Hypernuclear γ-ray Spectroscopy

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$$m_\Lambda \sim m_N + 176 \text{ MeV} \qquad \tau_\Lambda \sim 260 \text{ ps}$$

Formation of hypernuclei

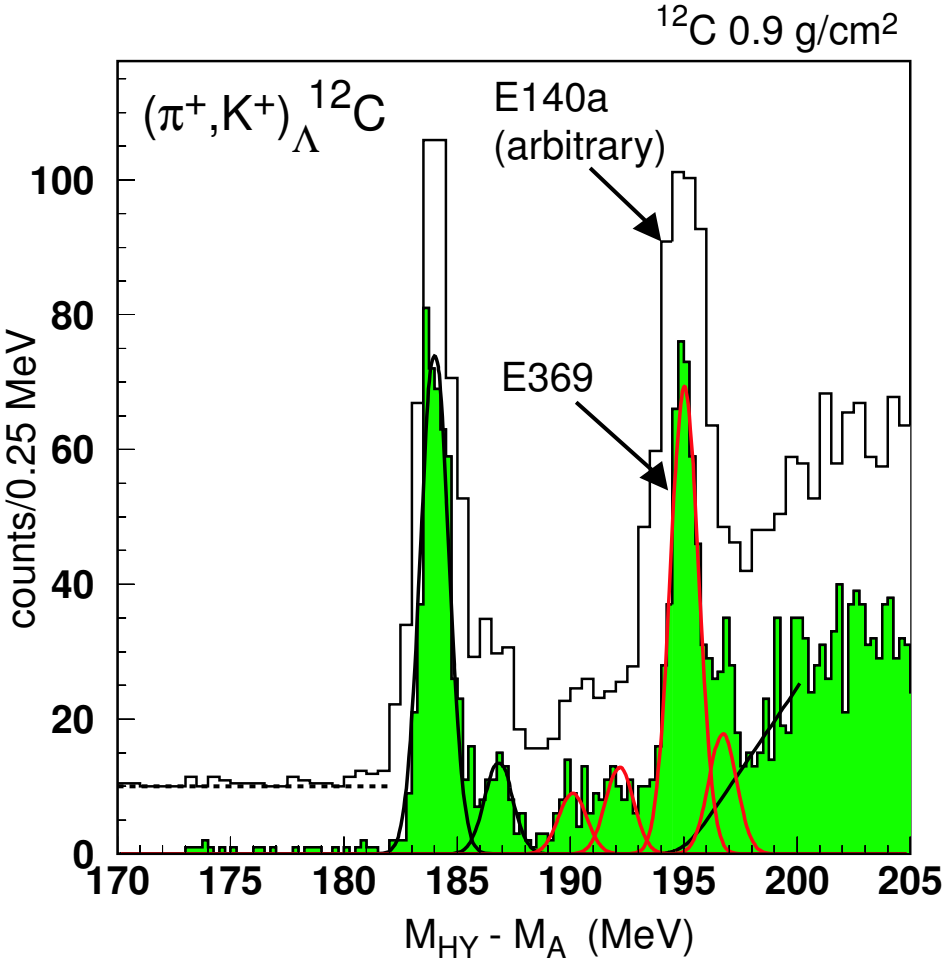
- $n(K^-, \pi^-)\Lambda$ – stopped or in-flight; first emulsions $\Rightarrow B_\Lambda$, then CERN, BNL, KEK, Frascati
- $n(\pi^+, K^+)\Lambda$ – BNL, KEK
- $p(e, e'K^+)\Lambda$ – JLab, Hall A and Hall C

Decay of hypernuclei

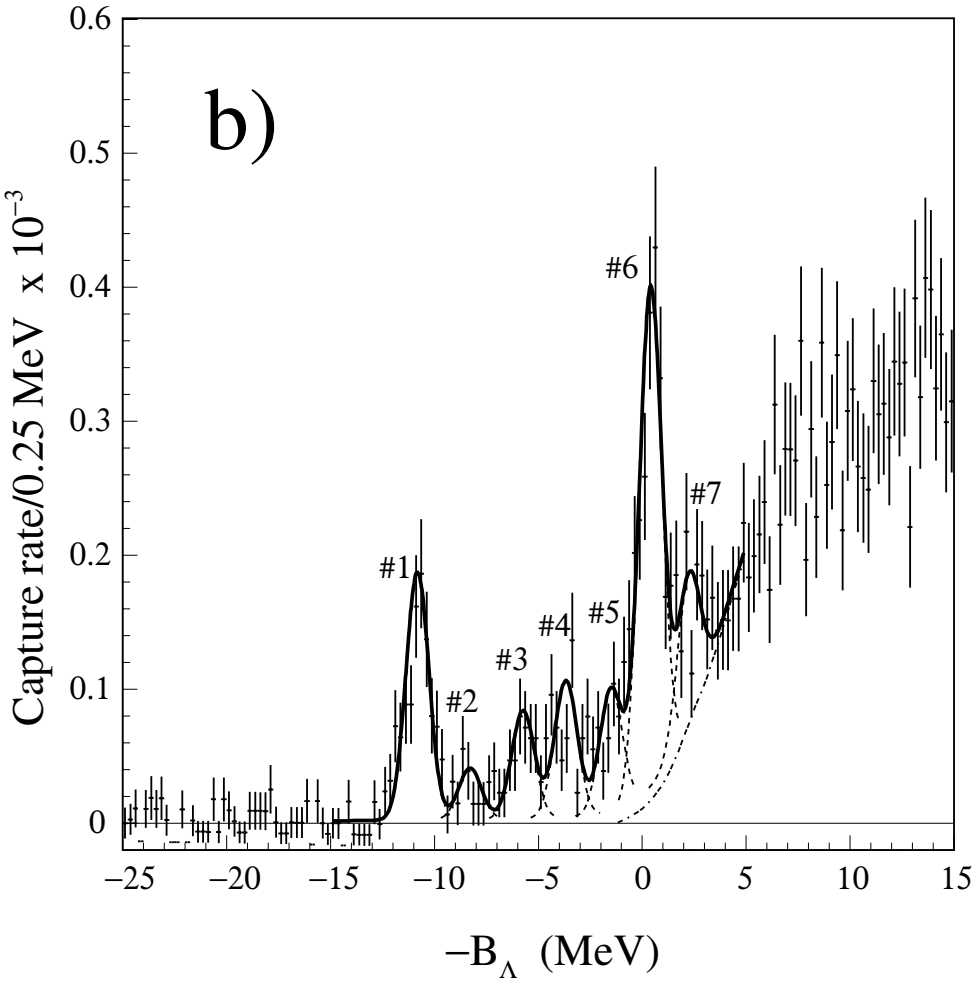
- Weak decay from ground state with $\tau \sim 200$ ps

$$\begin{aligned} \Gamma_{\pi^-} &\quad \Lambda \to p + \pi^- \\ \Gamma_{\pi^0} &\quad \Lambda \to n + \pi^0 \\ \Gamma_n &\quad \Lambda n \to nn \\ \Gamma_p &\quad \Lambda p \to pn \end{aligned}$$

- γ decay from bound excited states or particle emission followed by γ decay from daughter hypernucleus



