E01-011 Analysis status
Mass and cross section evaluation
Comments on physics interpretation

Based on Ph.D presentation of A. Matsumura

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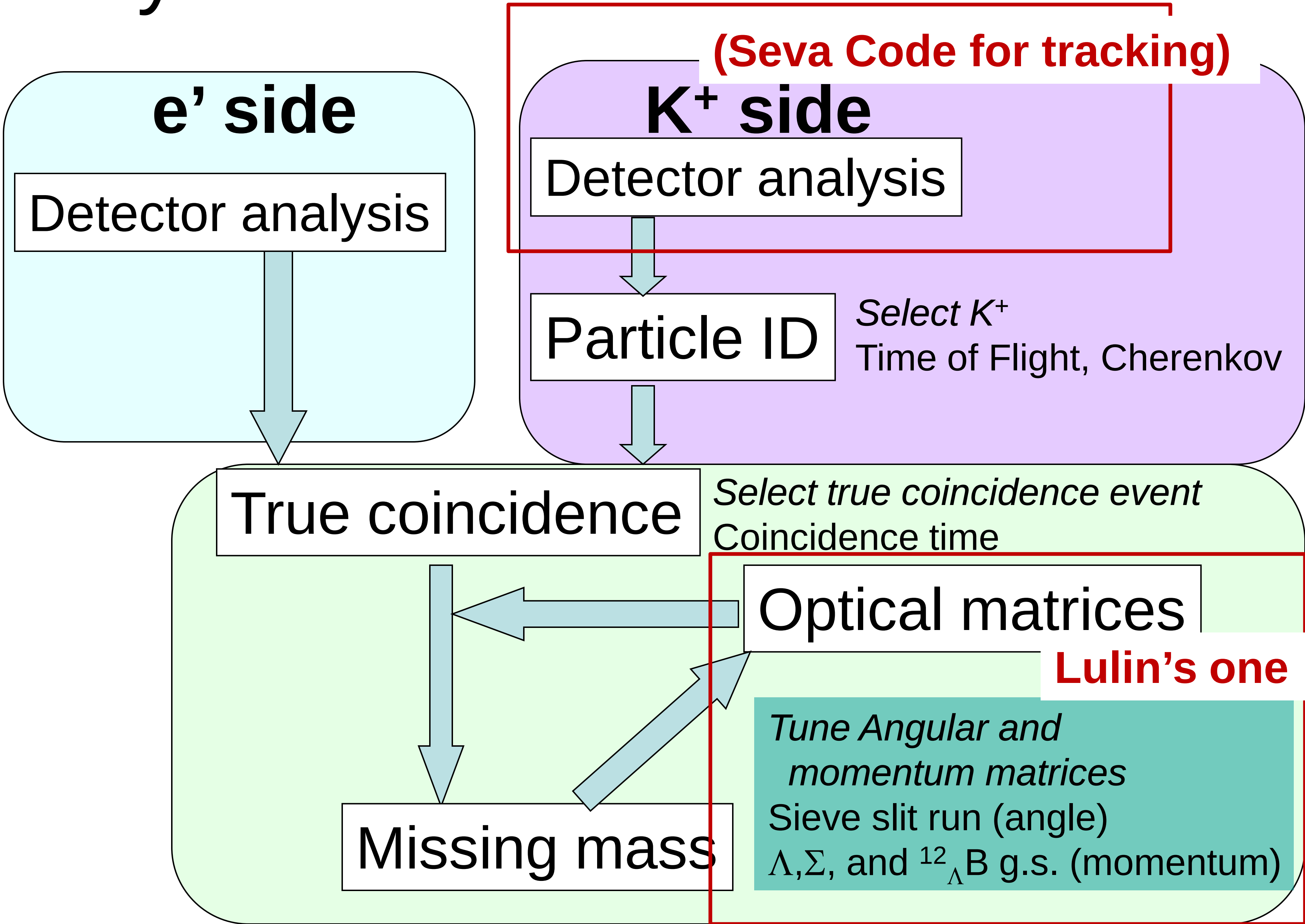
HKS-HES collaboration meeting at JLab, March 10-11, 2010

