γ-ray spectroscopy experiments (1998)

Hyperball (14 large volume Ge detectors with BGO shields)

- KEK E419 $\quad {}^{7}\mathrm{Li}(\pi^{+}, \mathrm{K}^{+}\gamma)^{7}_{\Lambda}\mathrm{Li}$
  1. M1 γ ray: measurement of ground-state ${}^{6}\mathrm{Li}(1^{+}) \otimes s_{\Lambda}$ doublet spacing
     H. Tamura et al., PRL 84 (2000) 5963
  2. B(E2): shrinkage of hypernuclear size
     K. Tanida et al., PRL 86 (2001) 1982
- BNL E930 $\quad {}^{9}\mathrm{Be}(\mathrm{K}^{-}, \pi^{-}\gamma)^{9}_{\Lambda}\mathrm{Be}$
  1. Splitting of ${}^{8}\mathrm{Be}(2^{+}) \otimes s_{\Lambda}$ doublet:
     ΛN spin-orbit interaction
     H. Akikawa et al., PRL 88 (2002) 082501

NaI arrays (72 detectors)

- BNL E929 $\quad {}^{13}\mathrm{C}(\mathrm{K}^{-}, \pi^{-}\gamma)^{13}_{\Lambda}\mathrm{C}$
  1. $\frac{1}{2}^{-}, \frac{3}{2}^{-} \to$ gs 11 MeV γ rays: ${}^{12}\mathrm{C}(0^{+}) \otimes p_{\Lambda}$ splitting
     ΛN spin-orbit interaction
     S. Ajimura et al., PRL 86 (2001) 4255
     H. Kohri et al., PRC 65 (2002) 034607

γ-ray spectroscopy with Hyperball (2001)

- BNL E930 $\quad {}^{16}\mathrm{O}(\mathrm{K}^-,\pi^-){}^{16}_{\Lambda}\mathrm{O}$ (Ukai)

  1. ${}^{16}_{\Lambda}\mathrm{O}$ 6.6 MeV γ rays to gs doublet
     ΛN tensor interaction

  2. ${}^{15}_{\Lambda}\mathrm{N}$ γ rays following ${}^{16}_{\Lambda}\mathrm{O} \to {}^{15}_{\Lambda}\mathrm{N} + p$

- BNL E930 $\quad {}^{10}\mathrm{B}(\mathrm{K}^-,\pi^-){}^{10}_{\Lambda}\mathrm{B}$

  1. Search for gs doublet M1 transition
  2. γ rays from ${}^{9}_{\Lambda}\mathrm{Be}$ and ${}^{7}_{\Lambda}\mathrm{Li}$ seen

Hyperball back to KEK (2002)

- KEK E509 Look for hypernuclear γ rays following stopped K^- on ${}^{7}\mathrm{Li}$, ${}^{9}\mathrm{Be}$, ${}^{10}\mathrm{B}$, ${}^{11}\mathrm{B}$, and ${}^{12}\mathrm{C}$ (Miwa)

  1. No tag - use intrinsic resolution of Ge detectors

- KEK E518 $\quad {}^{11}\mathrm{B}(\pi^+, K^+\gamma){}^{11}_{\Lambda}\mathrm{B}$ (Miura)

  1. 6 γ transitions

ΛN (YN) interaction parameters

$V_{N\Lambda}$	$s_N s_\Lambda$	$p_N s_\Lambda$	${}^7_\Lambda$Li values MeV
V_0	I_0^e	$\bar{V} = \frac{1}{2}(I_0^e + I_1^o)$	(-1.22)
$V_\sigma s_N.s_\Lambda$	I_0^e	$\Delta = \frac{1}{2}(I_0^e + I_1^o)$	0.480
$V_\Lambda l_{N\Lambda}.s_\Lambda$		$S_\Lambda = \frac{1}{2}I_1^o$	-0.010
$V_N l_{N\Lambda}.s_N$		$S_N = \frac{1}{2}I_1^o$	-0.400
$V_T S_{12}$		$T = \frac{1}{3}I_1^o$	0.021

Free-Space YN Interactions

- Spin-spin interaction (Δ) is basically undetermined
- Similarly for odd-state central interaction
- Similarly for strength of $\Lambda - \Sigma$ coupling
- NSC97 models - Th.A. Rijken, V.J.G. Stoks, and Y. Yamamoto Phys. Rev. C 59 (1999) 21
- NSC97a,b,c $\Delta < 0$, NSC97d,e,f $\Delta > 0$; models e and f favored on these grounds

Three-body ΛNN Interactions

Dispersive

- Fetisov (HYP2000)

$$V_{\Lambda NN} = \delta(r_\Lambda - r_1)\delta(r_\Lambda - r_2)\left(t + t_s \sigma_\Lambda.(\sigma_1 + \sigma_2)\right)$$

1. need t for Skyrme-like fit to B_Λ
2. exploit t_s together with $\Delta\ s_N.s_\Lambda$ to fit doublet separations

- Bodmer and Usmani,.. finite range...

Double–OPE ΛNN

- Gal and Dalitz
    1. Independent of Λ spin
    2. Proportional to both σ_1 and σ_2
    3. Proportional to $\tau_1.\tau_2$
- For p-shell hypernuclei

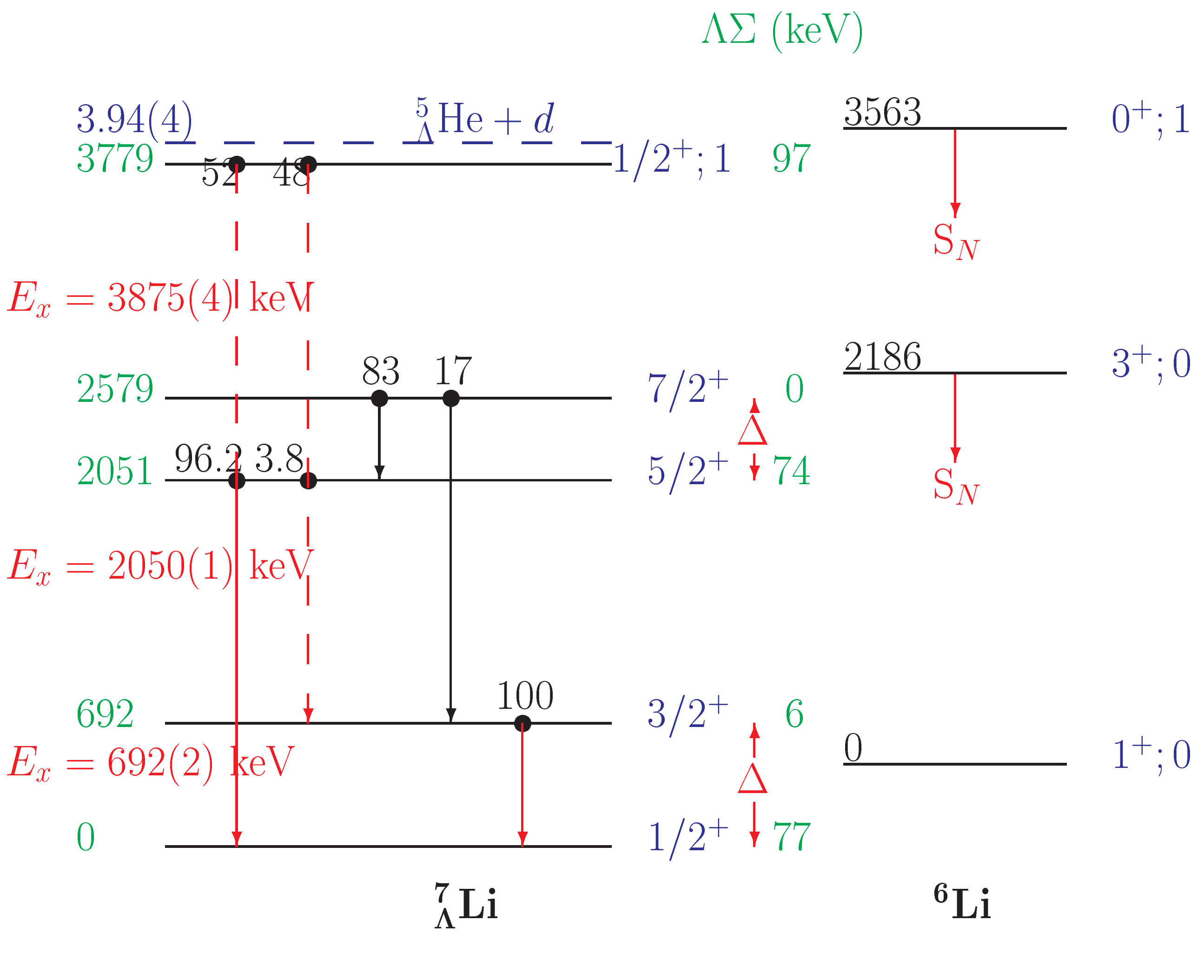
  a $0s_\Lambda$ with p_N^2

  b $0s_\Lambda$ with s_N and p_N. Gives contributions to $p_N s_\Lambda$ interaction, in particular $S_N\ l_{N\Lambda}.s_N$

