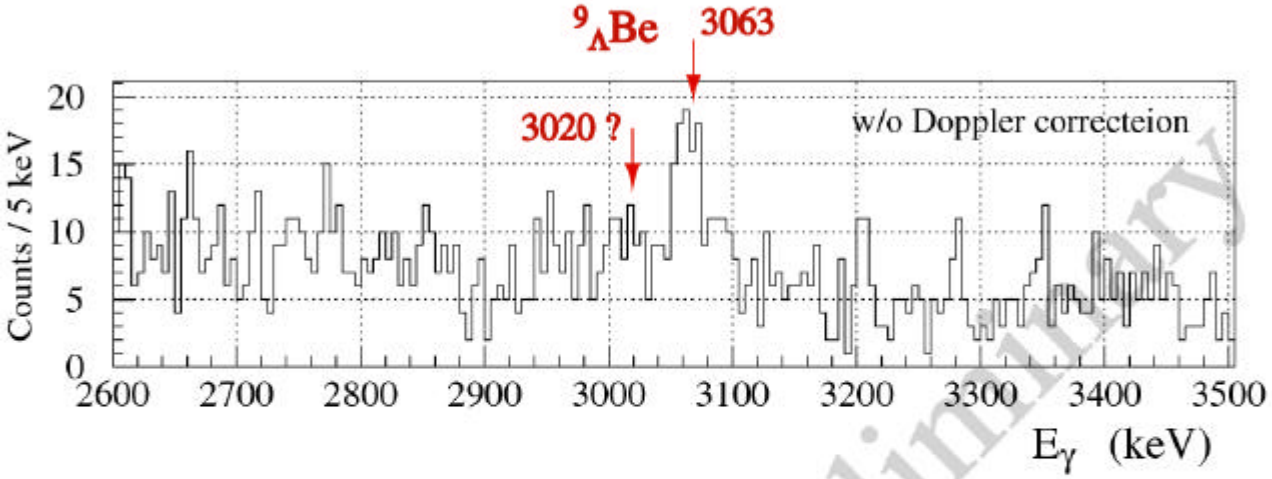
We apologize you.

Spin assignment of $^{9}_{\Lambda}$Be (E930-2)

Population of $^{9}_{\Lambda}$Be ($3/2^+$,$5/2^+$)

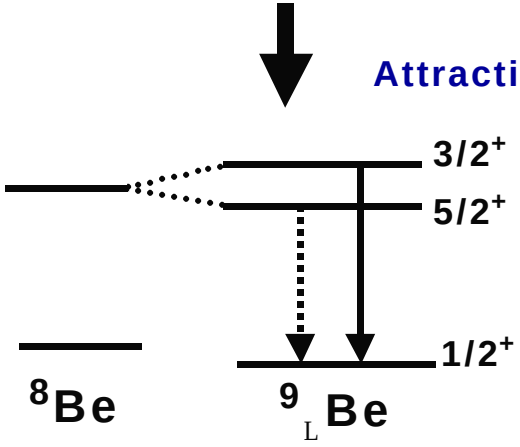
from ^{10}B (K^-,p^-) $^{10}_{\Lambda}$B* -> $^{9}_{\Lambda}$Be + p

$-35 < -B_\Lambda^* < -5$ MeV *uncalibrated



Yield ratio (calc. Millener)

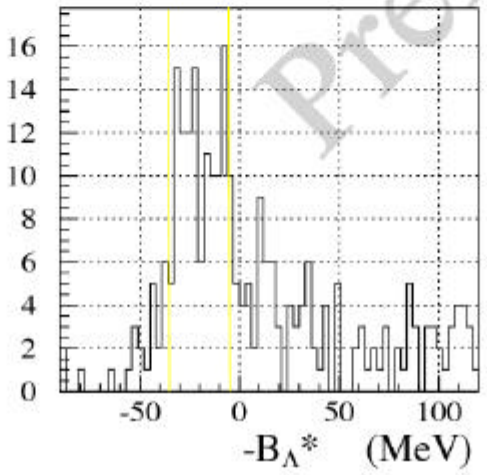
$Y(5/2^+) : Y(3/2^+) = 1 : 3.5$



Attractive for *LS* parallel

- **Consistent with $^{13}_{\Lambda}$C ($p_{1/2}$,$p_{3/2}$)**
- **$S_\Lambda < 0$**

Excitation spectrum for 3063 keV peak

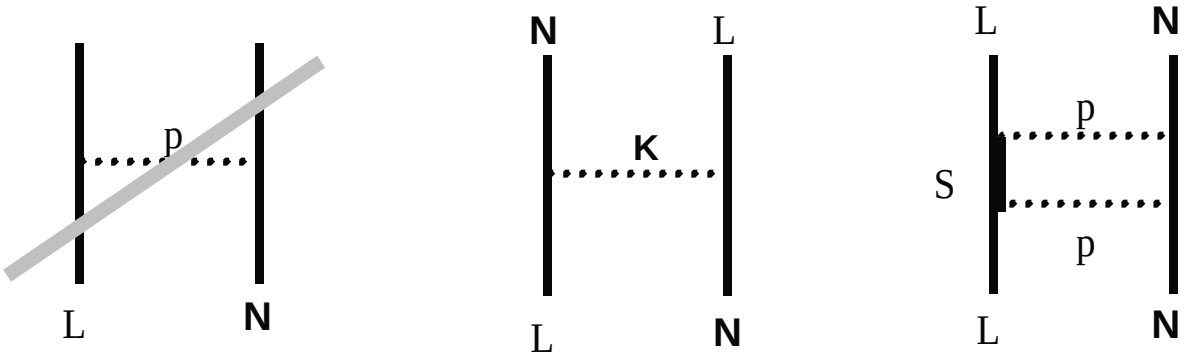


$^{9}_{\Lambda}$Be alone: $|S_\Lambda| < 0.03$ MeV -> $-0.02 < S_\Lambda < 0.0$ MeV (for $0.02 < T < 0.06$)

$^{16}_{\Lambda}$O and $^{15}_{\Lambda}$N for ΛN tensor force (BNL E930-2)

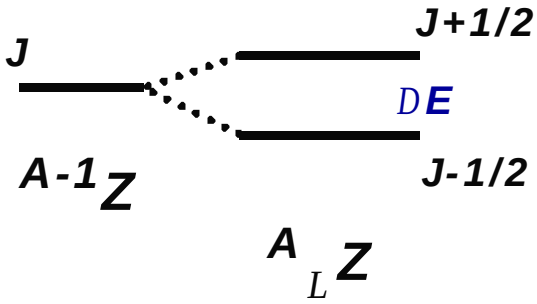
M.Ukai in Parallel -1

Motivation: ΛN tensor force



Tensor force really very small?