Analysis flowchart



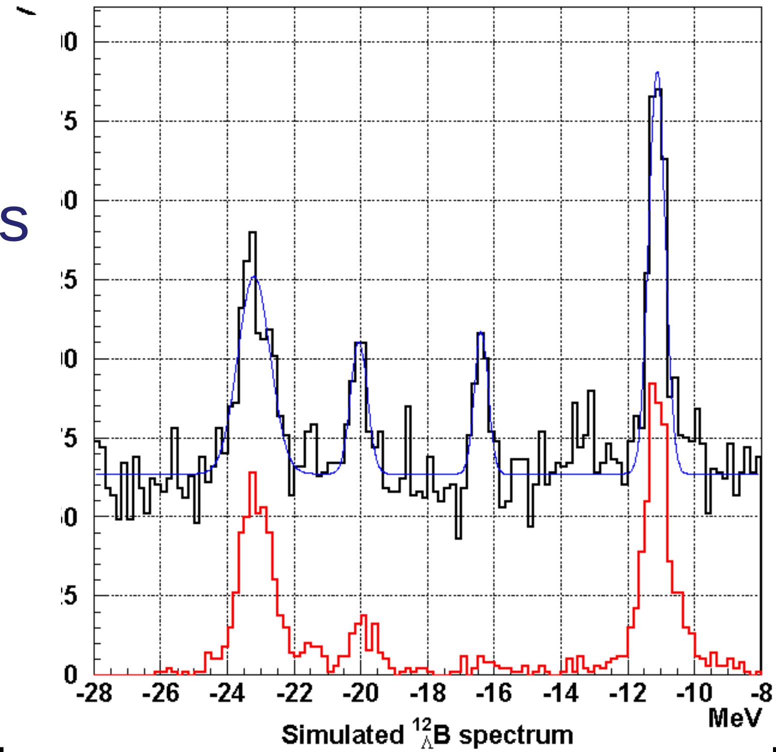
Major procedures to evaluate mass and cross sections

- Systematic error estimation using blind analysis
- Mixed event analysis to obtain high-statistics accidental coincidence spectrum
- Efficiency evaluation to derive cross section

Black: All events

Red: Events generated as "$^{12}_{\Lambda}B$"

Blue: Fitting results with 4 gaussians

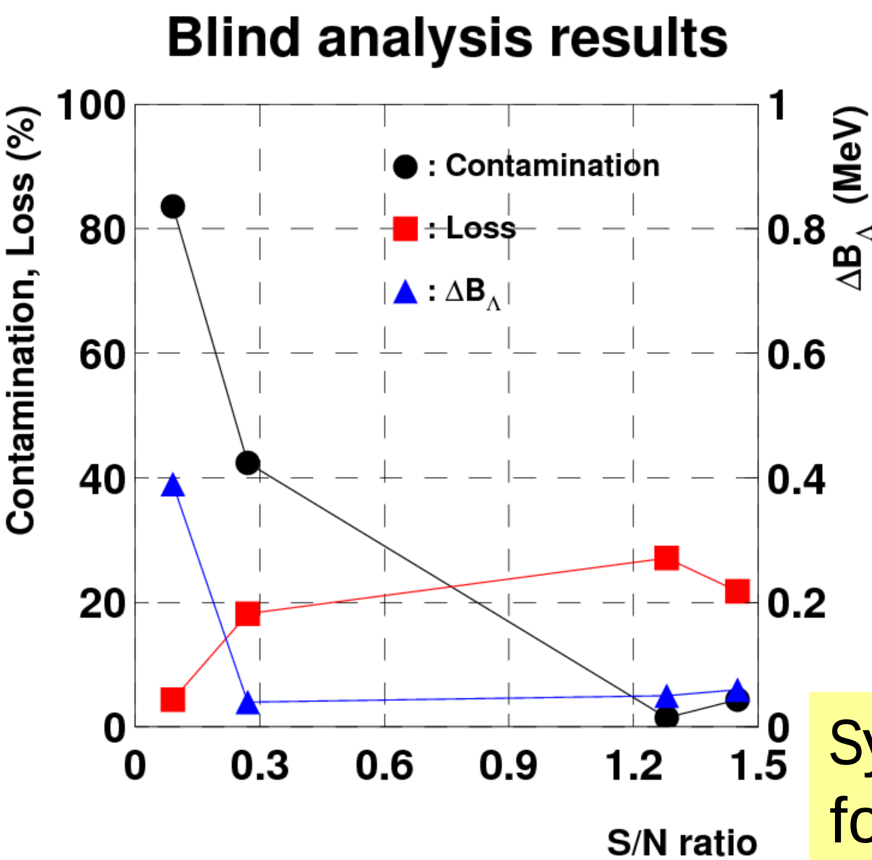


Blind analysis result			Assumed in simulation		
Binding energy [MeV]	Yield [counts]	Contamination [%]	Binding energy [MeV]	Yield [counts]	S/N
11.43 (g.s.)	~491	4.4	11.37 (g.s.)	600	1.45
16.70	~191	83.6	16.31	30	0.09
20.35	~142	42.4	20.31	100	0.27
23.32	~407	1.5	23.37	550	1.28