$^{7}_{\Lambda}$Li γ rays – Hyperball, KEK E419

H. Tamura et al., PRL 84 (2000) 5963

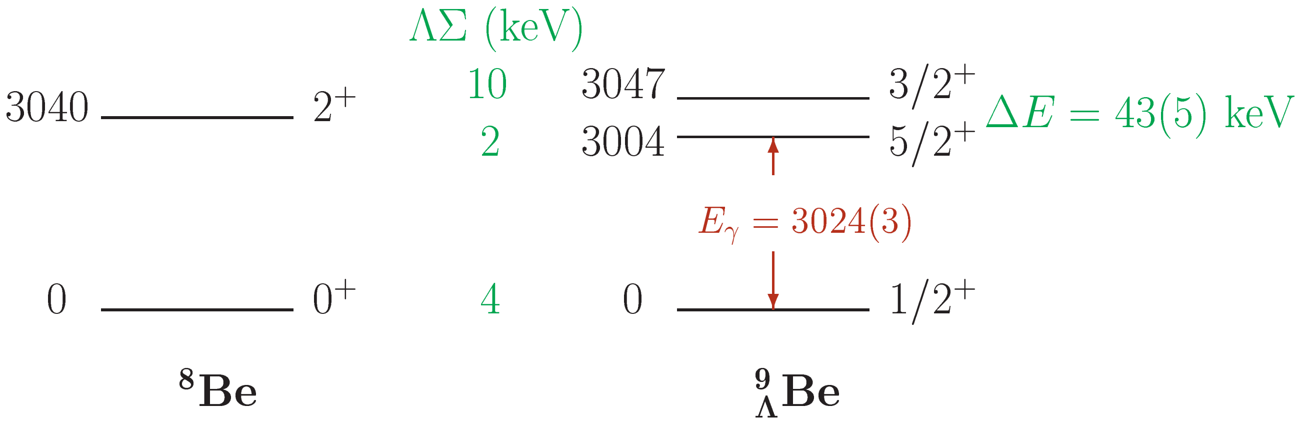
K. Tanida et al., PRL 86 (2001) 1982



$\Delta = 0.432 \quad S_{\Lambda} = -0.010 \quad S_{N} = -0.380 \quad T = 0.021$

$\Delta E(7/2^{+} - 5/2^{+}) = 470$ keV from $\gamma\gamma$ coincidence E906 – Tamura

Spacing reduced by larger S_{Λ} and T



Old BNL E930 - H. Akikawa et al., PRL 88 (2002) 082501

$E_\gamma = 3029(2), \quad 3060(2)$ keV, $\quad \Delta E = 31(3)$ keV

$\Delta = 0.557 \quad \mathrm{S}_\Lambda = -0.013 \quad \mathrm{S}_\mathrm{N} = -0.549 \quad T = 0.038$

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
-8	-20	32	-1	38	43 keV
	-0.037	-2.464	0.003	0.994	

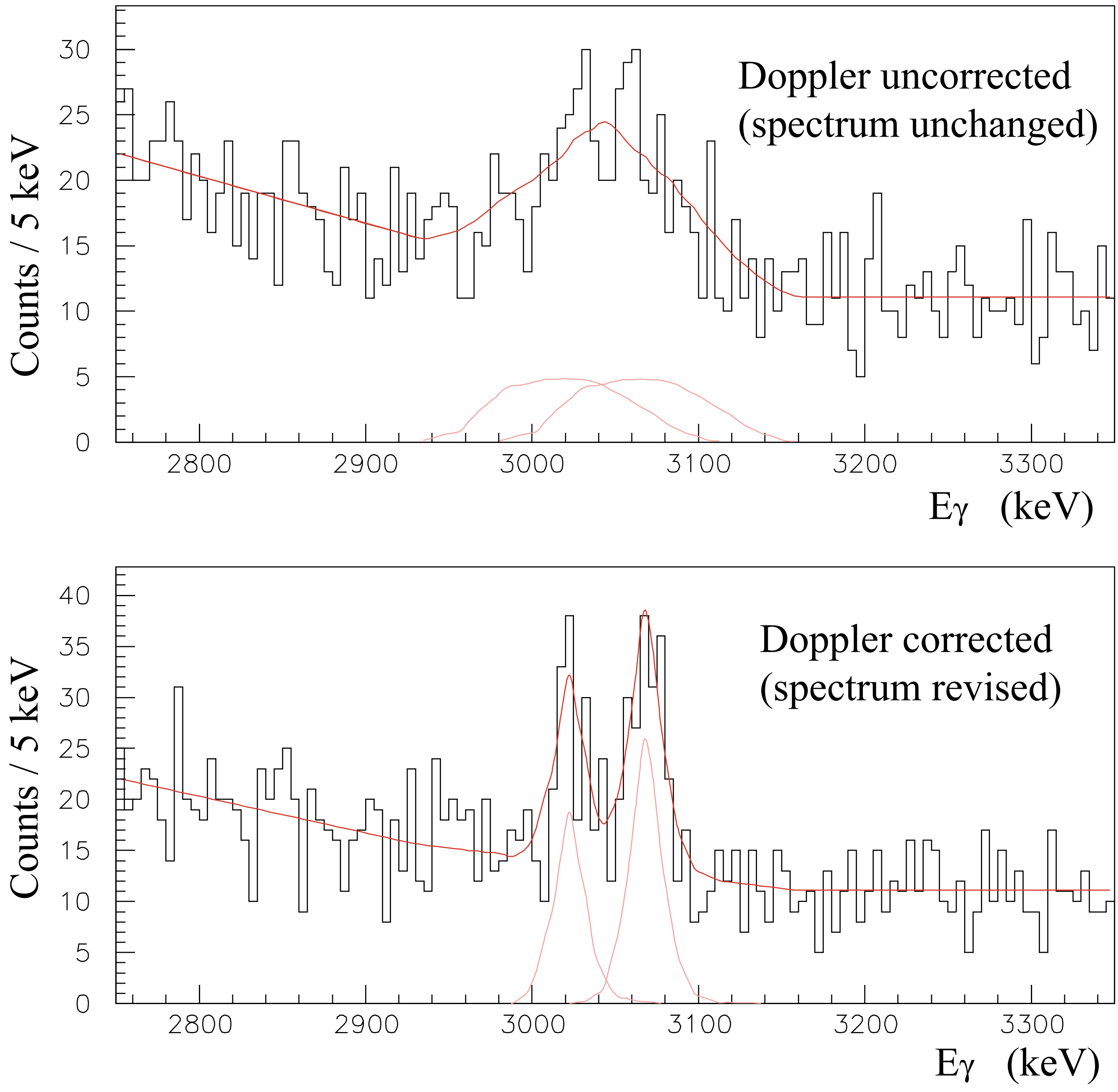
Order of $3/2^+$, $5/2^+$ not determined from this experiment.

In 2001 run on ^{10}B target, the upper level is seen following

$^{10}_{\Lambda}\mathrm{B} \to {}^{9}_{\Lambda}\mathrm{Be} + p$

enabling us to deduce $J^\pi = 3/2^+$ for the upper member of the doublet.