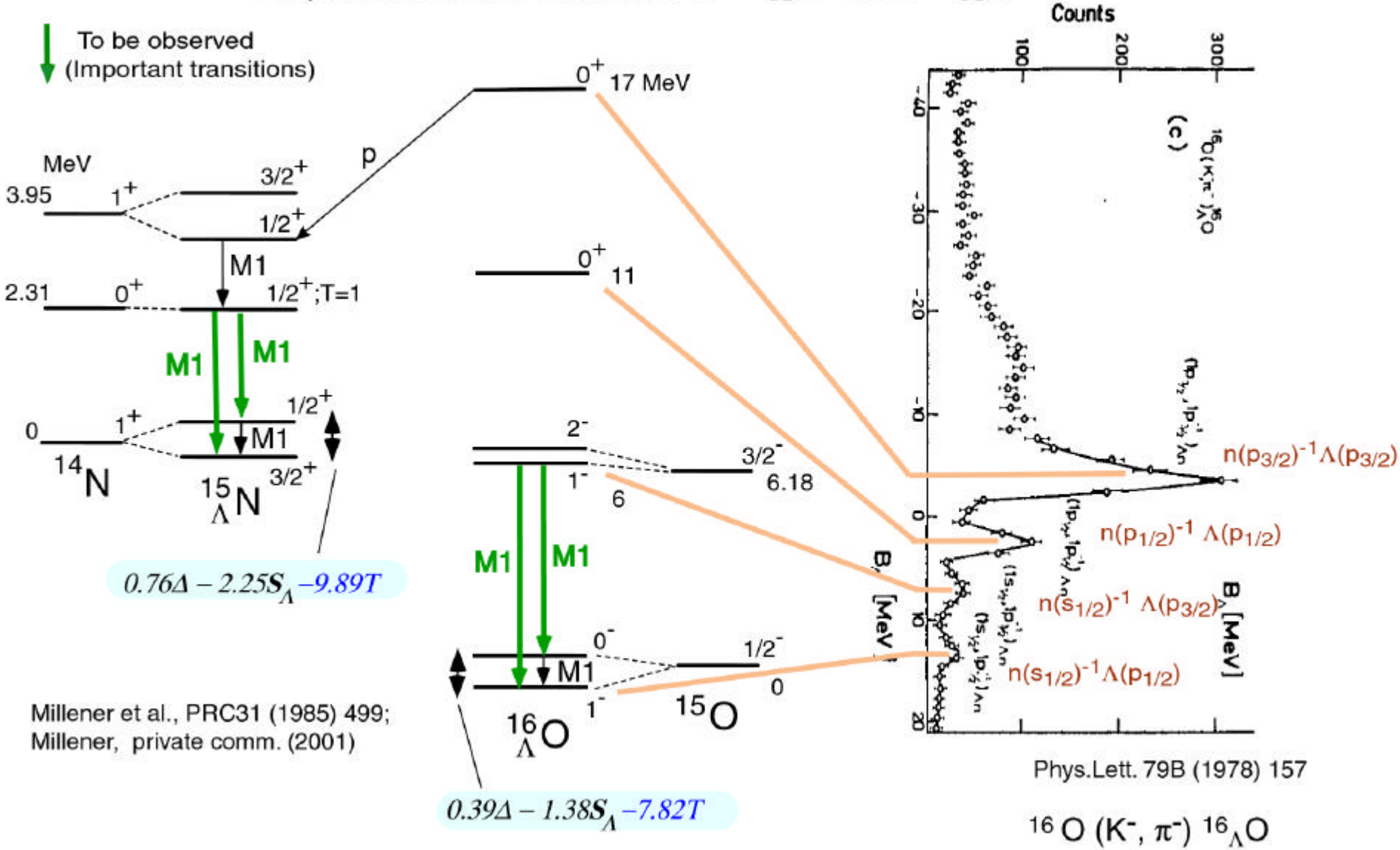
Explained by OBEP?



$p_{3/2}^{-1}s_{1/2}$ ($^{12}_{\Lambda}$C) : $\Delta E = 2/3\ \Delta + 4/3\ S_\Lambda - 8/5\ T$

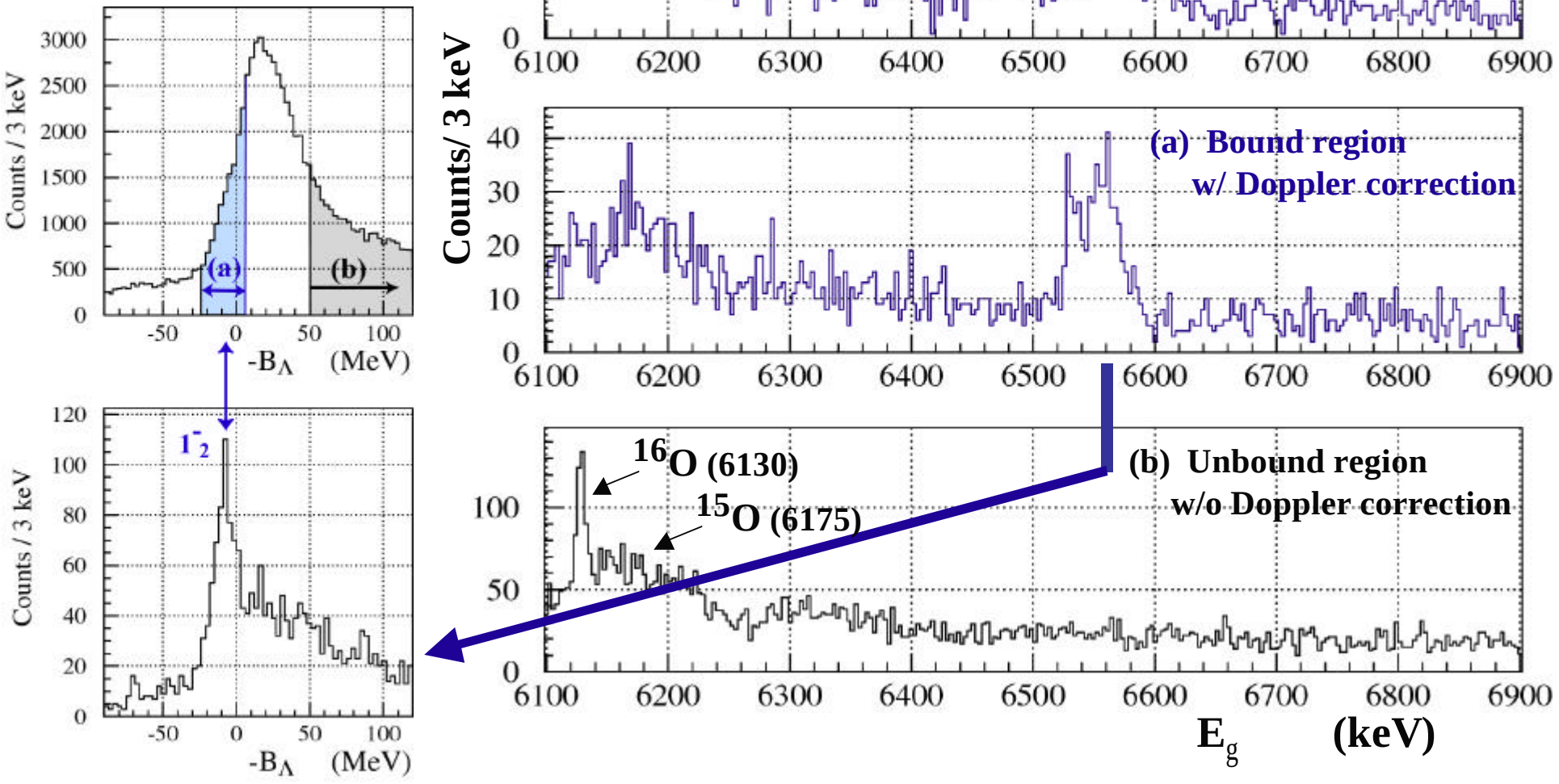
$p_{1/2}^{-1}s_{1/2}$ ($^{16}_{\Lambda}$O) : $\Delta E = -1/3\ \Delta + 4/3\ S_\Lambda + 8\ T$