ΔB_{Λ}

Loss

Simulated data blind analysis result



Contamination : Ratio of misidentified event (negative side)

Loss : Ratio of lost event (positive side)

ΔB_Λ : binding energy difference

Systematic error ….

for major peaks (S/N > 1),

Accuracy of binding energy < 100 keV

cross section < +30%, -5%

Mass difference in blind analysis

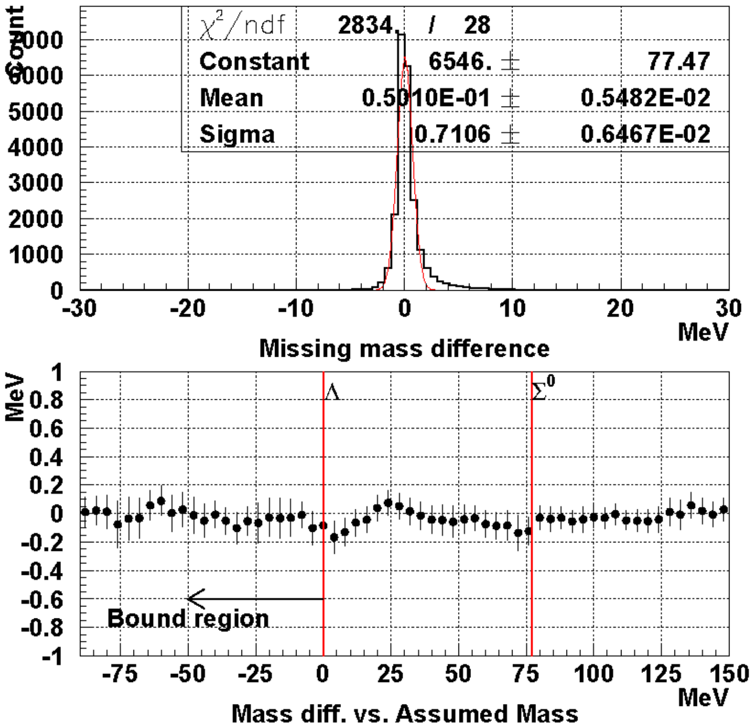
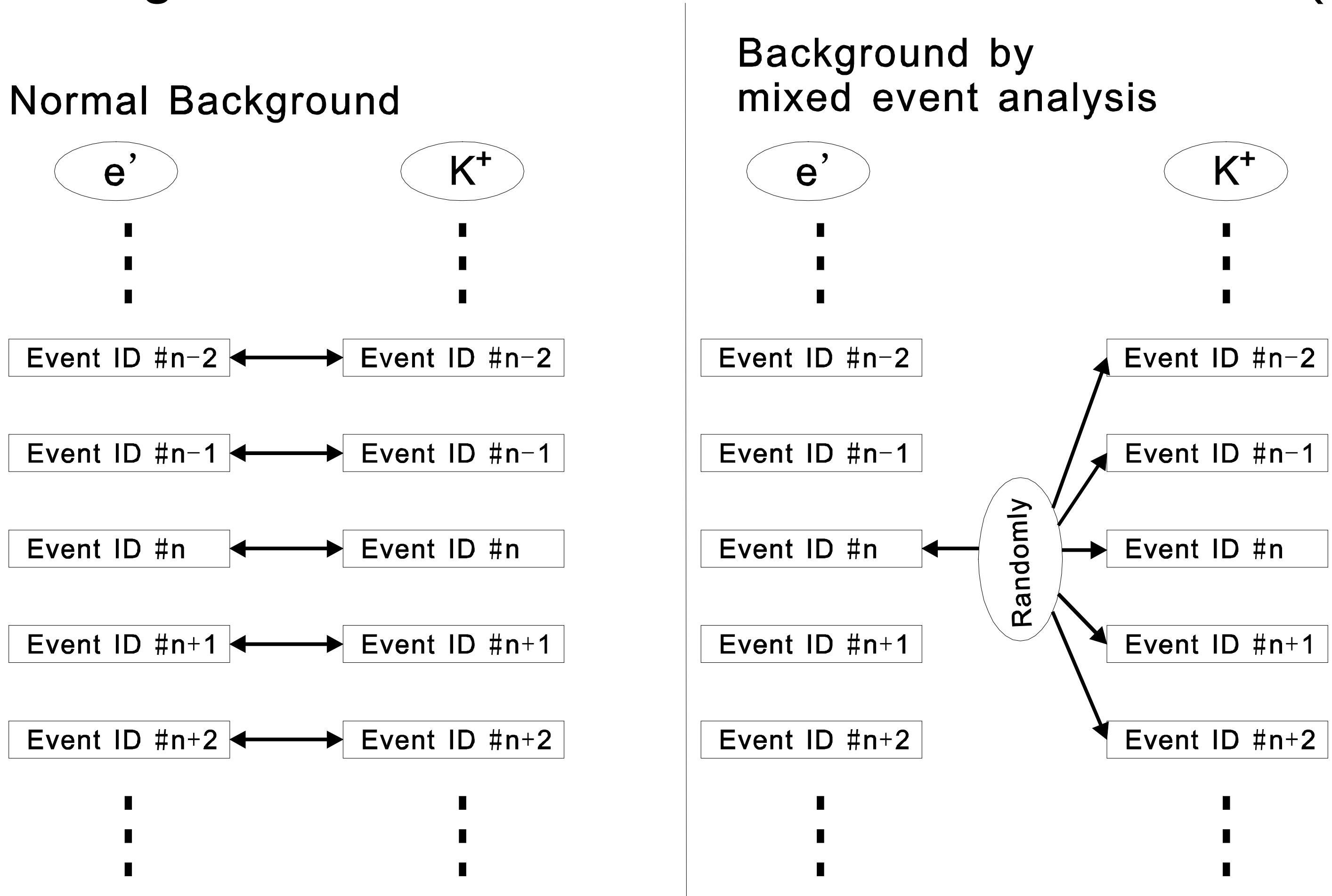