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



FINUDA, Phys. Lett. B 622 (2005) 35

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
$V_\Lambda l_{N\Lambda}.s_\Lambda$		$S_\Lambda = \frac{1}{2} I_1^o$	-0.015
$V_N l_{N\Lambda}.s_N$		$S_N = \frac{1}{2} I_1^o$	-0.400
$V_T S_{12}$		$T = \frac{1}{3} I_1^o$	0.030

$$V_0 = \frac{1}{4} V_C(S=0) + \frac{3}{4} V_C(S=1) \qquad V_\sigma = V_C(S=1) - V_C(S=0)$$

$$V_\Lambda = V_{LS} l_{N\Lambda}.(s_\Lambda + s_N) + V_{ALS} l_{N\Lambda}.(s_\Lambda - s_N)$$

$$V_N = V_{LS} l_{N\Lambda}.(s_\Lambda + s_N) - V_{ALS} l_{N\Lambda}.(s_\Lambda - s_N)$$

S-Shell Λ Hypernuclei

Hypernucleus	$J^\pi(gs)$	B_Λ MeV	J^π	E_x MeV
${}^{3}_{\Lambda}$H	$1/2^+$	0.13(5)		
${}^{4}_{\Lambda}$H	0^+	2.04(4)	1^+	1.04(5)
${}^{4}_{\Lambda}$He	0^+	2.39(3)	1^+	1.15(4)
${}^{5}_{\Lambda}$He	$1/2^+$	3.12(2)		

Recent "Exact" Calculations

- $A = 3, 4$ A. Nogga et al., PRL 88 (2002) 172501
  Faddeev and Faddeev-Yakubovsky
- $A = 4$ E. Hiyama et al., PRC 65 (2002) 011301(R)
  Jacobi-coordinate Gaussian basis
- $A = 3, 4, 5$ H. Nemura et al., PRL 89 (2002) 142504
  Stochastic variation with correlated Gaussians

$\Lambda - \Sigma$ coupling for ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He

Y. Akaishi et al., PRL 84 (2000) 3539

$$|{}^{4}_{\Lambda}\mathrm{He}(\mathrm{T}=1/2)\rangle = \alpha s^3 s_\Lambda + \beta s^3 s_\Sigma$$

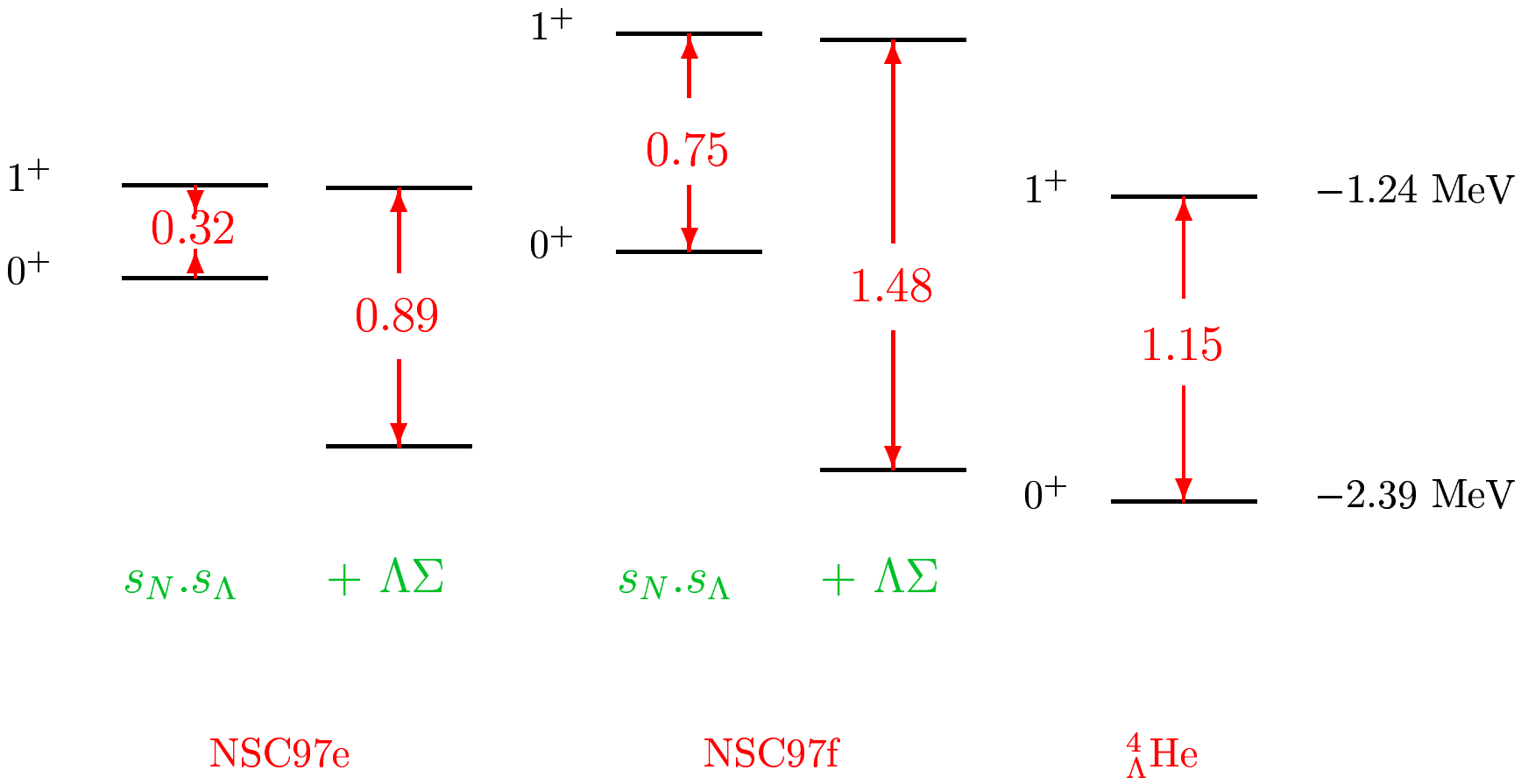
From ΛN$-\Sigma$N g matrix for $0s$ orbits

$v = \langle s^3 s_\Lambda | g | s^3 s_\Sigma \rangle, \quad \Delta E \sim 80$ MeV

0^+ $\qquad v = \frac{3}{2}\,{}^3g_{ss} - \frac{1}{2}\,{}^1g_{ss}$ $\qquad$ Admixture $\sim v/\Delta E$

1^+ $\qquad v = \frac{1}{2}\,{}^3g_{ss} + \frac{1}{2}\,{}^1g_{ss}$ $\qquad E^{shift} \sim v^2/\Delta E$