Expected Level Scheme of $^{16}_{\Lambda}O$ and $^{15}_{\Lambda}N$



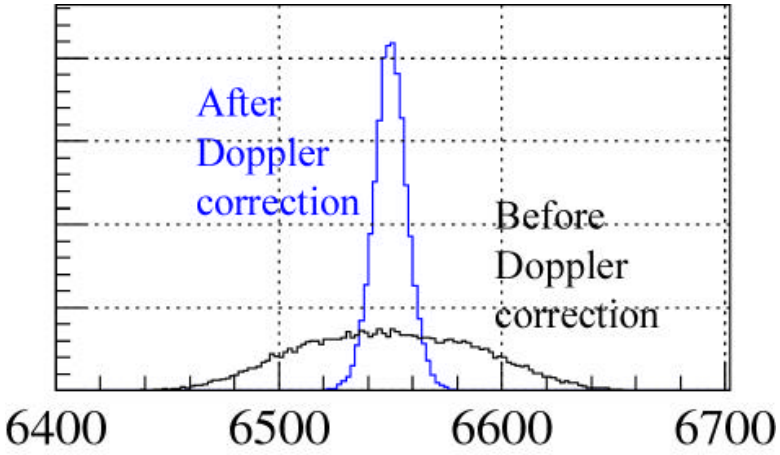
p1/2 shell --- Large contribution of the tensor term

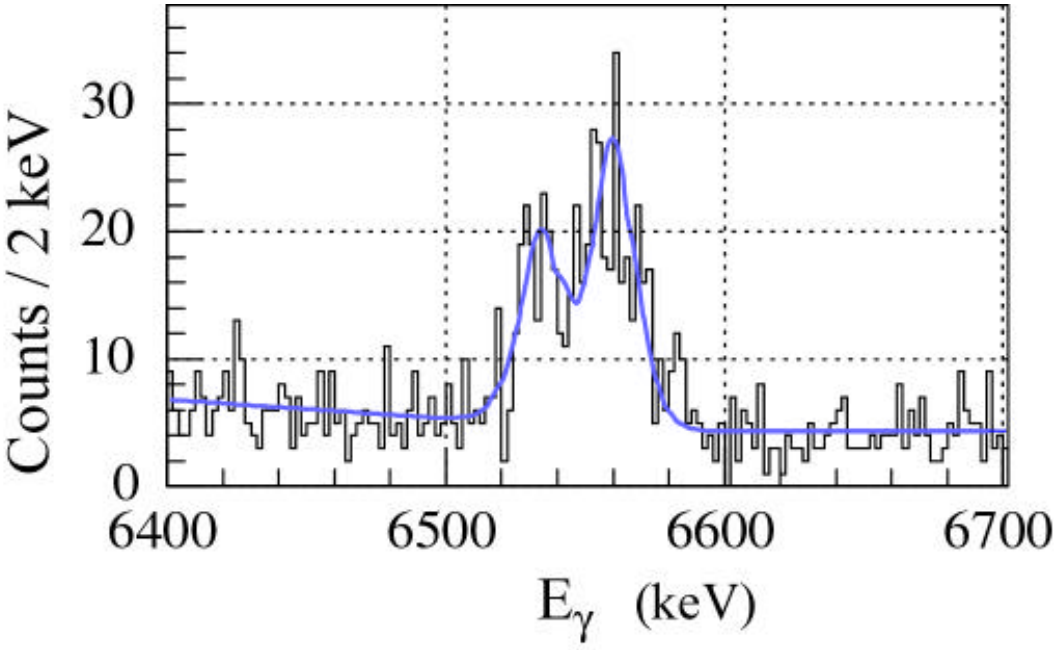
g spectrum of $^{16}_{\Lambda}$O



Fitting of $^{16}_{L}$O spectrum

Simulated peak shape for a fast transition





6534.1±1.5 keV, 149±18 counts

6560.2±1.3 keV, 226±30 counts

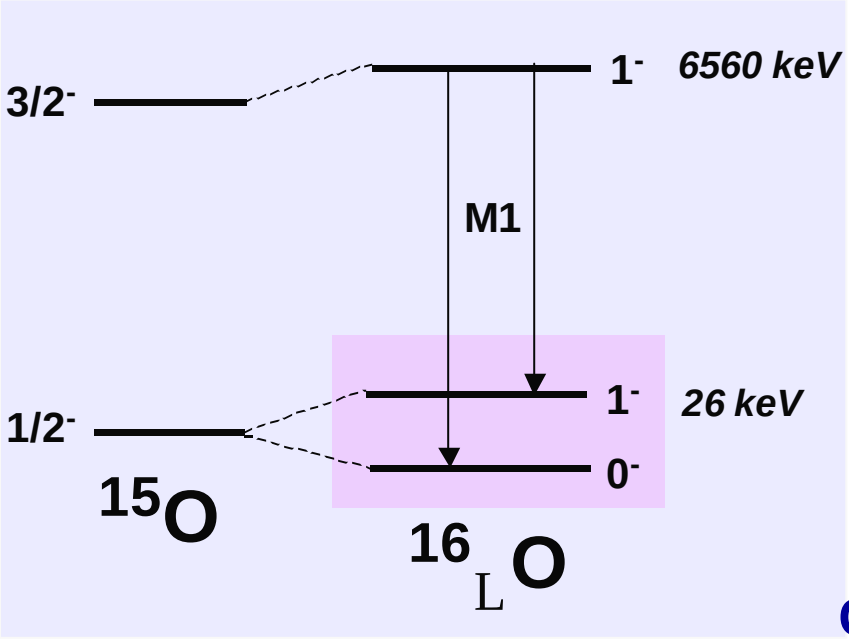
DE = 26.1±2.0 keV (prelim.)

Structure of $^{16}_{L}$O and tensor force

Assignment

N(1⁻ ->1⁻) / N(1⁻ ->0⁻) = 1/2 (weak coupling)
0.41 (Millener)