E930 $^{9}_{\Lambda}$Be revised results



Both spectra are simultaneously fitted
with simulated peak shapes

Best fit for $\tau \sim 0.01$ ps

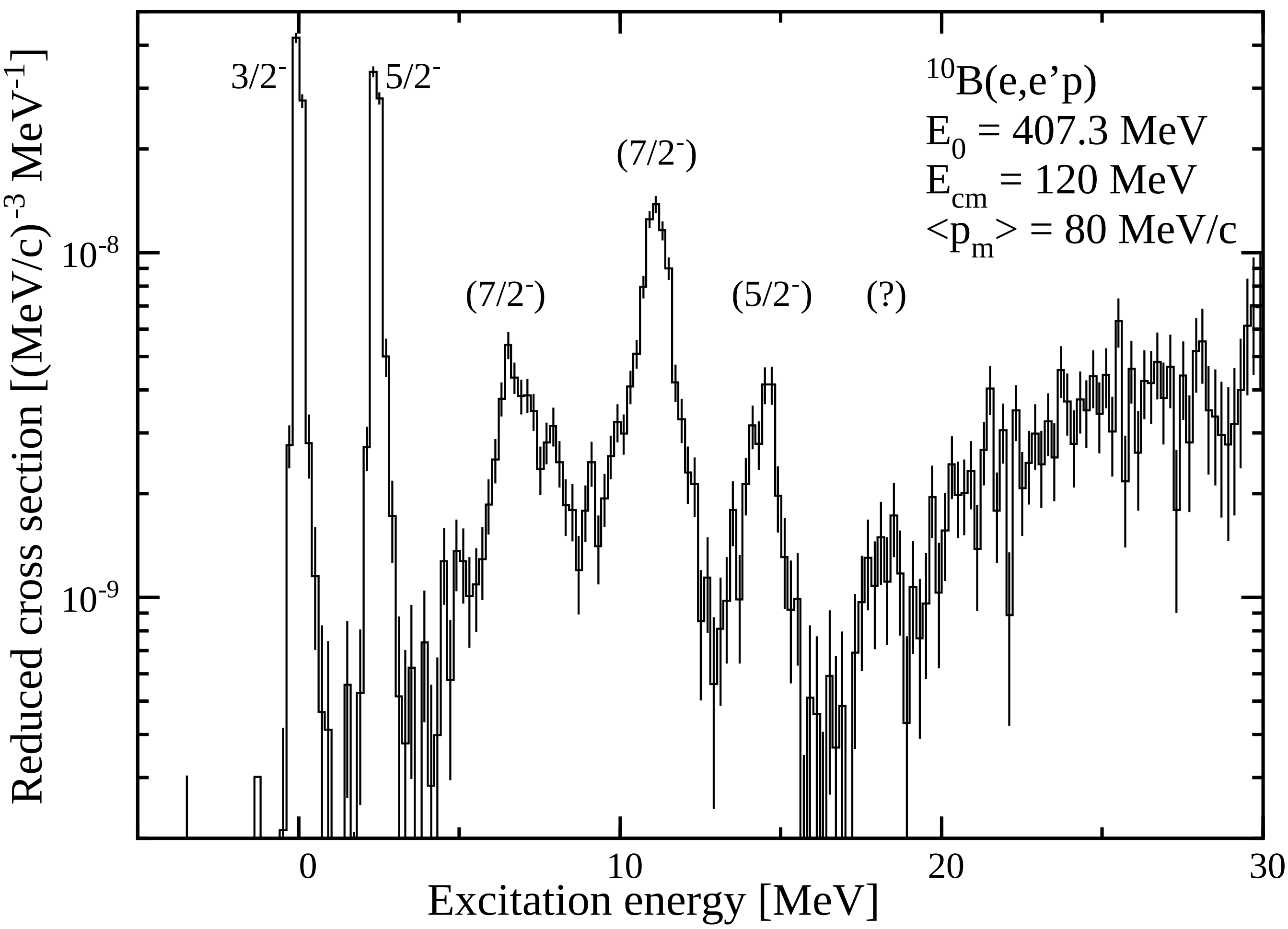
Results

$\tau < 0.10$ ps

$\Delta E = 43 \pm 5$ keV

χ^2/dof = 1.22

L. de Bever et al., PRL 80 (1998) 3924



$$|^{10}\mathrm{B}\ 3^+\ K=3\rangle = \sqrt{6/7}|L=2\rangle - \sqrt{3/22}|L=3\rangle + \sqrt{1/154}|L=4\rangle$$

92.7% $K=3$ out of 93.4% [42]

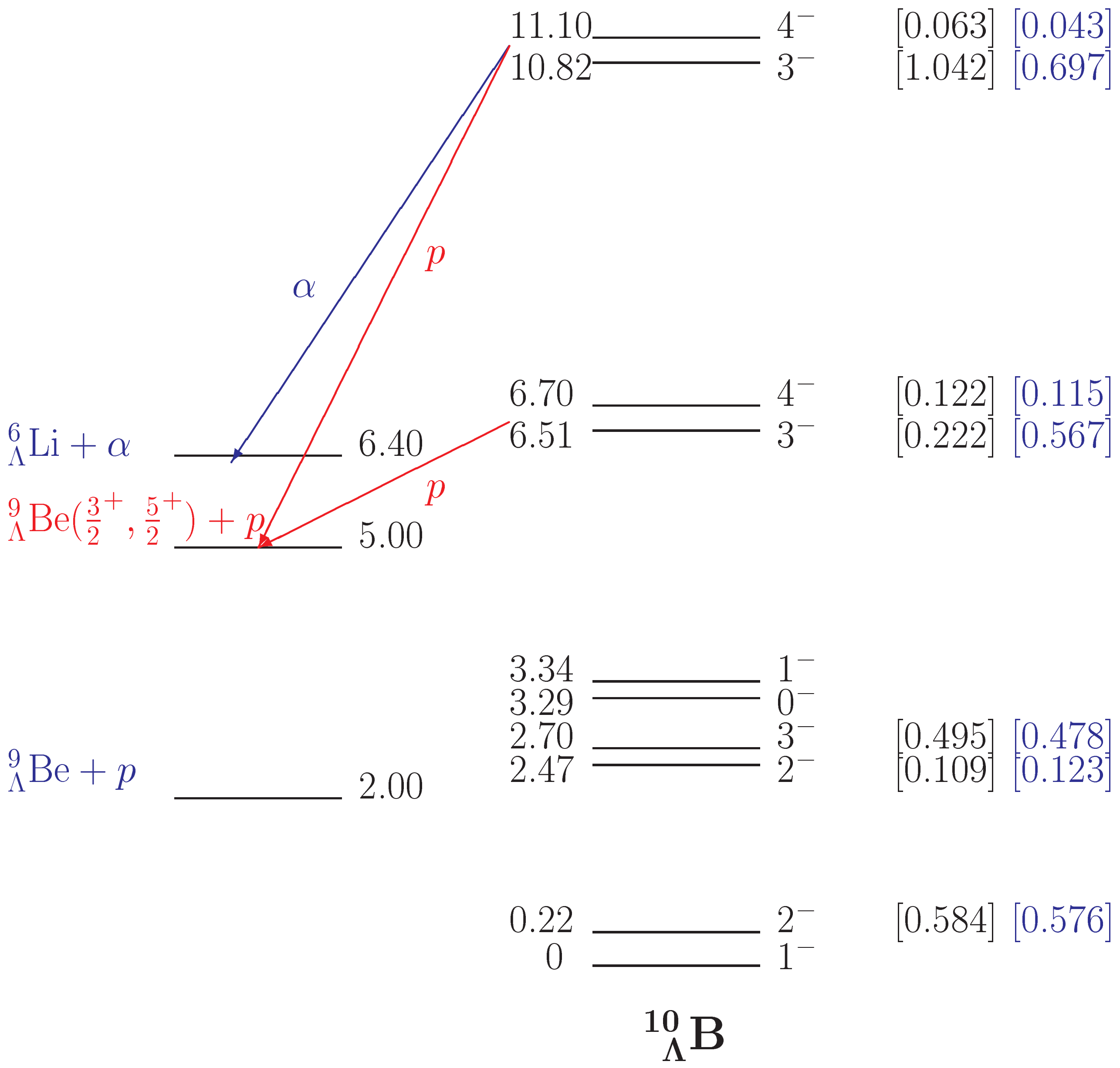
$$|^{9}\mathrm{Be}\ 3/2^-\ K=3/2\rangle = \sqrt{21/26}|L=1\rangle - \sqrt{5/26}|L=2\rangle$$

94.2% $K=3/2$ out of 95.7% [41]

Strong states are $3/2^-$, $5/2^-$, and $7/2^-$ of ground-state band, together with $7/2^-_2$ at 11.28 MeV ([32] L=2 S=3/2) and $5/2^-_4$ at 14.48 MeV ([32] L=2 S=3/2).

Ratio $\mathrm{S}(7/2^-_1)/\mathrm{S}(7/2^-_2)$ is very sensitive to mixing of [41] and [32] by the spin-orbit interaction - $0.30/1.87 = 0.16$ for no mixing versus 0.51 from $(e,e'p)$.