NSC97f: $\quad v \sim 7.6$ MeV $\quad \Rightarrow \quad E^{shift} \sim 0.72$ MeV

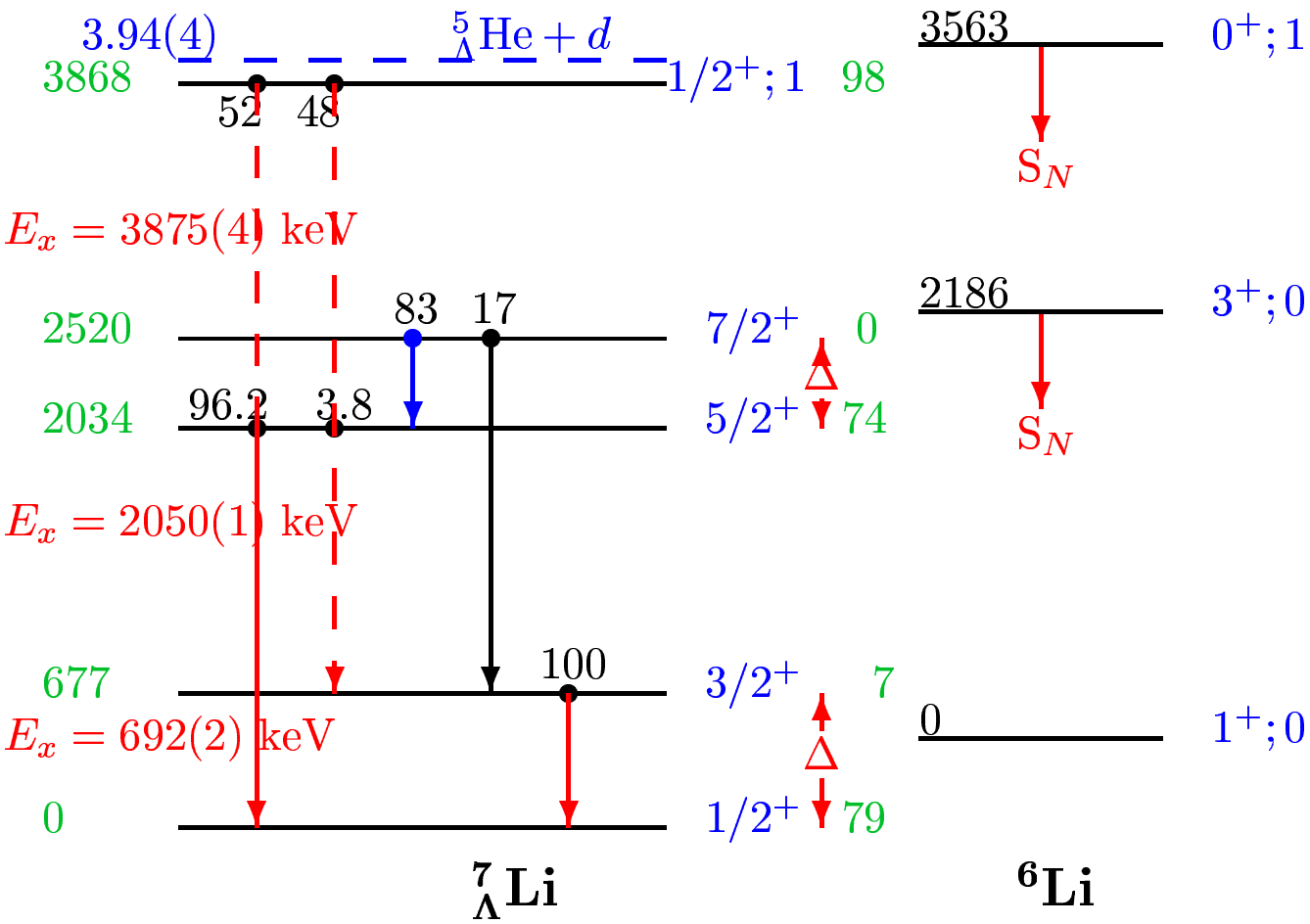

1+
0+
0.32
0.89
$s_N.s_\Lambda$
$+ \Lambda\Sigma$
NSC97e
1+
0+
0.75
1.48
$s_N.s_\Lambda$
$+ \Lambda\Sigma$
NSC97f
1+
0+
1.15
−1.24 MeV
−2.39 MeV
$^{4}_{\Lambda}$He

$\Lambda N - \Sigma N$ Coupling for $\langle p_N s_\Lambda | V | p_N s_\Sigma \rangle$

Can use the same parametrization as for ΛN

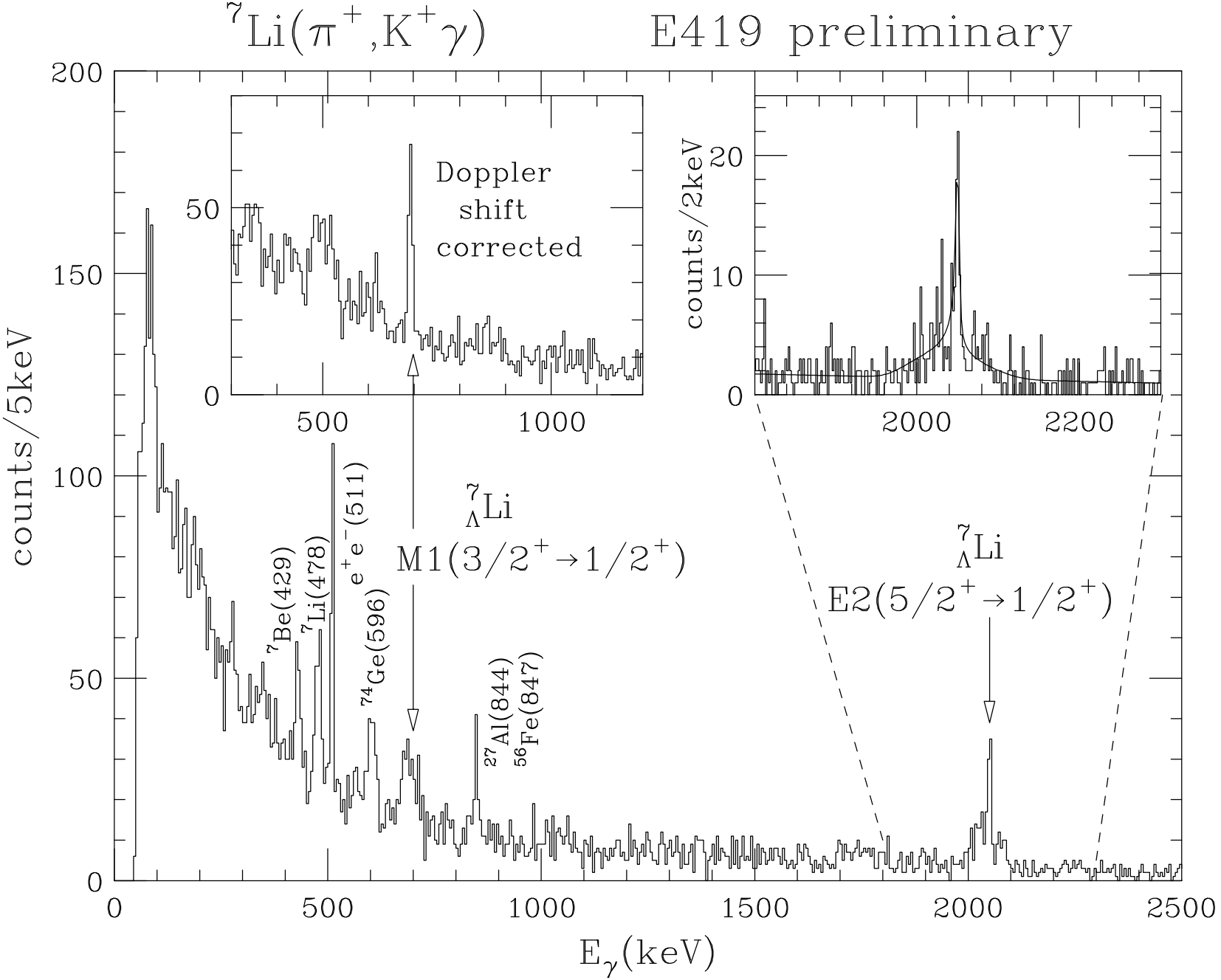
$$|\bar{V}| = 1.45\text{MeV} \qquad |\Delta| = 3.04\text{MeV}$$