N(6532) / N(6559) = 0.64±0.12



Extraction of *T*

E(1⁻) - E(0⁻) *(Millener)*

= -0.38 D + 1.38 S_L + 7.85 T + LS

= 26 keV : cancellation between D and T

<- D = 0.47, S_L = -0.01 MeV

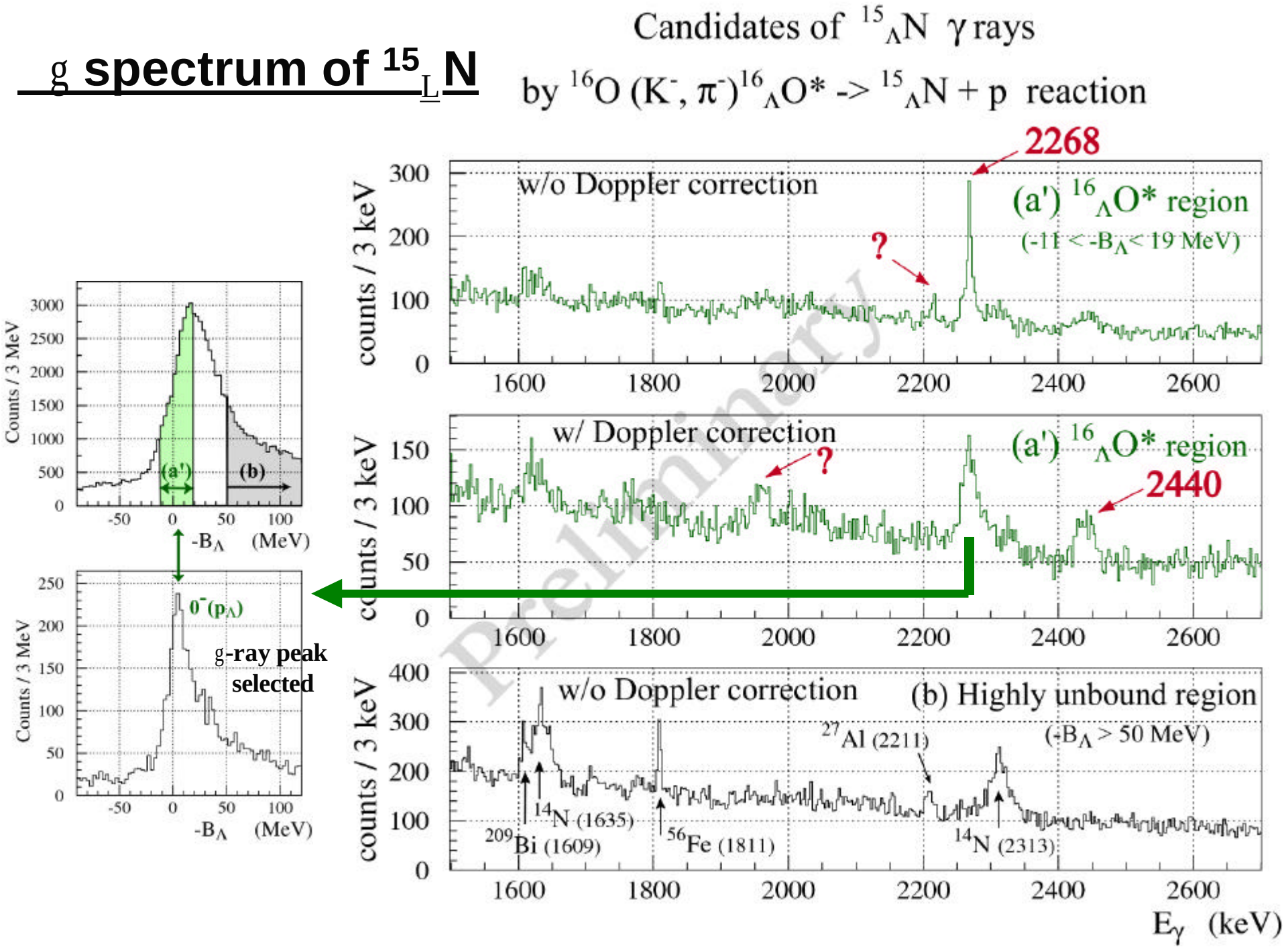
-> T ~ 30 keV (prelim.)

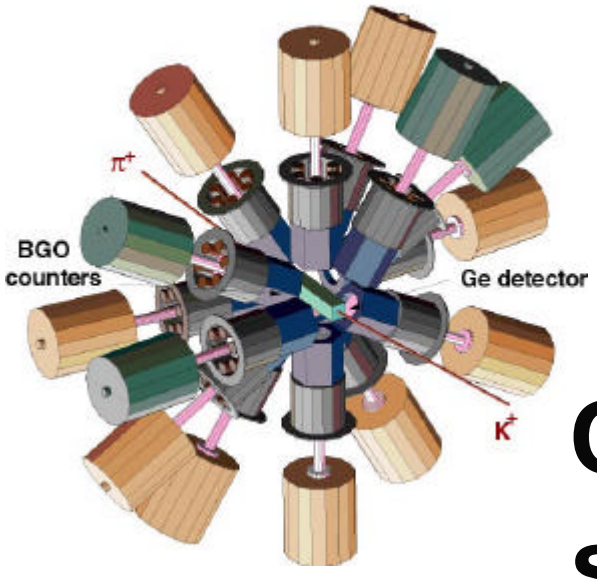
Comparison

	ND	NF	NSC89	NSC97f
T (keV)	18	33	36	54

OBEP predictions agree with the experimental value.

g spectrum of $^{15}_{\Lambda}$N



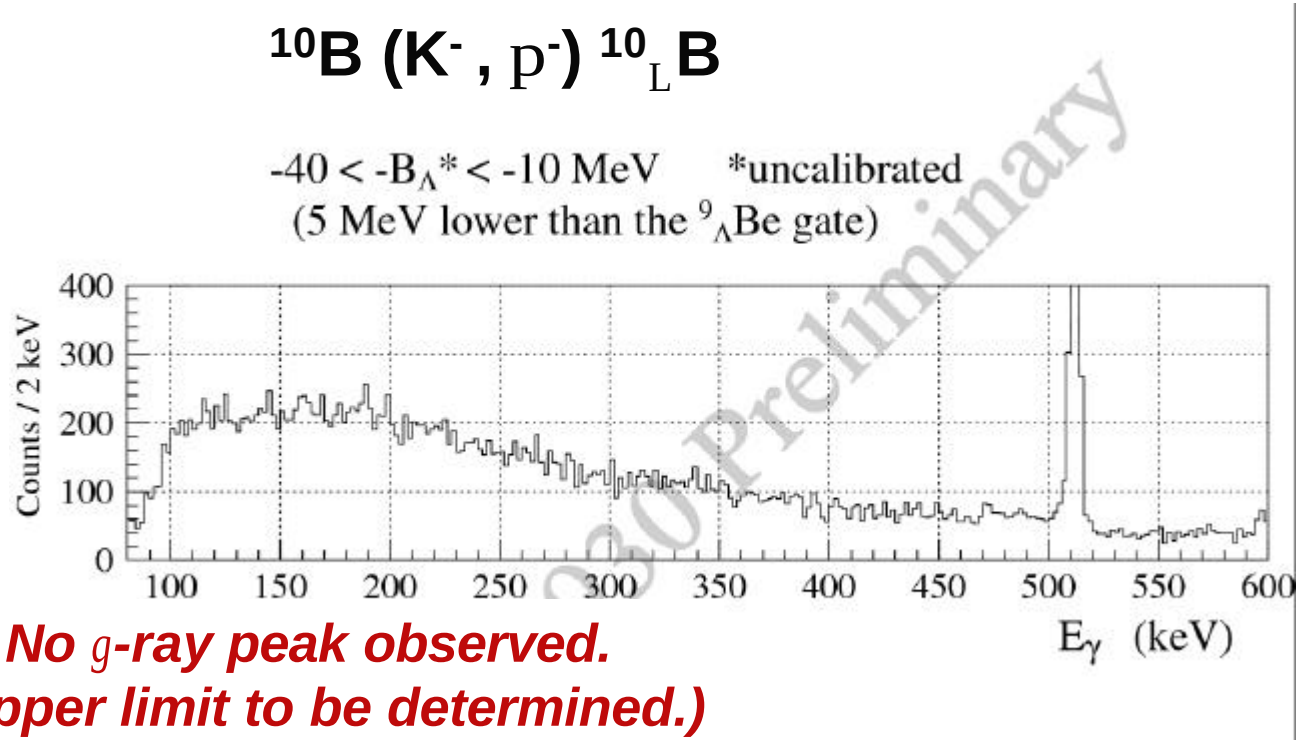


Cross Check of spin-depdendent forces

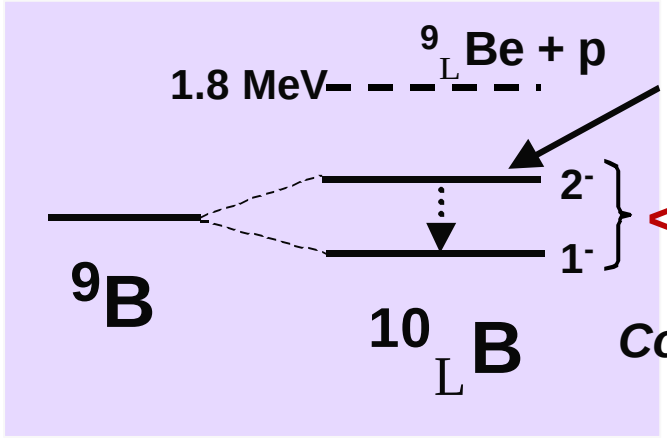
- $^{10}_{\Lambda}$B (E930-2)
- $^{11}_{\Lambda}$B (KEK E518)

γ spectrum of $^{10}_{\Lambda}$B (E930-2)

^{10}B (K^-, p^-) $^{10}_{\Lambda}$B



No γ-ray peak observed.
(Upper limit to be determined.)