Proton decay of $^{10}_{\Lambda}$B to $^{9}_{\Lambda}$Be

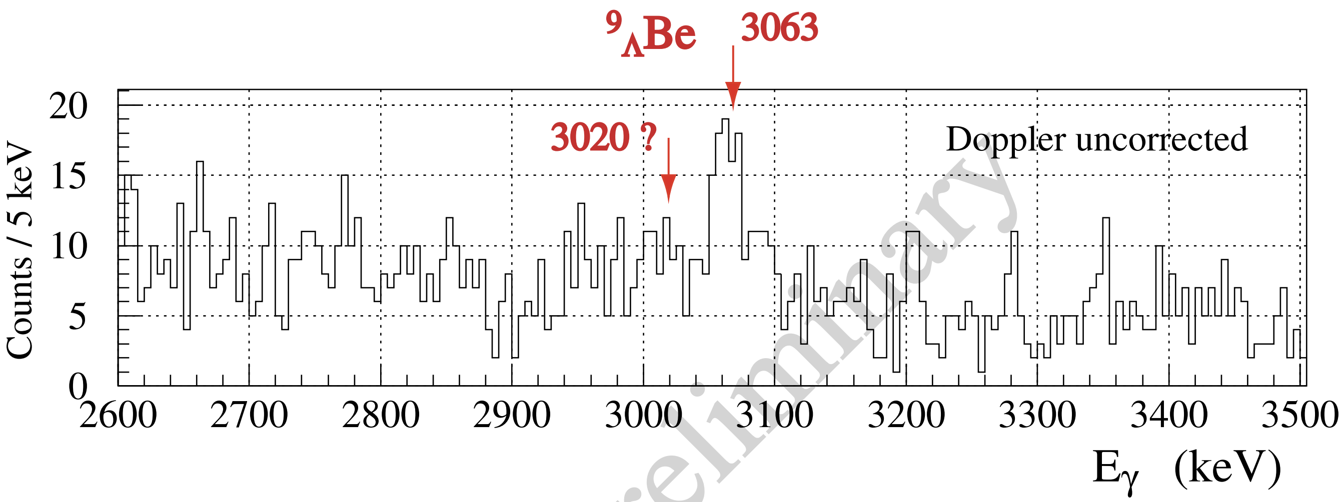


Formation and decay of ${}^{10}_{\Lambda}$B

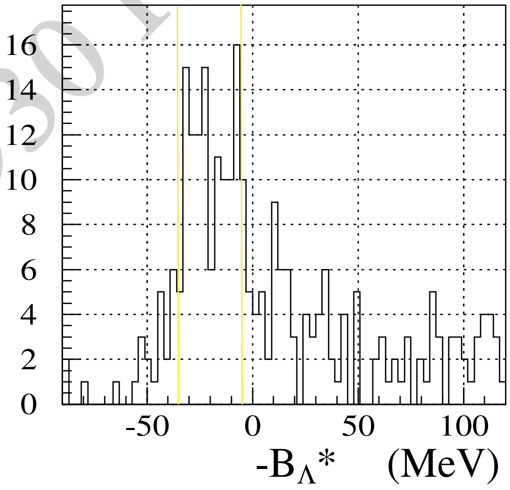
- Four states of ^{9}B reached strongly by neutron removal from ^{10}B
- The two $7/2^-$ states give rise to 3^- and 4^- states of ${}^{10}_{\Lambda}$B above the ${}^{9}_{\Lambda}\mathrm{Be}^* + p$ threshold
- 3^- is favored for the dominant $p_{3/2}$ removal by the coupling to get $\Delta L = 1$ and $\Delta S = 0$. Details depend on the amplitudes for $p_{1/2}$ and $p_{3/2}$
- Decay arises from ${}^{9}\mathrm{B}(7/2^-) \to {}^{8}\mathrm{Be}(2^+) + p$
- Recouple $(2^+ \times p_{3/2})7/2^- \times s_\Lambda \to (2^+ \times s_\Lambda)J_f \times p_{3/2}$
- 4^- decays to ${}^{9}_{\Lambda}\mathrm{Be}(5/2^+)$
- 3^- decays to $3/2^+$, $5/2^+$ in ratio of 32 to 3
- Overall: $3/2^+$ is strongly favored by proton emission
- Caveat: uppermost 3^- state doesn't α decay too much

Hyperfragments from ^{10}B (K^-, π^-) reaction : $^{9}_{\Lambda}$Be

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



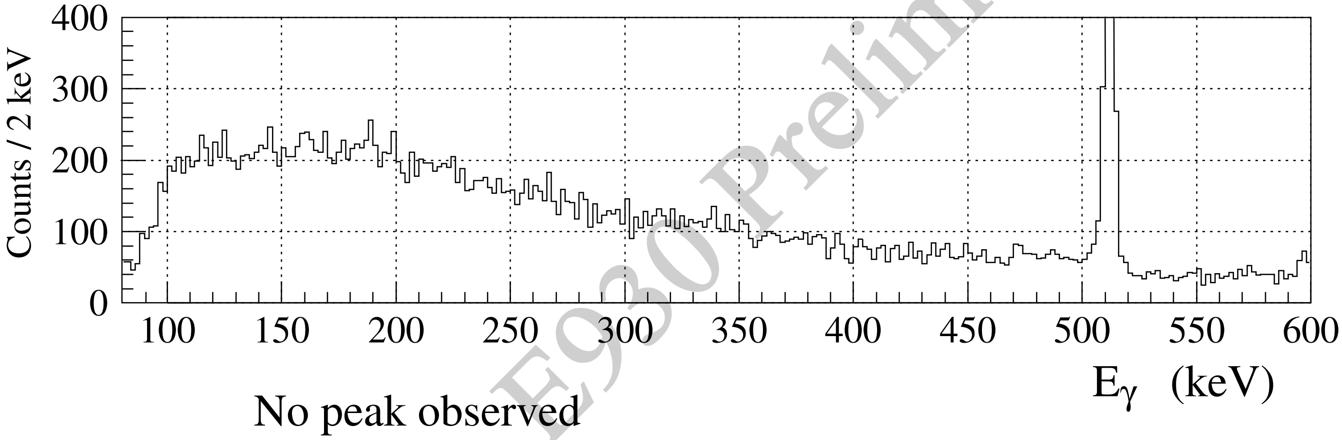
Excitation spectrum for 3063 keV peak



The upper member of the $^{9}_{\Lambda}$Be doublet is seen following proton emission from $^{10}_{\Lambda}$B and from the preceding arguments it is identified as the $3/2^+$ state.

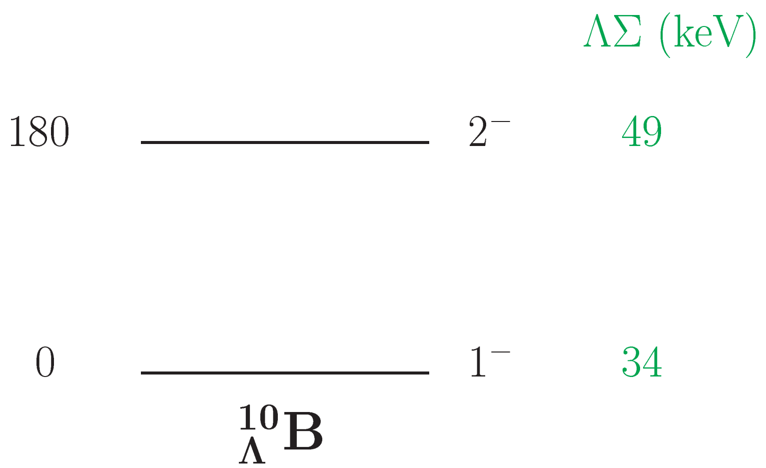
$^{10}B\,(K^-, \pi^-)\,^{10}_{\Lambda}B$ reaction

$-40 < -B_\Lambda^* < -10$ MeV   *uncalibrated
(5 MeV lower than the $^{9}_{\Lambda}Be$ gate)



No peak observed
(upper limit to be derived)

R.E. Chrien et al., PRC 41 (1990) 1062   no γ ray



Only case in which Δ and $\Lambda\Sigma$ oppose one another

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
	0.579	1.413	0.013	-1.073	
-15	250	-14	-5	-32	180 keV