${}^{7}_{\Lambda}$Li γ rays – Hyperball, KEK E419 and BNL E930

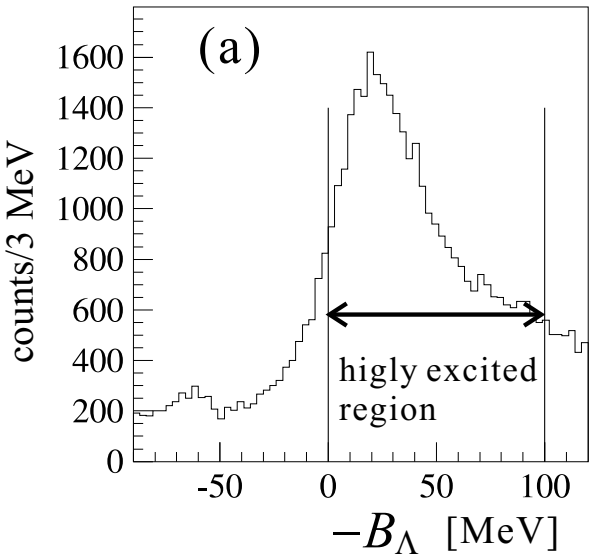


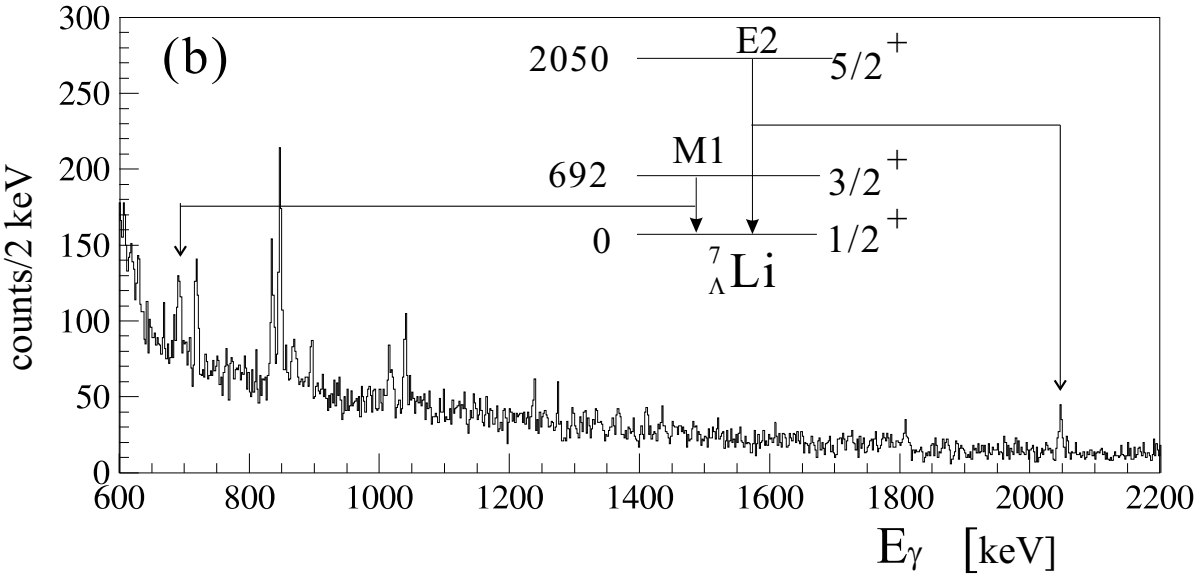
H. Tamura et al.,
PRL 84 (2000) 5963
K. Tanida et al.,
PRL 86 (2001) 1982

$\Delta = 0.425 \quad S_\Lambda = -0.015 \quad S_N = -0.390 \quad T = 0.030$


^{7}Li(π^+,K$^+\gamma$)
E419 preliminary
counts/5keV
counts/2keV
Doppler
shift
corrected
$^{7}_{\Lambda}$Li
M1(3/2$^+\rightarrow$1/2$^+$)
$^{7}_{\Lambda}$Li
E2(5/2$^+\rightarrow$1/2$^+$)
^{7}Be(429)
^{7}Li(478)
e$^+$e$^-$(511)
^{74}Ge(596)
^{27}Al(844)
^{56}Fe(847)
E$_\gamma$(keV)

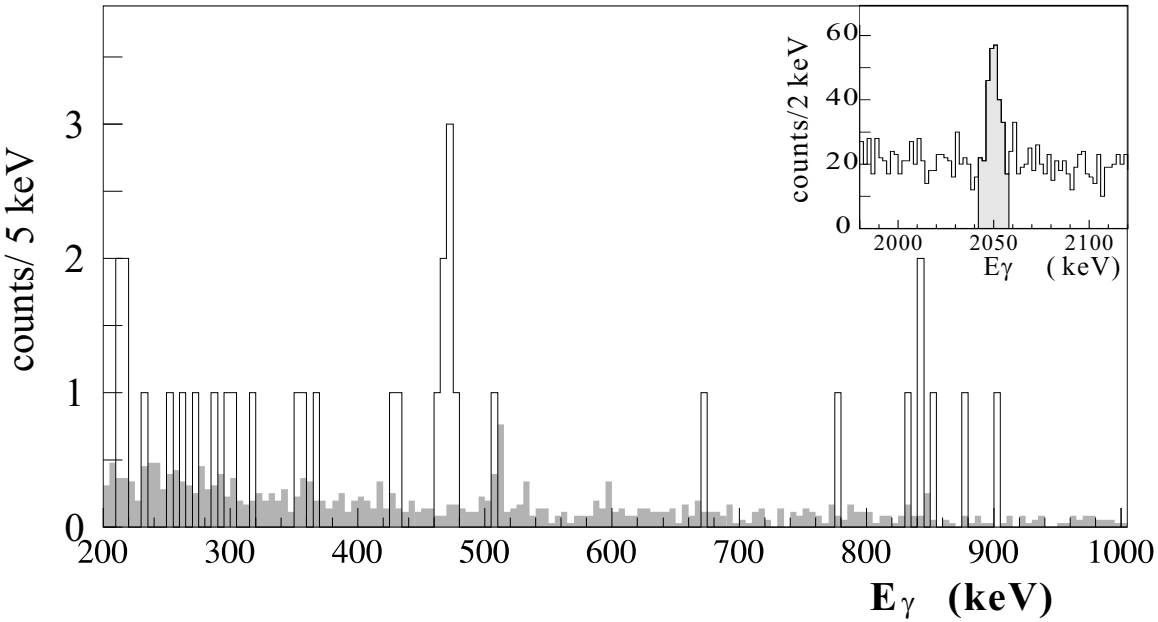
(a) Mass spectrum of ${}^{10}_{\Lambda}$B from ^{10}B(K^-,π^-) (b) γ-ray spectrum