< 100 keV ⇔ ***~ 200 keV from D = 0.5 MeV***

Confirmed
Chrien et al., Phys. Rev. C 41 (1990) 1062.

Spectroscopy of $^{11}_{\Lambda}$B (KEK E518)

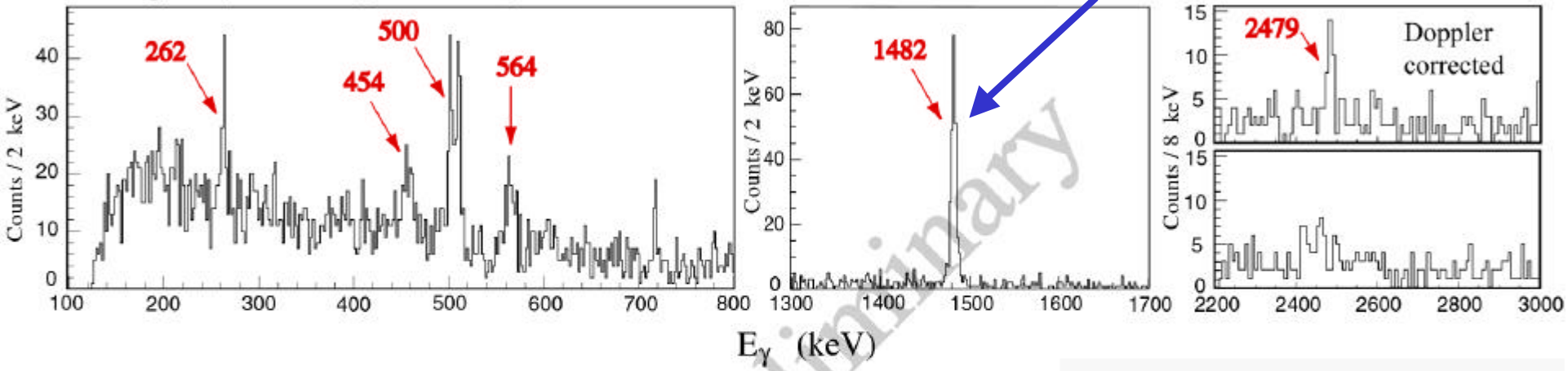
Y.Miura in Parallel -1

^{11}B (p^+,K^+g) $^{11}_{\Lambda}$B

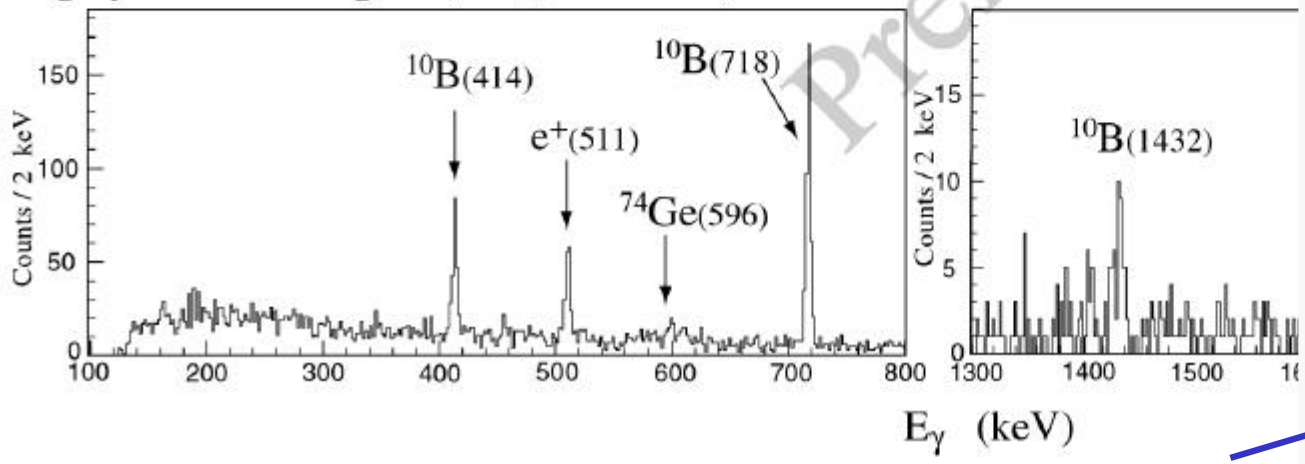
Not Doppler broadened
t > 10ps => E2

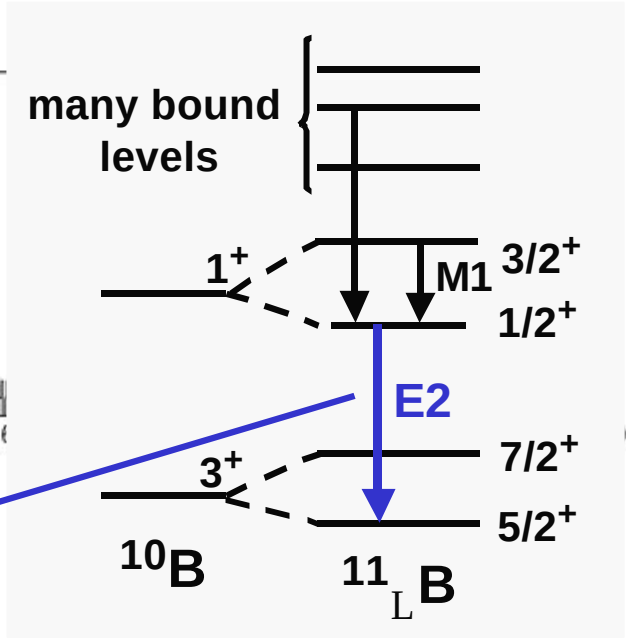
Bound region (-20 < -B_Λ < -2 MeV)

Six γ rays from $^{11}_{\Lambda}$B

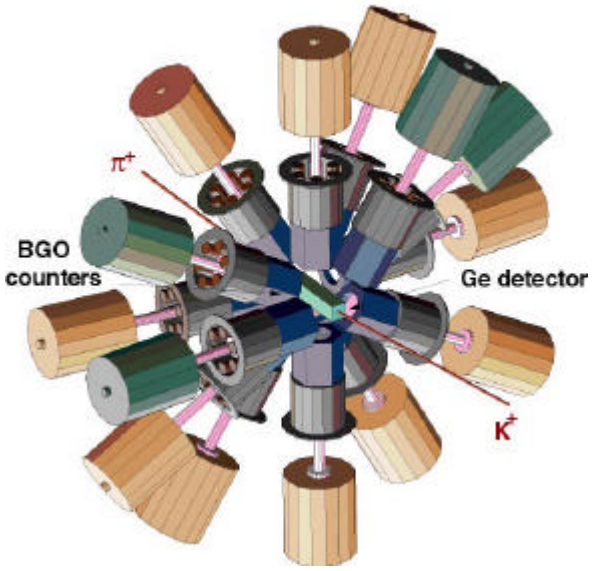


Highly Unbound region (-B_Λ > 20 MeV)