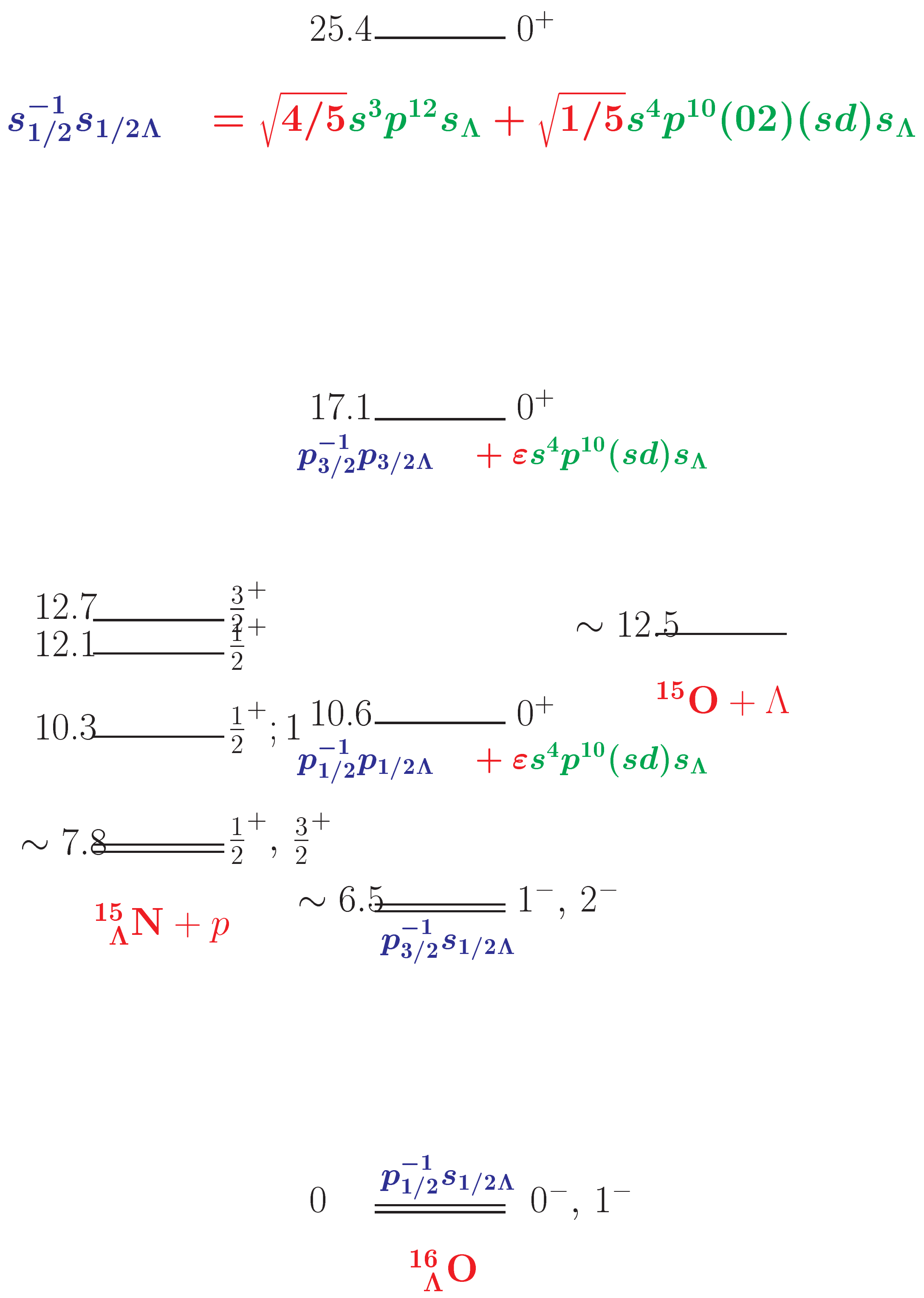
$^{7}_{\Lambda}Li$: $\Delta = 0.432$ $S_\Lambda = -0.010$ $S_N = -0.380$ $T = 0.030$

CK616 gives $\Delta E = 164$ keV - larger coefficient of T

This transparency showed the $^{16}\mathrm{O}(K^-, \pi^-)^{16}_{\Lambda}\mathrm{O}$ spectrum from W. Brückner et al., Phys. Lett. B **79** (1978) 157.

The prominant structures are the 1^- s_Λ states and the 0^+ p_Λ states based on the $0p^{-1}_{1/2}$ and $0p^{-1}_{3/2}$ states of the $^{15}\mathrm{O}$ core. The broad distribution of strength at higher excitation energy corresponds 0^+ s_Λ states based on the $0s^{-1}_{1/2}$ neutron-hole strength.

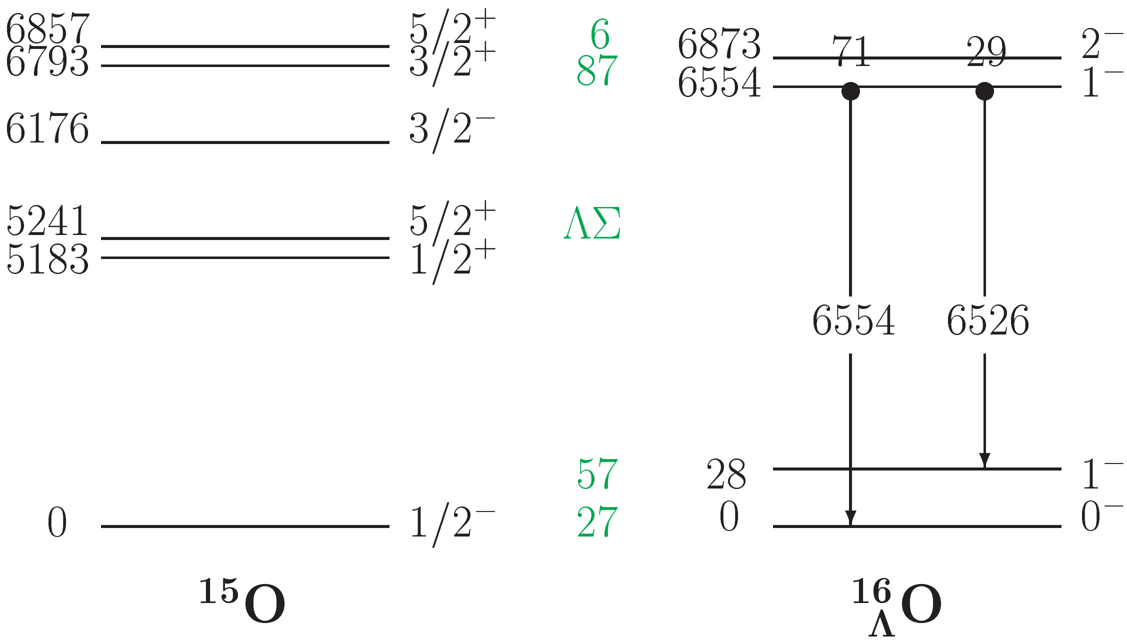
Strong 1^- and 0^+ states in $^{16}\mathrm{O}(K^-,\pi^-)^{16}_{\Lambda}\mathrm{O}$



Tensor Interaction

For pure $p_{1/2}^{-1}s_\Lambda$, the combination of parameters governing the doublet splitting is

$$E(1_1^-) - E(0^-) = -\frac{1}{3}\Delta + \frac{4}{3}S_\Lambda + 8T$$



$\Delta = 0.468 \quad \mathrm{S}_\Lambda = -0.011 \quad \mathrm{S_N} = -0.354 \quad T = 0.030$