$\gamma - \gamma$ coincidence spectrum

$E_\gamma = 470.8 \pm 1.9 \pm 0.6$ keV

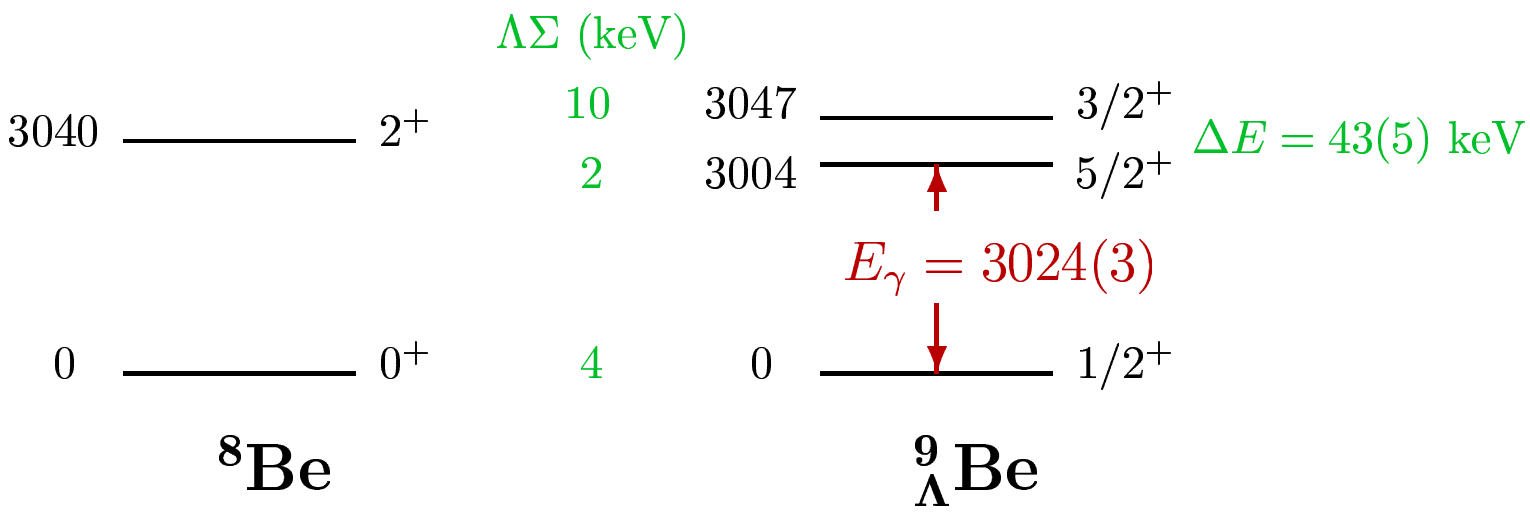


Energy spacings in ${}^{7}_{\Lambda}$Li

Energy contributions are in keV $\quad \Delta E = \Delta E_C + \Delta E_{\Lambda N}$

$\Delta = 0.425 \quad S_\Lambda = -0.015 \quad S_N = -0.390 \quad T = 0.030$

$J_i^\pi - J_f^\pi$	ΔE_C	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
$3/2^+ - 1/2^+$			1.455	0.043	0.003	−0.450	
	0	72	618	−1	−1	−14	677
$5/2^+ - 1/2^+$			0.177	−1.138	0.756	0.976	
	2186	5	75	17	−294	29	2034
$1/2^+ - 1/2^+$			0.969	−0.026	0.229	−0.209	
	3565	−19	412	0	−89	−6	3868
$7/2^+ - 5/2^+$			1.294	2.166	0.020	−2.380	
	0	74	550	−32	−8	−71	486



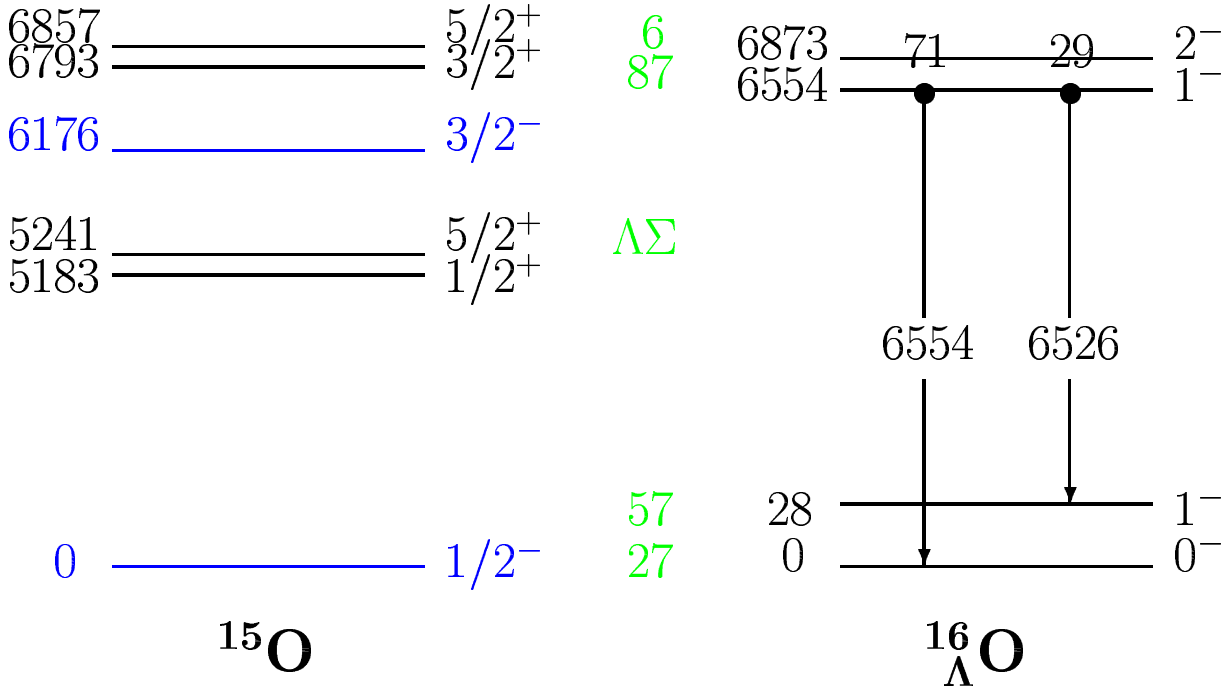
ΛΣ	Δ	S_Λ	S_N	T	ΔE
	−0.037	−2.464	0.003	0.994	
−8	−16	37	−1	30	35 keV

- Order of $3/2^+$, $5/2^+$ not determined from this experiment.
- In 2001 run on ^{10}B target, the upper level is seen following $^{10}_{\Lambda}\mathrm{B} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + p$ enabling us to deduce $J^\pi = 3/2^+$ for the upper member of the doublet.