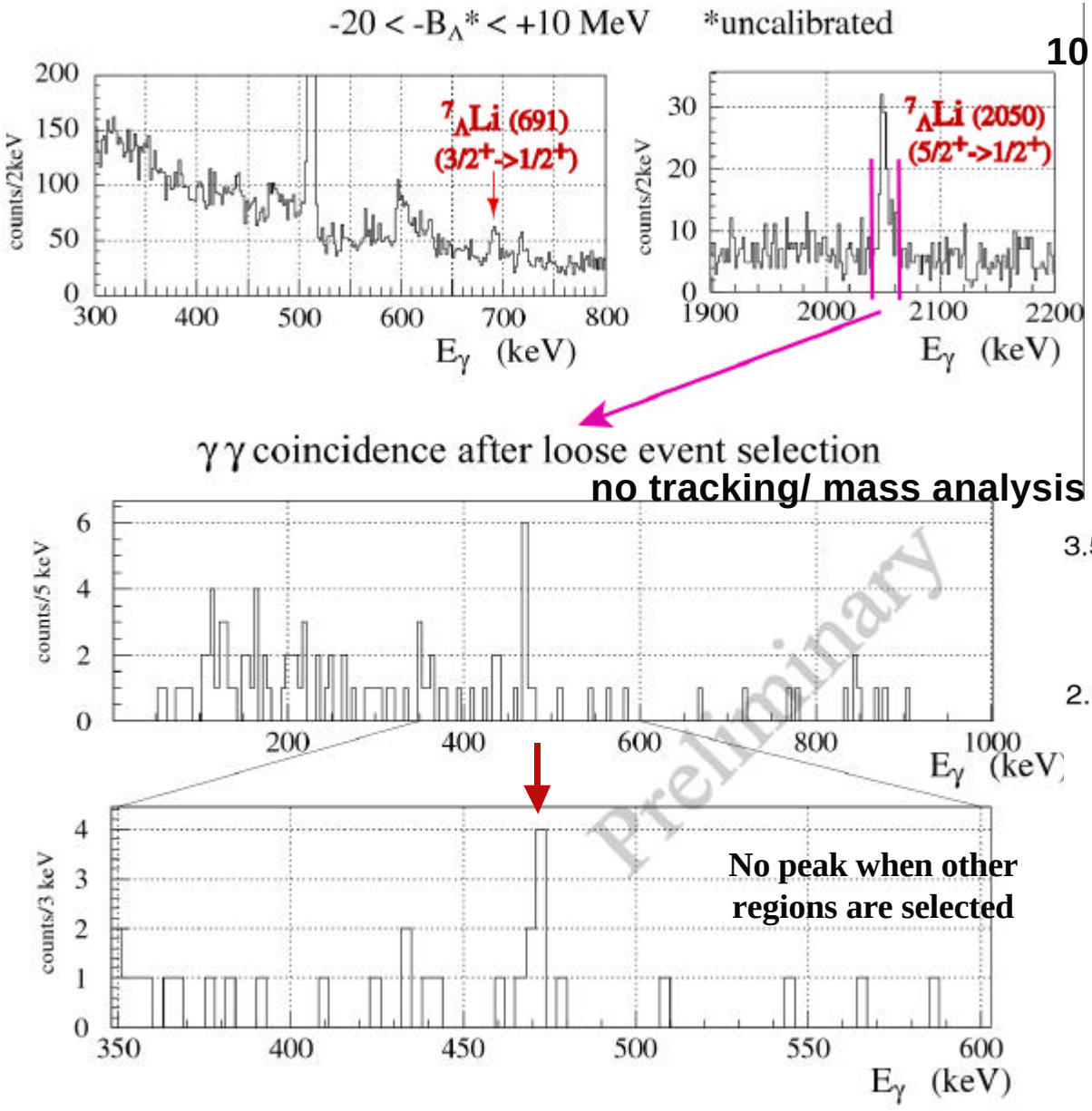
Millener: E2(1/2⁺->5/2⁺) 1020 keV ⇔ Exp. 1482 keV ?



Hyperfragments

- $^{10}_{\Lambda}$B* -> $^{7}_{\Lambda}$Li (7/2^{+}->5/2^{+}) (E930-2)
- (stopped K^{-} , g) (KEK E509)

Hyperfragments and gg coincidence (E930-2)

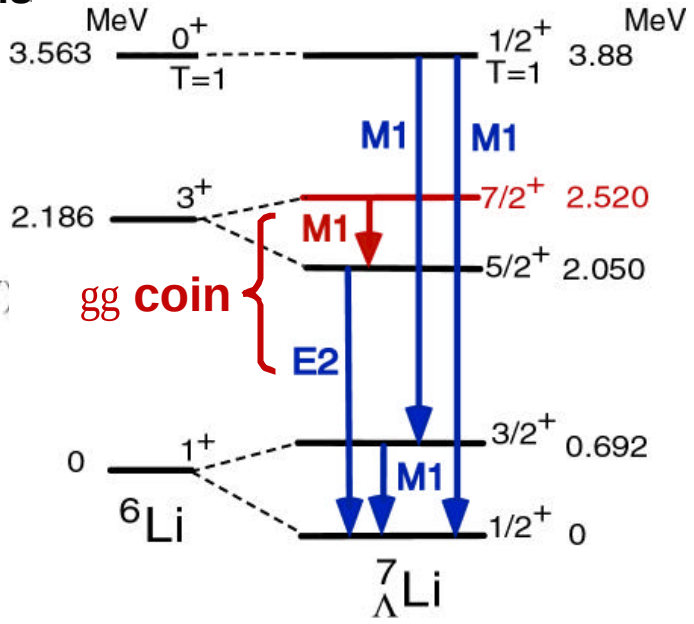


Prob.for a 6 event peak to appear anywhere in 400-600 keV region <0.06%
in 350-600 keV region <1%

^{10}B (K^-,p^-) $^{10}_{\Lambda}$B* -> $^{7}_{\Lambda}$Li

First gg coincidence for hypernuclei

$^{7}_{\Lambda}$Li (7/5$^+$->5/2$^+$) observed at 470 keV

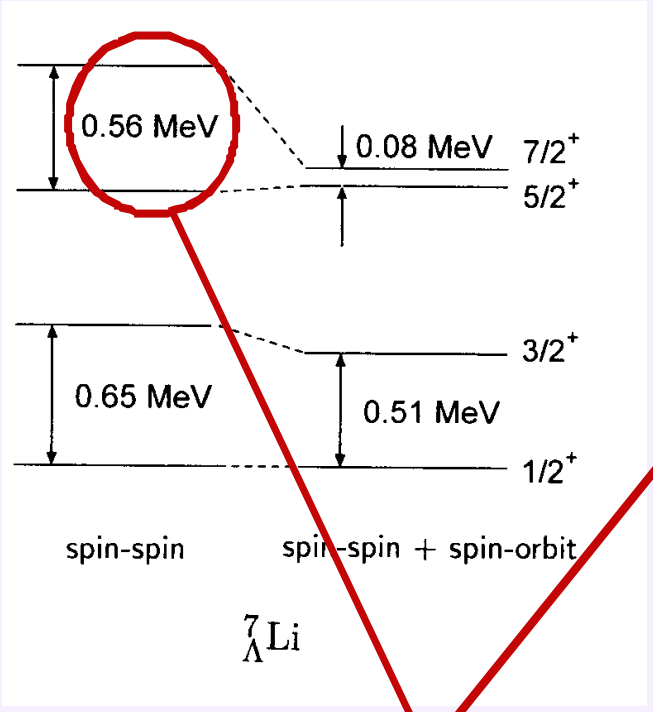


KEK E419 PRL 84 (2000) 5963
BNL E930-2

$^{7}_{\Lambda}$Li (7/5^{+}->5/2^{+}) and spin-dep. forces

Predictions

Hiyama et al. (HYP97)