Figure 4.24: Top shows Mass difference between Blind analysis results and assumed values all over the acceptance. Bottom represents mass difference as a function of missng mass scale. Dots and errors represent the mean and sigma values of gaussian fitting, respectively.

Δm < 100 keV over entire mass region

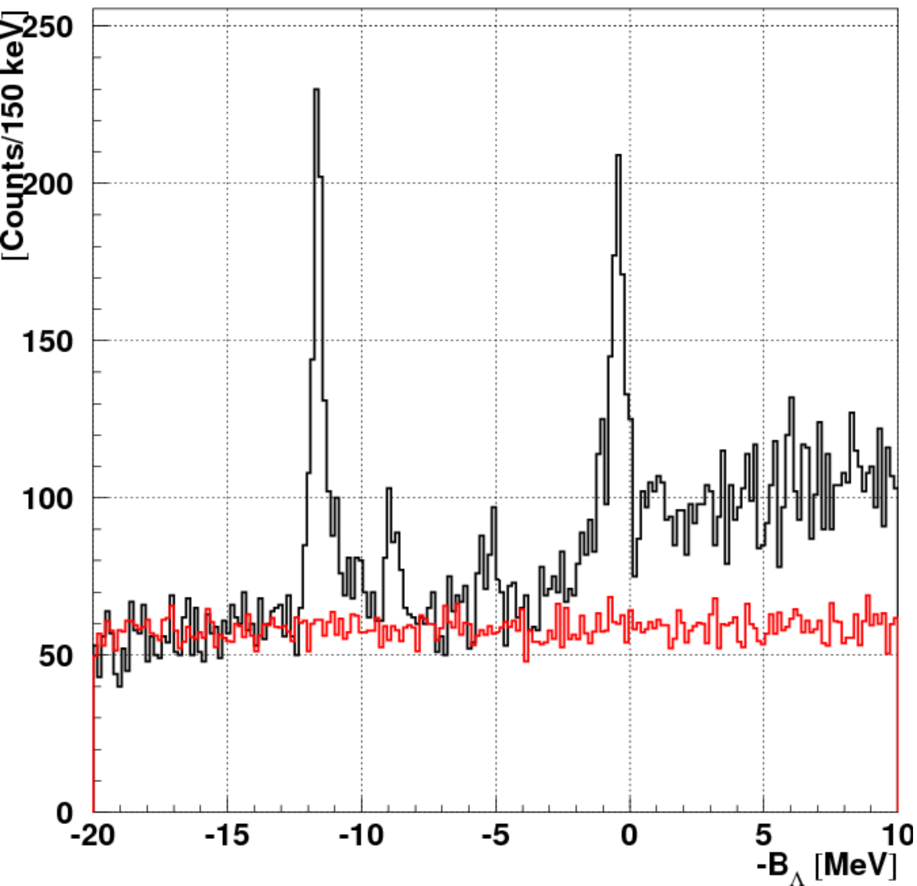
Background estimation by mixed event analysis