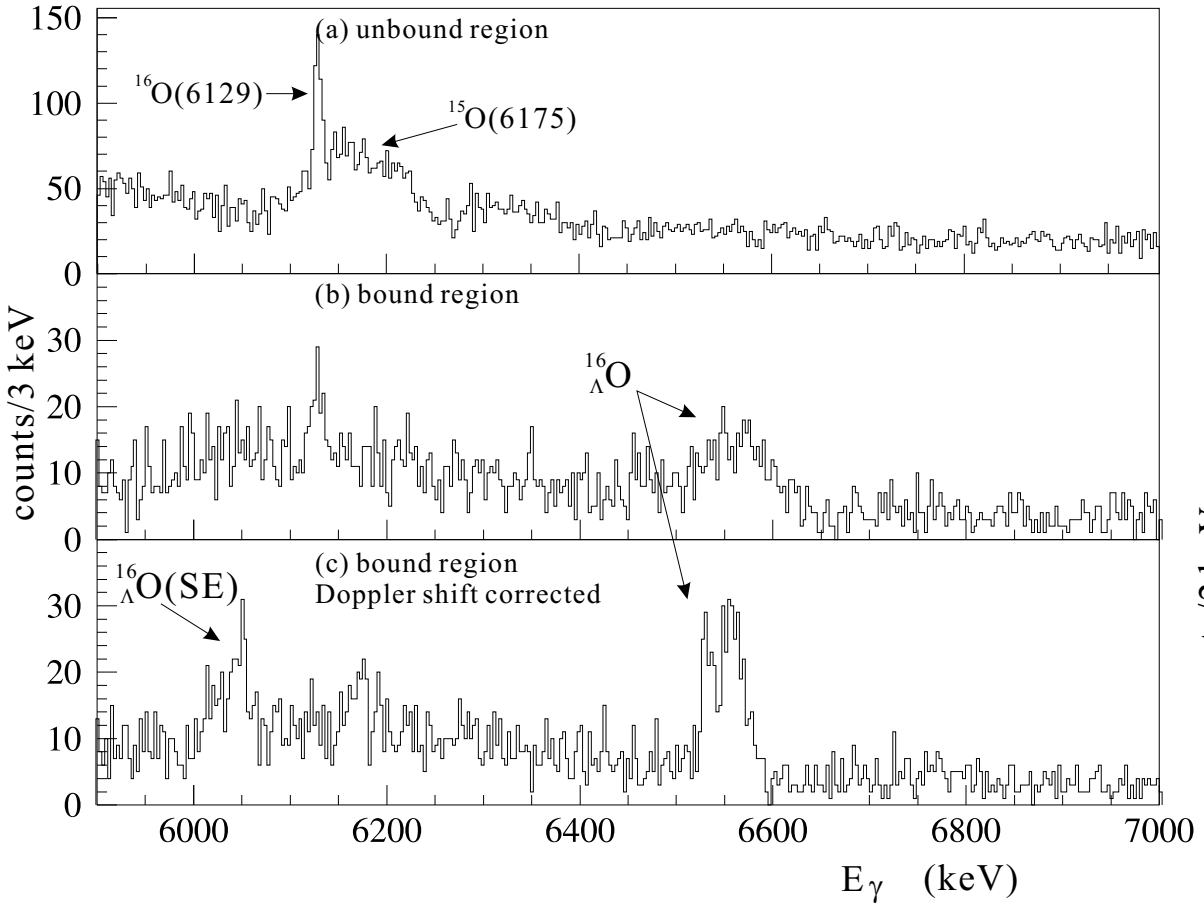
Tensor Interaction

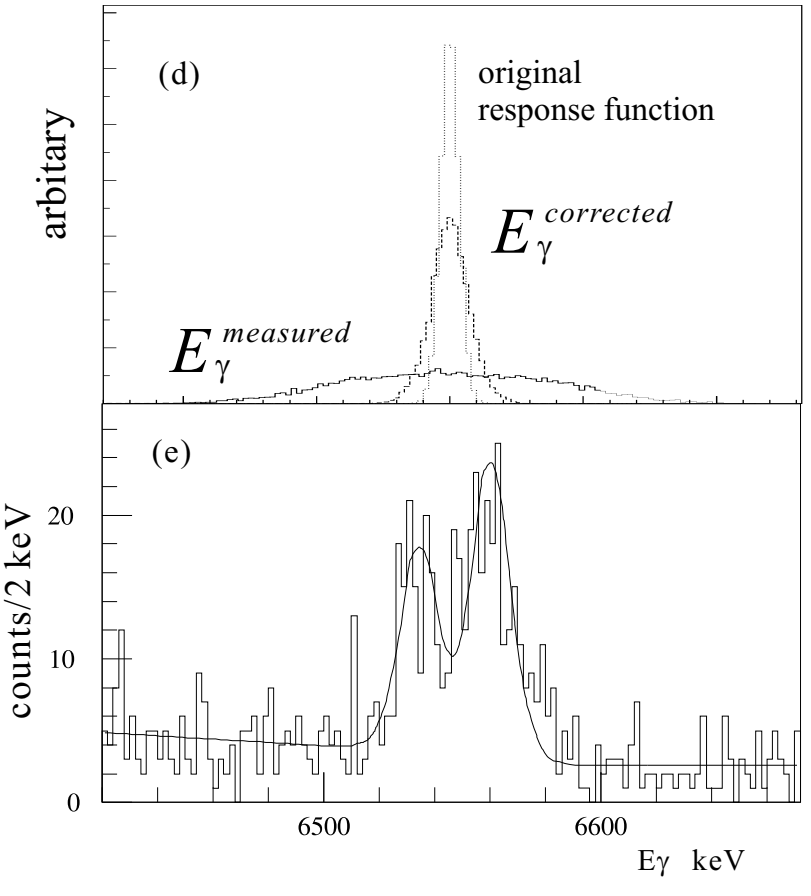
For pure $p_{1/2}^{-1}s_\Lambda$, the combination of parameters governing the doublet splitting is