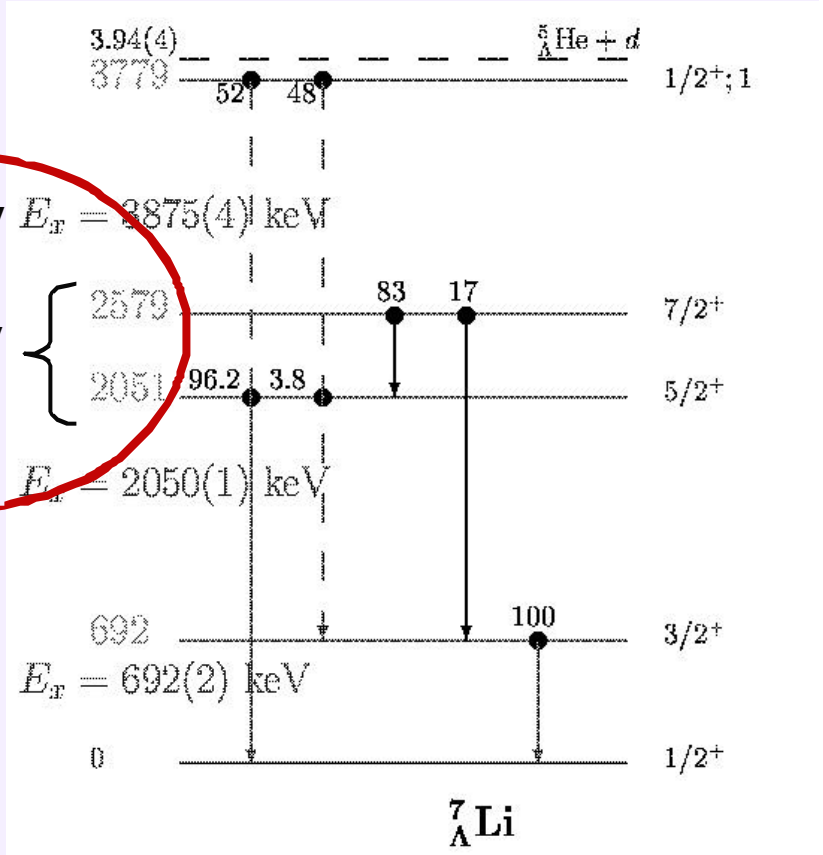
Close to 470 keV

Consistent with the small spin-orbit force (S_L)

Millener (HYP00, DNP01)

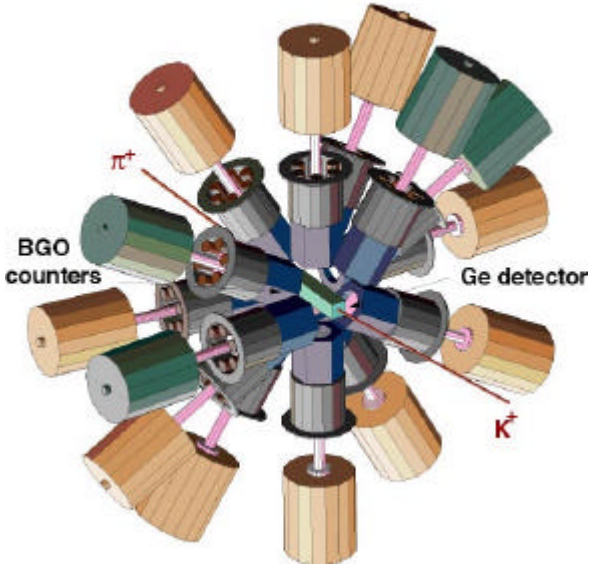
431 keV (no LS)

528 keV (w/ LS)



DE(7/2-5/2) = *1.3D + 2.2 S_L + 0.02S_N - 2.4T*

Large effect of S_L



Future

- Hyperball2
- Experimental plans

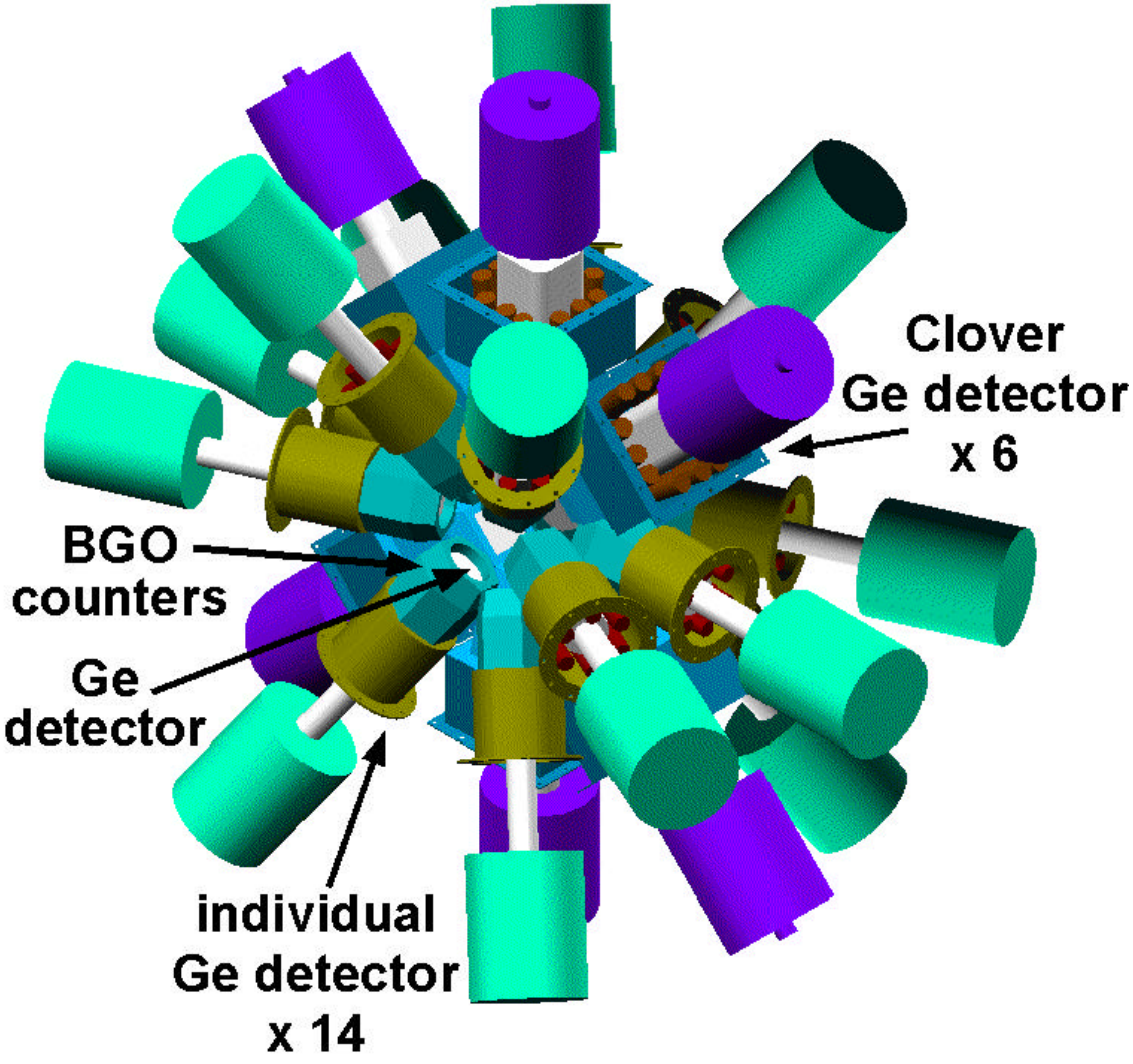
Hyperball2

Construction in progress. Ready in 2004

- **Clover Ge (r.e. >120%)**
  +BGO x 6 added
- **Peak eff.**
  ~ 2.5% -> 5% at 1 MeV

x 4 improvement for gg coin

- **Beam test of Clover Ge**
  (T536, June 2003) OK
- **VME-based fast readout**
- **Improvement of preamplifie**