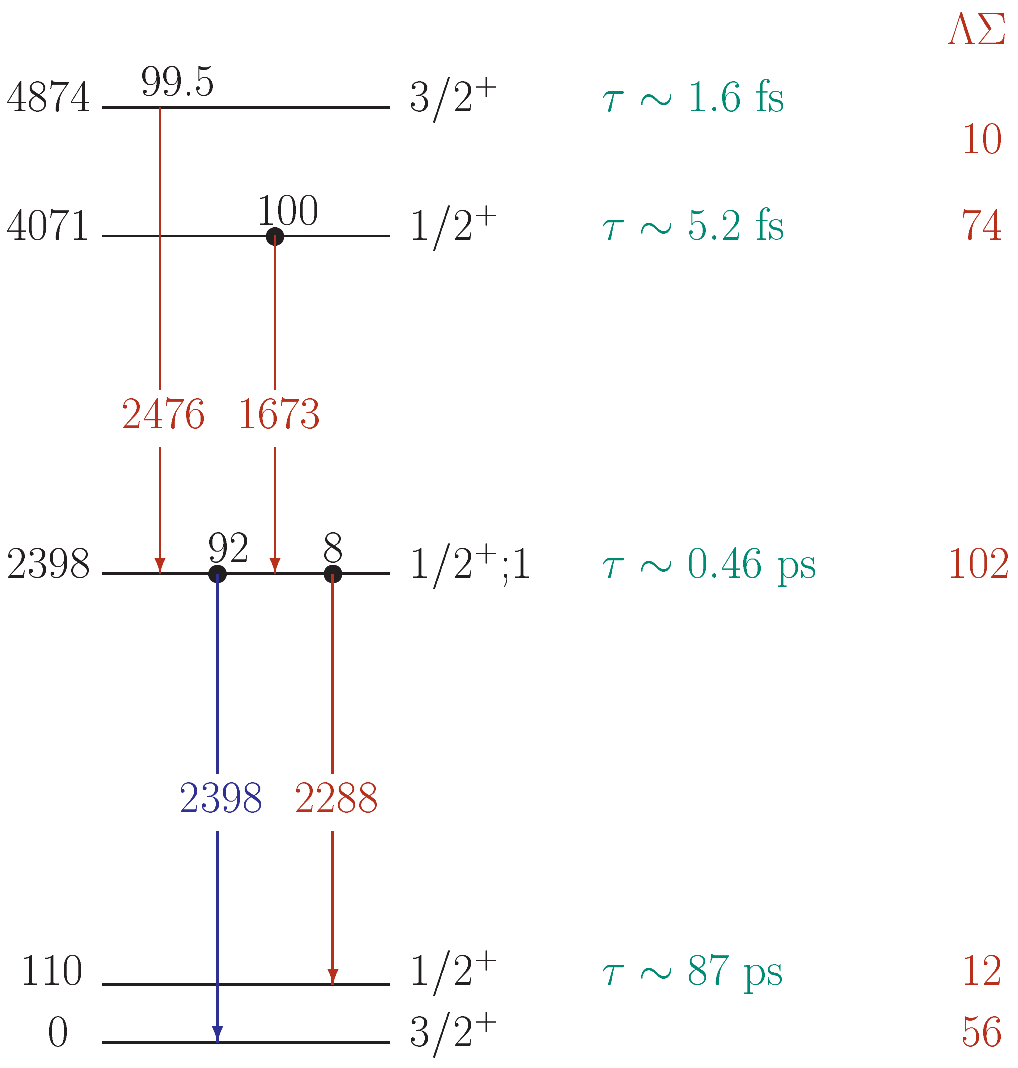
Ukai – Sendai03

$$\begin{aligned} E(1_2^- - 0_1^-) &= 6558.6 \pm 1.4 \ \text{keV} \ \ (200 \pm 23 \ \text{counts}) \\ E(1_2^- - 1_1^-) &= 6532.1 \pm 1.8 \ \text{keV} \ \ (128 \pm 20 \ \text{counts}) \\ \Delta E &= 26.5 \pm 2.3 \ \text{keV} \end{aligned}$$

The ${}^{15}_{\Lambda}$N spectrum based on the three lowest levels of the core using the (8-16)2BME interaction of Cohen and Kurath for

$\Delta = 0.468 \quad \mathrm{S}_\Lambda = -0.011 \quad \mathrm{S}_\mathrm{N} = -0.354 \quad T = 0.030$.

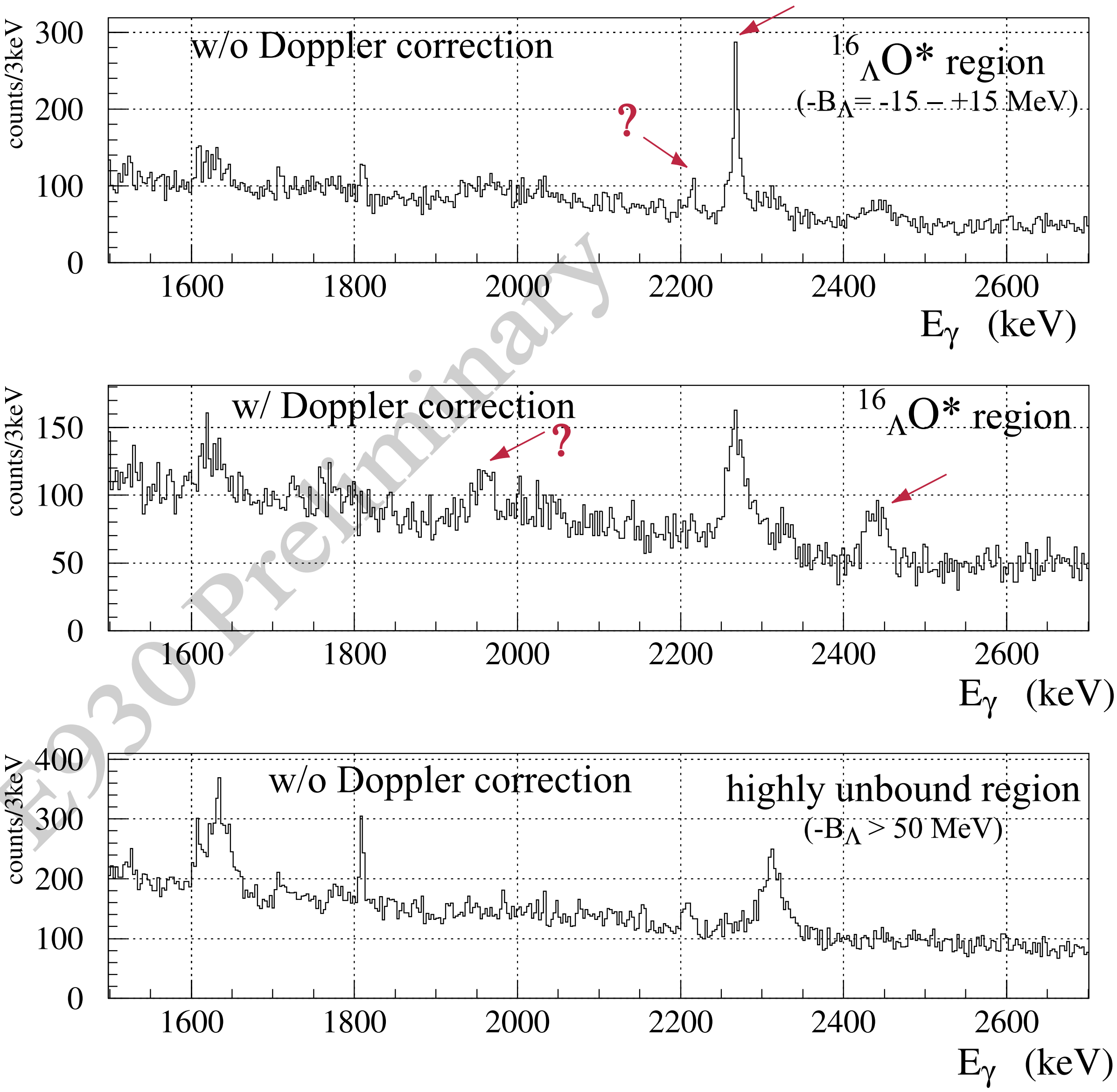
which fit the results of E930 for ${}^{16}_{\Lambda}$O.



$$E(1/2^+) - E(3/2^+) = 0.756\Delta - 2.250S_\Lambda + 0.035S_N - 9.862T$$

ΛΣ contribution = 44 keV

Candidates of $^{15}_{\Lambda}N$ γ rays
by $^{16}O\ (K^-, \pi^-)^{15}_{\Lambda}N + p$ reaction



$^{16}_{\Lambda}$O $\quad \Delta E(1^- - 0^-)$ $\quad$ Experiment $\sim$ 27 keV

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
	-0.382	1.378	-0.004	7.850	
-30	-179	-15	1	235	28 keV

$^{15}_{\Lambda}$N $\quad \Delta E(1/2^+ - 3/2^+)$

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
	0.756	-2.250	0.035	-9.864	
44	354	25	-12	-296	110 keV

$^{16}_{\Lambda}$O $\quad E(1^-_2 - 1^-_1) = 6176 + \Delta E$ $\quad$ Experiment $\sim$ 6532 keV

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
	-0.234	-1.257	-1.496	-0.708	
-30	-110	14	530	-21	350 keV

$^{15}_{\Lambda}$N $\quad E(1/2^+;1 - 3/2^+) = 2313 + \Delta E$ $\quad$ Experiment $\sim$ 2263 keV

$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
	0.284	-0.778	-0.249	-3.197	
-46	133	9	88	-96	85 keV