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



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



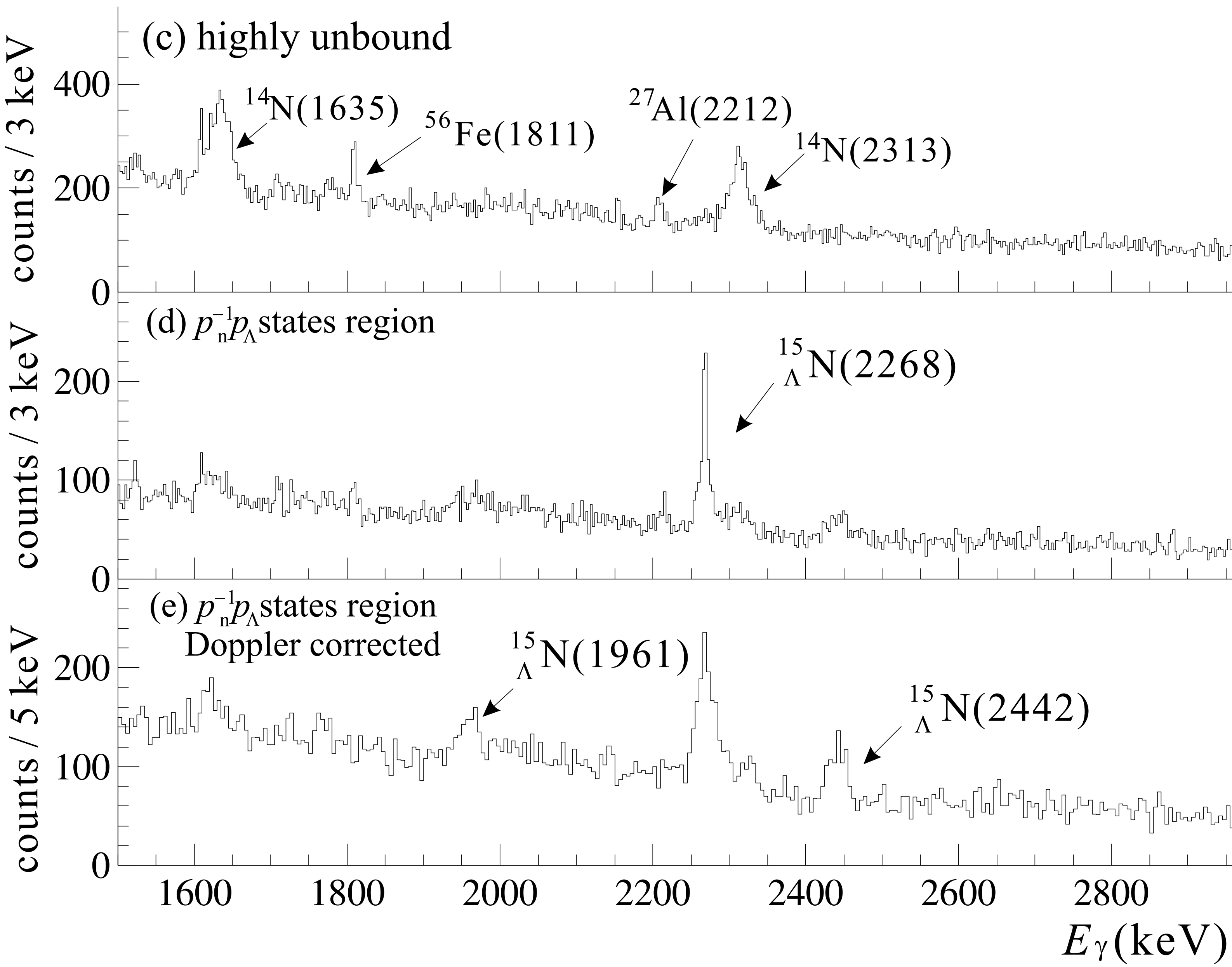


M. Ukai *et al.* – Phys. Rev. Lett. 93 (2004) 232501

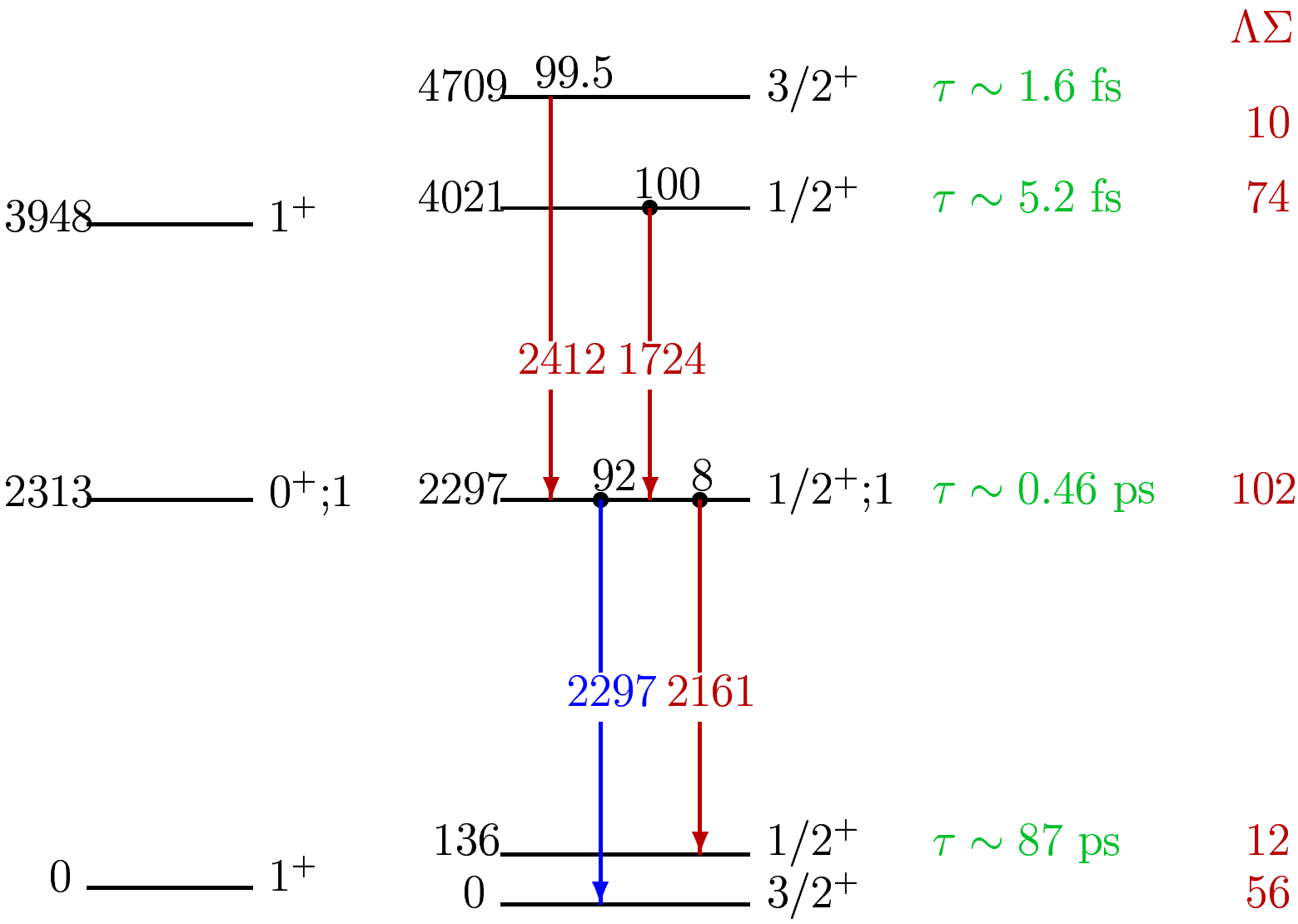
$$E(1_2^- - 0_1^-) = 6561.7 \pm 1.1 \pm 1.7 \text{ keV} \quad (183 \pm 15 \pm 5 \text{ counts})$$

$$E(1_2^- - 1_1^-) = 6535.3 \pm 1.2 \pm 1.7 \text{ keV} \quad (127 \pm 15 \pm 5 \text{ counts})$$

$$\Delta E = 26.4 \pm 1.6 \pm 0.5 \text{ keV}$$


(c) highly unbound
counts / 3 keV
^{14}N(1635)
^{56}Fe(1811)
^{27}Al(2212)
^{14}N(2313)
(d) $p_n^{-1}p_\Lambda$ states region
counts / 3 keV
$^{15}_{\Lambda}$N(2268)
(e) $p_n^{-1}p_\Lambda$ states region
Doppler corrected
counts / 5 keV
$^{15}_{\Lambda}$N(1961)
$^{15}_{\Lambda}$N(2442)
0
100
200
400
1600
1800
2000
2200
2400
2600
2800
E_γ(keV)

$^{15}_{\Lambda}$N γ rays – Hyperball, BNL E930 ('01)