Experimental Plans

Before J-PARC (Hyperball2)

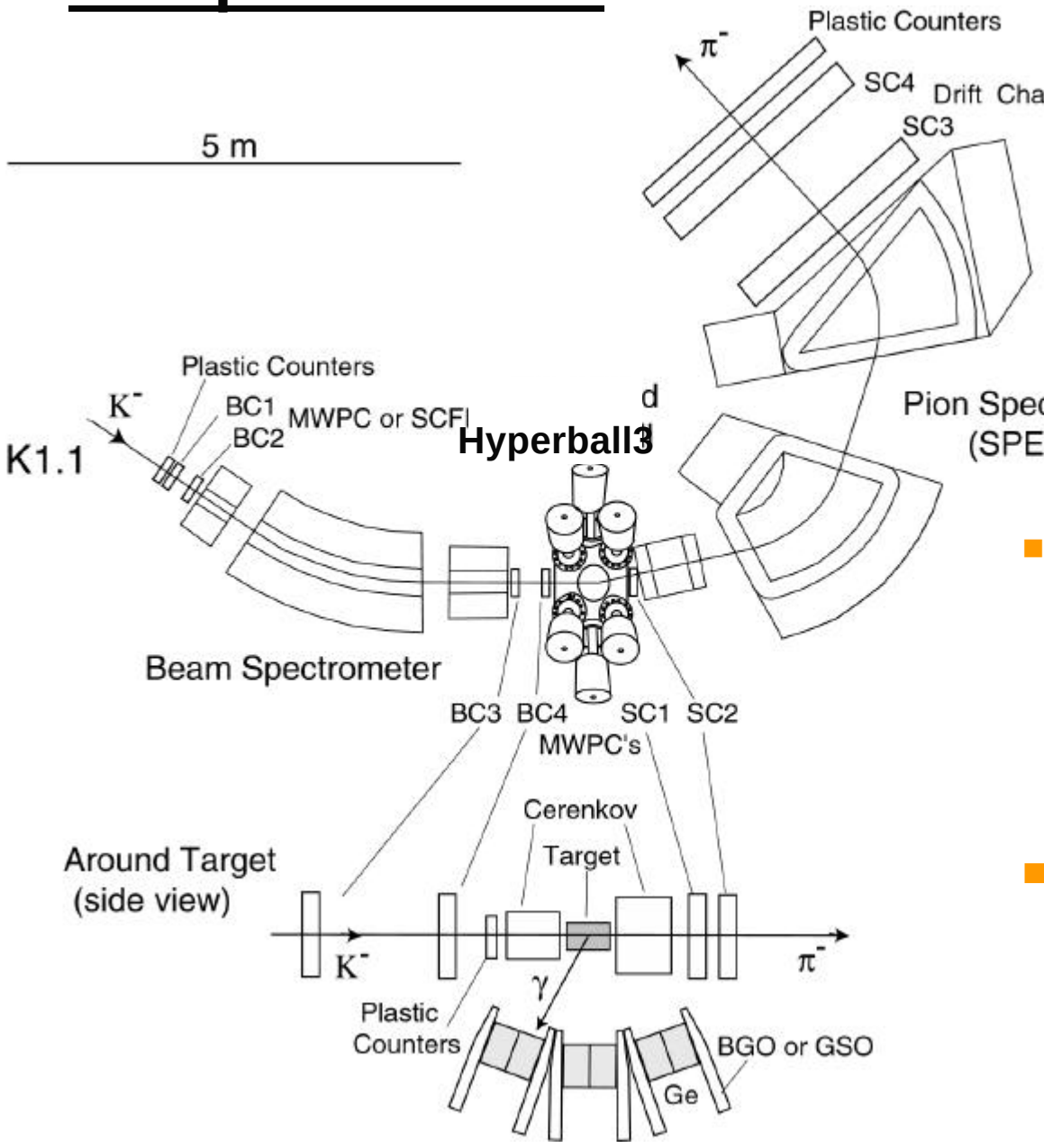
- BNL: E930-3 (more p-shell), E964 Ξ-atomic X-rays
- KEK: More hyperfragments data, more $^{11}_{\Lambda}$B data

J-PARC (Hyperball3)

γ spectroscopy is a “Day-1” experiment.

- Systematic study of all light (A<30) hypernuclei
- Medium heavy hypernuclei
- Mirror and n-rich hypernuclei using (K^-,π^0) reaction and hyperfragments (CSB, shrinkange of n-halo,..)
- B(M1) for magnetic moment of Λ in a nucleus

Setup at J-PARC



- **Beamline: K1.1**
  - **K^- at 1.1, 0.8 GeV/c**
  - **1.2×10^7 K^-/spill**
  - **K/p > 1**
  - **p^+ at 1.05 GeV/c**
  - **K1.8 for K^- at 1.5-1.8 GeV/c**
- **Spectrometer:**
  - **SPESII (or SKS) (existing)**
  - **Δp/p < 2 MeV (FWHM)**
  - **Ω ~ 20 msr**
- **Hyperball3 (2007?)**
  - **ε > 10% at 1 MeV**
  - **or Hyperball2 (2003)**
  - **ε ~ 5% at 1 MeV**

Summary

- **All the ΛN spin-dep. int. parameters determined (E930)**

  $^{9}_{\Lambda}$Be: $\Delta E(3/2^{+},5/2^{+})$ = 31 keV -> 43 keV.

  Spin assigned from ^{10}B(K^{-},p^{-})$^{10}_{\Lambda}$B* -> $^{9}_{\Lambda}$Be + p

  $^{16}_{\Lambda}$O: M1(1_2^{-}->1_1^{-}, 0^{-}) observed. Spacing 26 keV -> $T \sim 30$ keV

  First data for ΛN tensor force. OBE model predictions OK.

  $^{15}_{\Lambda}$N: A few γ rays observed.

- **More data for cross check**

  $^{10}_{\Lambda}$B: (E930-2) $^{10}_{\Lambda}$B (2^{-}->1^{-}) not observed.

  $^{11}_{\Lambda}$B: (E518) Six γ rays observed. E2 energy too large?

  …….More experimental and theoretical efforts necessary

- **Hyperfagments**

  $^{7}_{\Lambda}$Li ($7/2^{+}$->$5/2^{+}$) observed from $^{10}_{\Lambda}$B*. First γγ coincidence (E930-2).

  Hyperfragment γ rays observed in (stopped K^{-}, γ) (E509).

  ……. K^{-} in-beam method seems promising.

- **Future**

  Hyperball2 under construction

  Various program at J-PARC with Hyperball3