$\Delta = 0.468 \quad S_\Lambda = -0.011 \quad S_N = -0.354 \quad T = 0.030$

M1 strengths from the $1/2^+; 1$ level of ${}^{15}_{\Lambda}$N

Main components of wave functions

$|1/2^+;1\rangle = 0.9992(0^+_1;1.s_\Lambda)$

$|1/2^+;0\rangle = 0.9980(1^+_1.s_\Lambda) + 0.0619(1^+_2.s_\Lambda)$

$|3/2^+;0\rangle = 0.9982(1^+_1.s_\Lambda) + 0.0302(1^+_2.s_\Lambda) + 0.0524(2^+.s_\Lambda)$

M1 matrix elements

Consider just the contribution of the $1^+_2 \times s_\Lambda$ components in addition to the dominant component in each wave function

$M(1/2^+ \to 1/2^+)$

$= -\{(0.9980)(0.9992)(-0.25496) + (0.0619)(0.9992)(3.21472)\}$

$= -\{-0.25427 + 0.19883\} = 0.0554$

where the third number in each product is the core matrix element

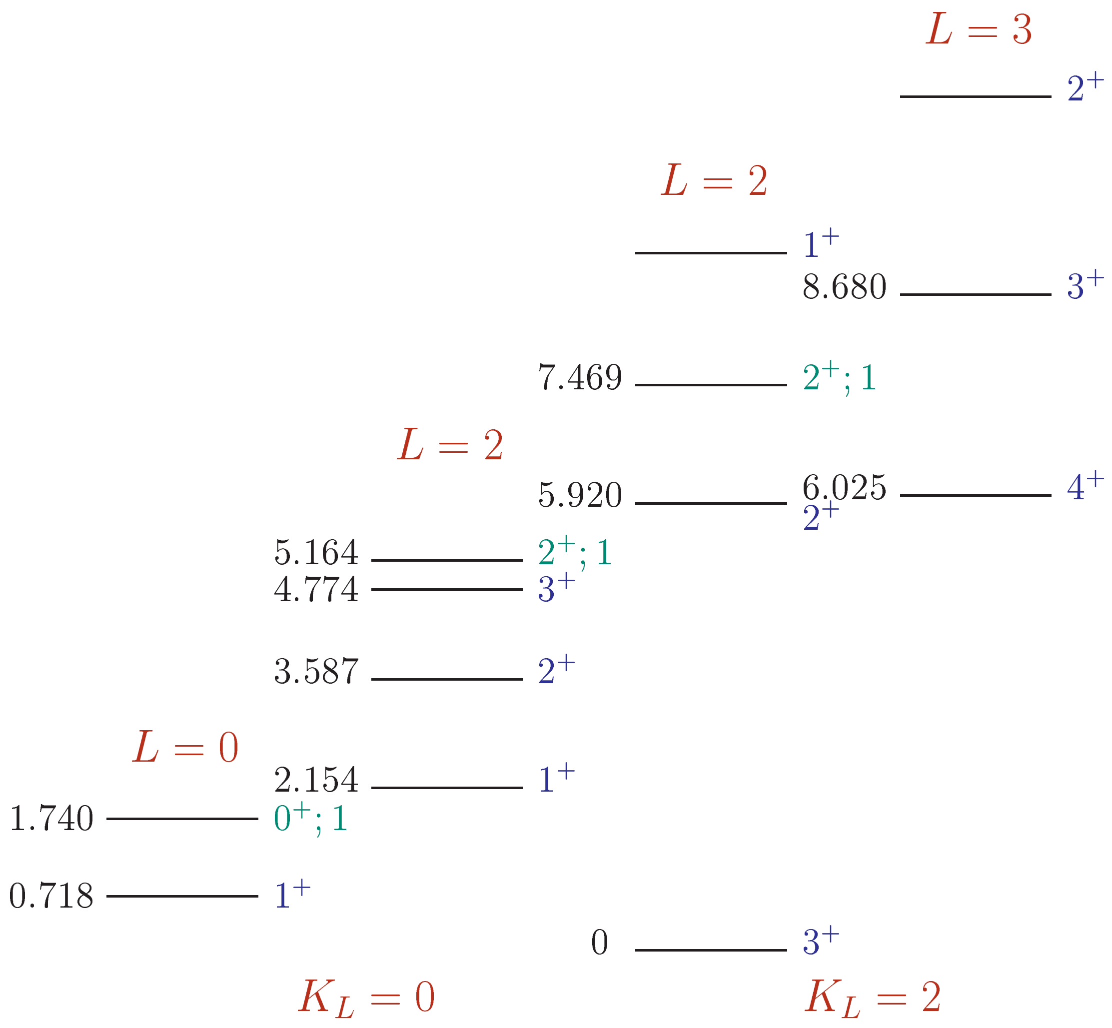
$M(1/2^+ \to 3/2^+)$

$= \{(0.9980)(0.9992)(-0.25496) + (0.0302)(0.9992)(3.21472)\}$

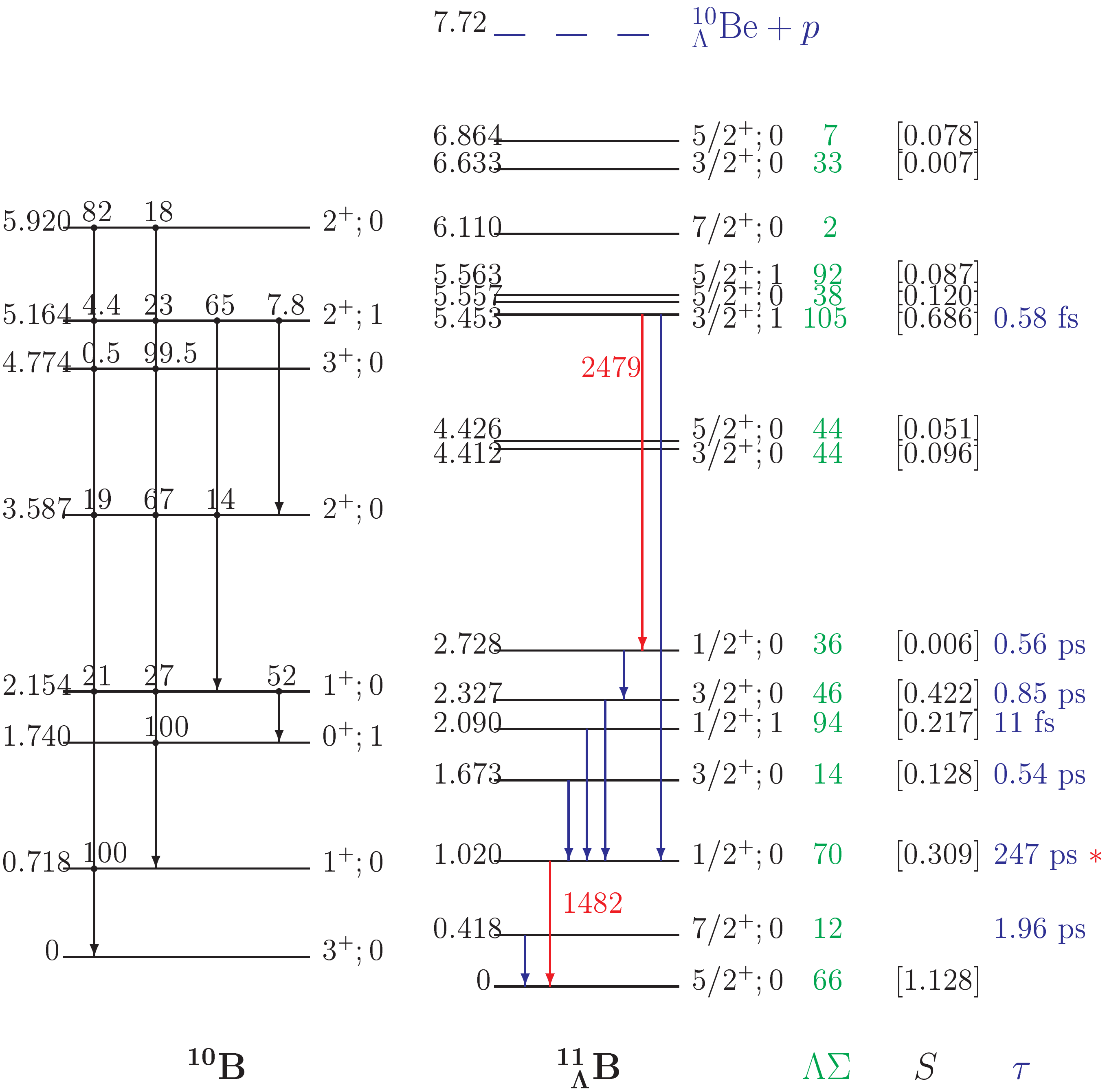
$= \{-0.25427 + 0.09700\} = -0.1573$

The full result for this transition translates into a partial lifetime of 0.5 ps (for $E_\gamma = 2263$ keV).