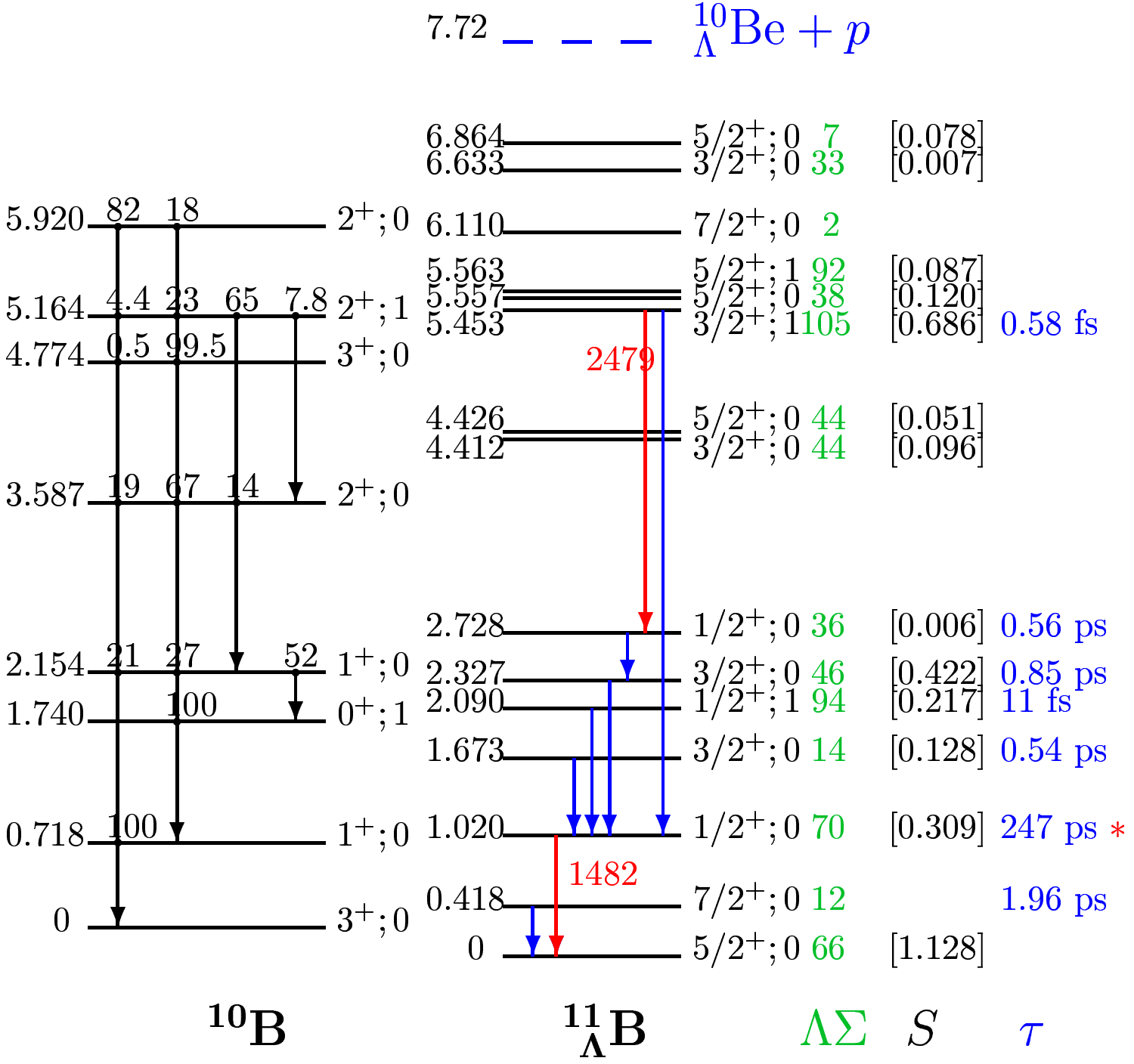


Energy spacings in ${}^{15}_{\Lambda}$N and ${}^{16}_{\Lambda}$O

Energy contributions are in keV $\quad \Delta E = \Delta E_C + \Delta E_{\Lambda N}$

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

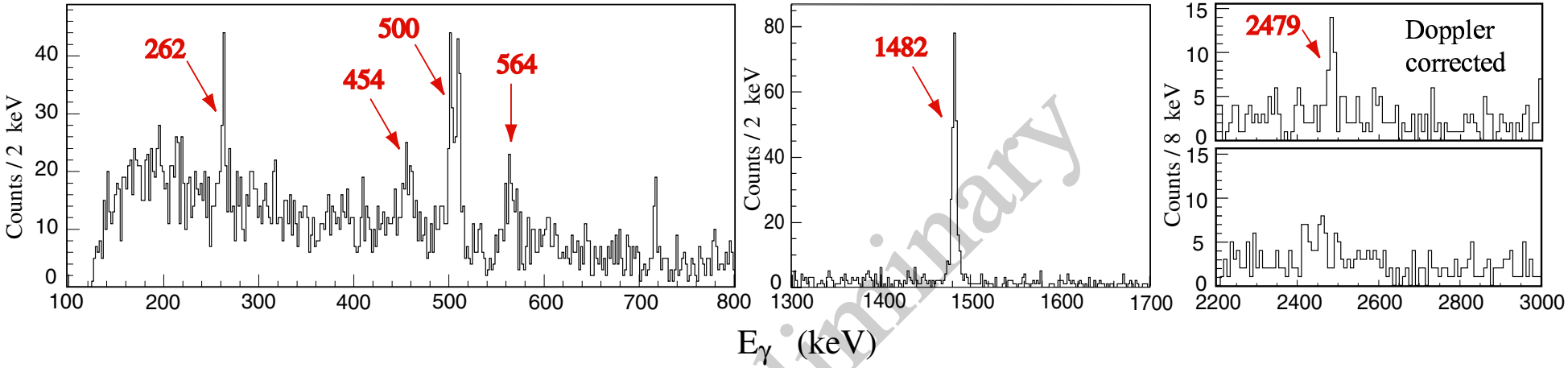
$J_i^\pi - J_f^\pi$	ΔE_C	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE
$1^- - 0^-$			−0.382	1.378	−0.004	7.850	
${}^{16}_{\Lambda}$O	0	−30	−179	−15	1	235	28
$1/2^+ - 3/2^+$			0.760	−2.254	0.031	−8.980	
${}^{15}_{\Lambda}$N	0	42	356	25	−11	−269	136
$1^-_2 - 1^-_1$			−0.234	−1.257	−1.496	−0.708	
${}^{16}_{\Lambda}$O	6176	−30	−110	14	530	−21	6526
$1/2^+; 1 - 3/2^+$			0.276	−0.771	0.019	−2.963	
${}^{15}_{\Lambda}$N	2313	−50	129	8	−7	−89	2297


7.72
$^{10}_{\Lambda}$Be + p
6.864 5/2+;0 7 [0.078]
6.633 3/2+;0 33 [0.007]
6.110 7/2+;0 2
5.563 5/2+;1 92 [0.087]
5.557 5/2+;0 38 [0.120]
5.453 3/2+;1 105 [0.686] 0.58 fs
2479
4.426 5/2+;0 44 [0.051]
4.412 3/2+;0 44 [0.096]
2.728 1/2+;0 36 [0.006] 0.56 ps
2.327 3/2+;0 46 [0.422] 0.85 ps
2.090 1/2+;1 94 [0.217] 11 fs
1.673 3/2+;0 14 [0.128] 0.54 ps
1.020 1/2+;0 70 [0.309] 247 ps *
1482
0.418 7/2+;0 12 1.96 ps
0 5/2+;0 66 [1.128]
5.920 82 18 2+;0
5.164 4.4 23 65 7.8 2+;1
4.774 0.5 99.5 3+;0
3.587 19 67 14 2+;0
2.154 21 27 52 1+;0
1.740 100 0+;1
0.718 100 1+;0
0 3+;0
^{10}B
$^{11}_{\Lambda}$B
ΛΣ
S
τ

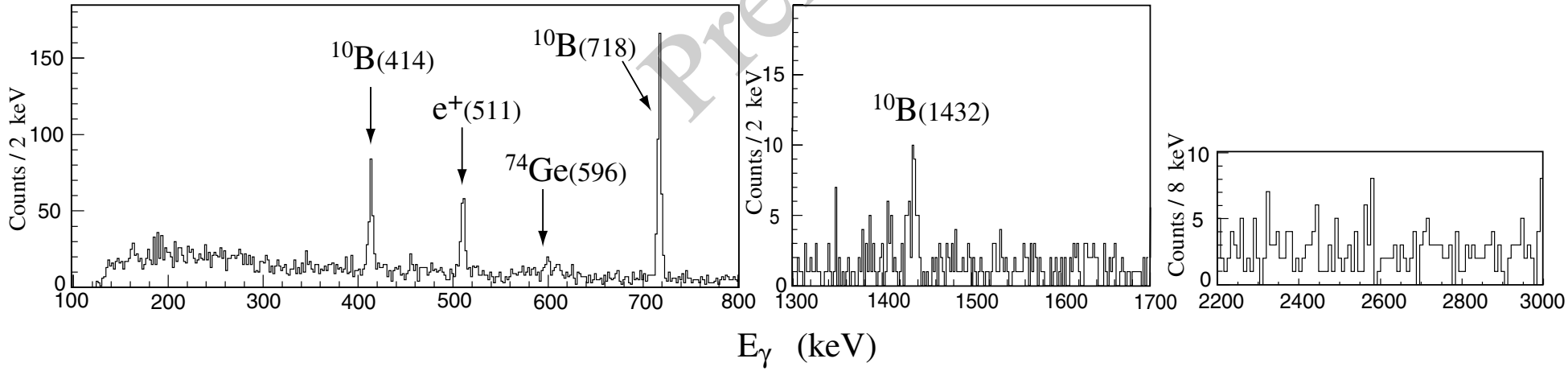
KEK E518 ^{11}B (π^+,$K^+\gamma$) $^{11}_{\Lambda}$B

Bound region (-20 < -B_Λ < -2 MeV)

Six γ rays from $^{11}_{\Lambda}$B



Highly Unbund region (-B_Λ > 20 MeV)



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