P-shell states of ^{10}B with [42] symmetry.



$T = 0$ states have $S = 1$ and $T = 1$ states have $S = 0$

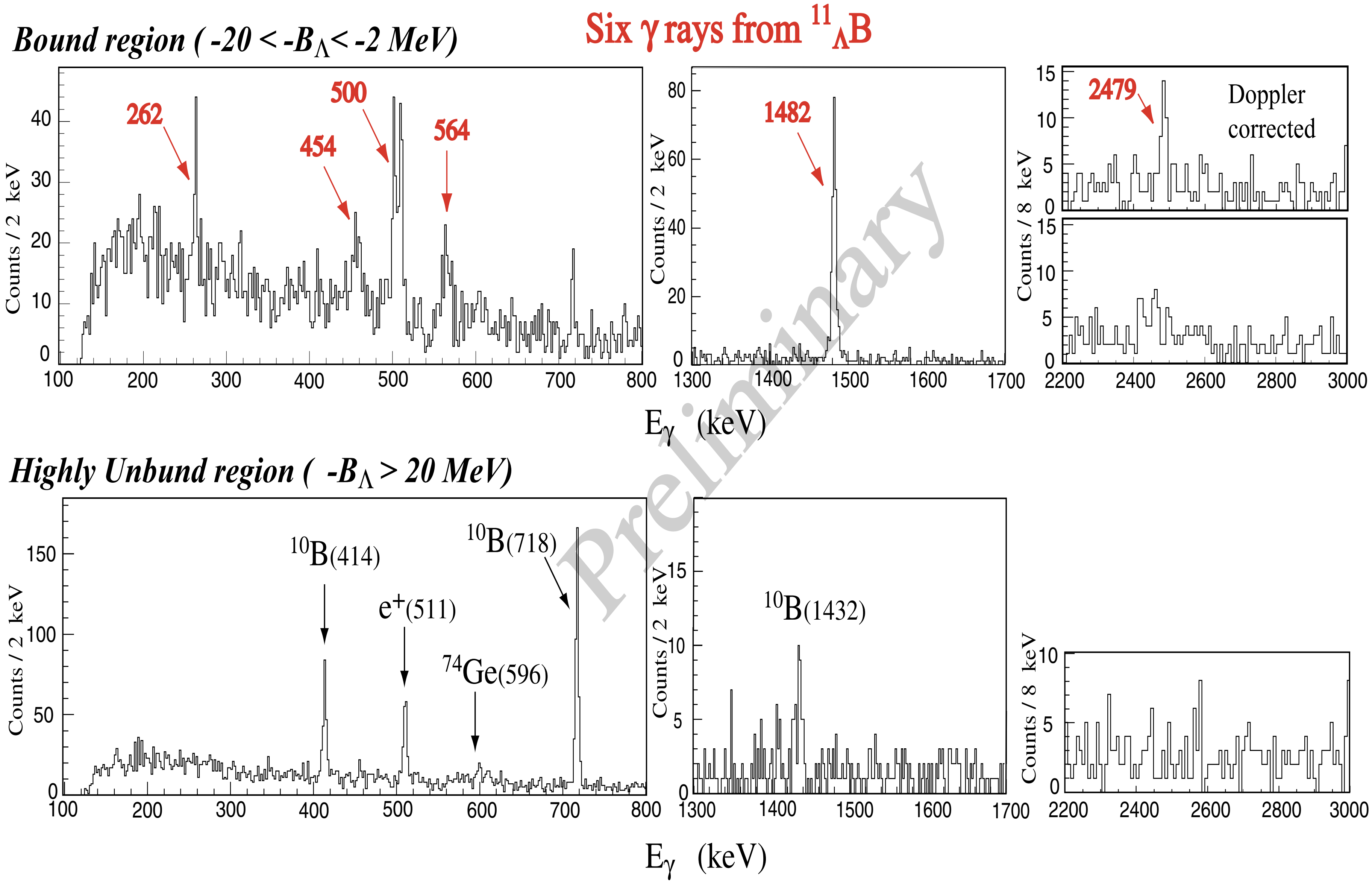


* τ (weak) $\sim$ 200 ps

For $E_\gamma = 1482$ keV, τ (EM) $\sim$ 38 ps

This level serves as a collection point for γ rays

KEK E518 $^{11}B(\pi^+,K^+\gamma)\,^{11}_{\Lambda}B$

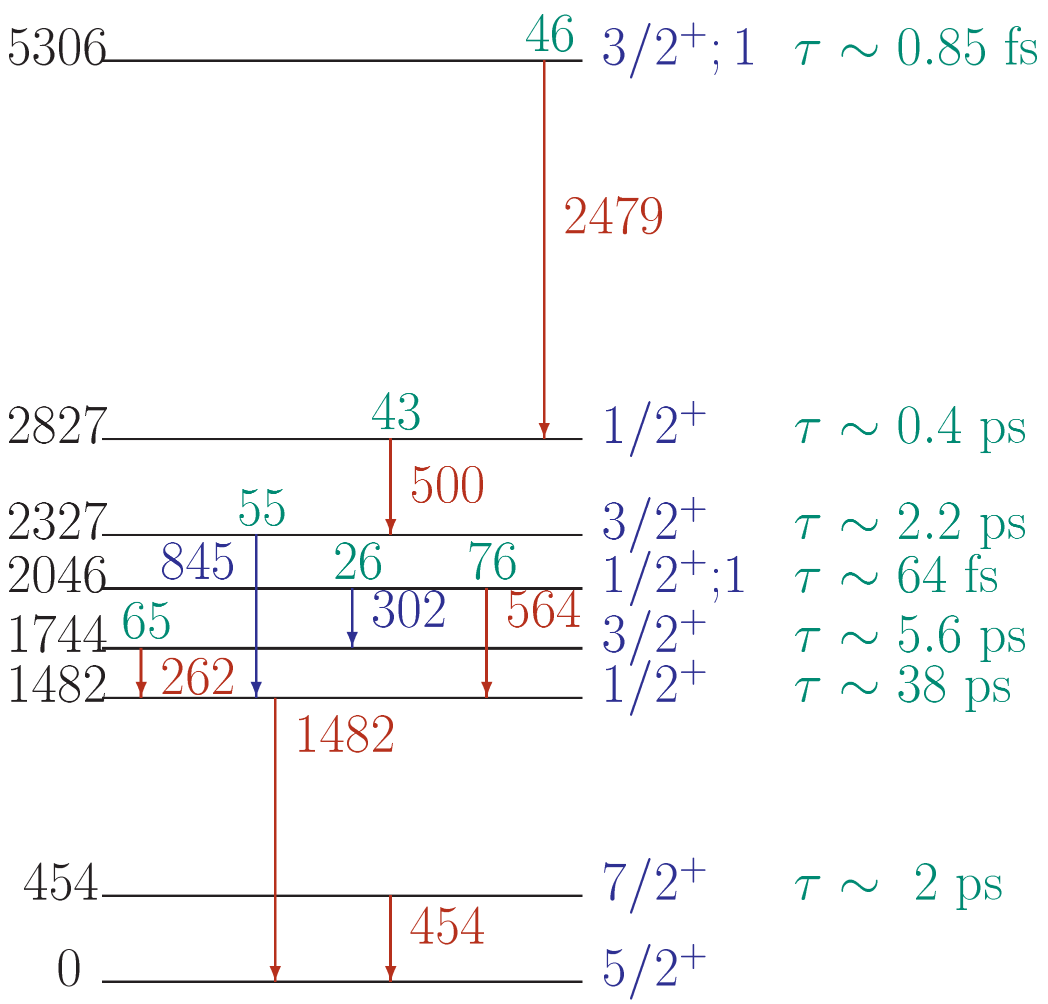


Conclusions

- We are making progress
- Can look forward to finalizing the analysis of BNL E930 and KEK E518

- Have had good K^- beams at BNL
- Have had a good spectrometer at KEK
- Hope to have both at JPARC along with Hyperball-3

Speculations on the placement of ${}^{11}_{\Lambda}$B γ rays.



- To reproduce the definitive 1482 keV line, the centroid of the lowest $1/2^+$, $3/2^+$ doublet needs to be high (small coefficient of S_N) and the separation needs to be small (Δ).
- Natural to identify the 2479 keV line with the strong M1 from the $3/2^+; 1$ level.
- For different core wave functions, ground-state doublet and T=1 levels are quite stable while $1/2^+$ and $3/2^+$ T=0 states are volatile.