- Background : accidental coincidence between e' and K^+
- Mixed background → random combination of real data (off gate)

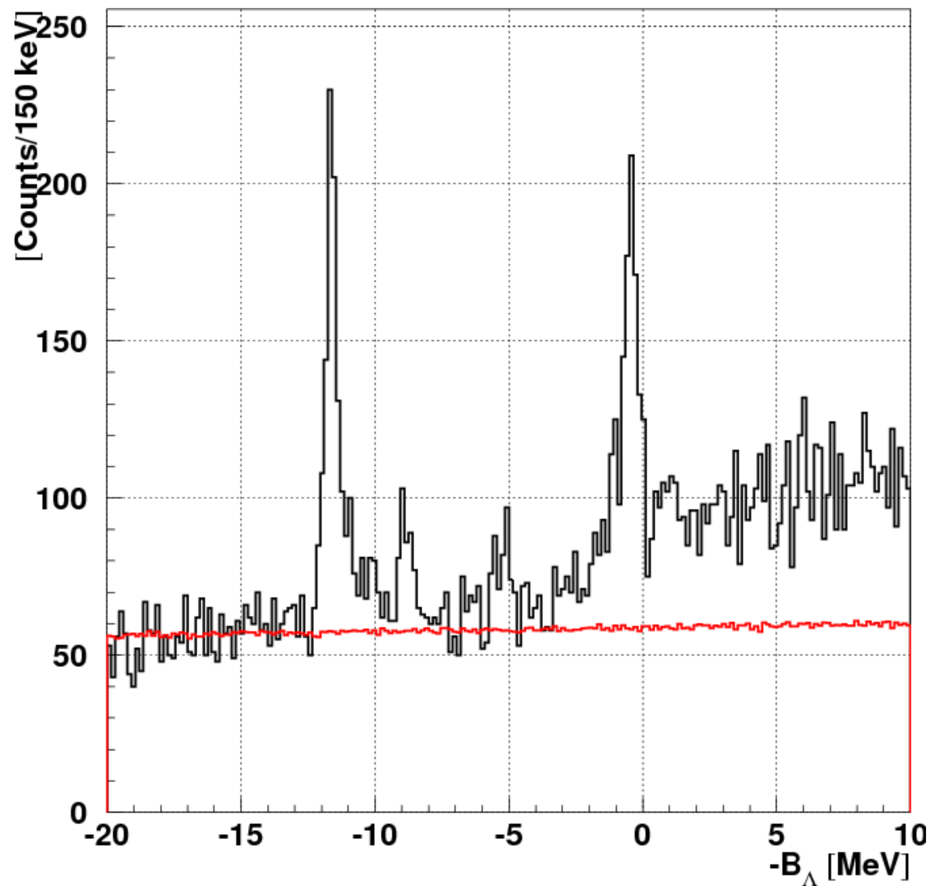


Background estimation by mixed event analysis

Normal background



Mixed event analysis



Efficiencies for cross section estimation

Cross section of the (γ^*, K^+):

$$\overline{\left(\frac{d\sigma}{d\Omega}\right)} = \frac{1}{N_T}\frac{1}{N_\gamma}\sum_{i=1}^{N_K}\frac{1}{\varepsilon_{total}\, d\Omega}$$

N_T : # of target

N_γ: # of V.P.

$d\Omega$: solid angle acceptance of HKS

N_K : yield of Λ, Σ^0, or hypernuclear state

$$\varepsilon_{total} = \varepsilon_{htrk} \cdot \varepsilon_{AC} \cdot \varepsilon_{WC} \cdot \varepsilon_{bk} \cdot f_{abs} \cdot f_{decay} \cdot \varepsilon_{etrk} \cdot f_{comp}$$

ε_htrk: ~ 0.96
  HKS tracking efficiency
ε_AC: ~0.96
  AC cut efficiency
ε_WC: ~0.95
  WC cut efficiency
ε_bk: ~0.98
  beta cut efficiency
ε_etrk: ~0.88
  ENGE tracking efficiency
f abs: ~0.82
  Kaon absorption factor
f decay: ~0.35
  Kaon decay factor
f comp: ~0.97
  Computer dead time factor

Systematic error [%]

Target	Thickness	N_γ	$d\Omega$	ε_{total}	*Tune (S/N>1)*		Total
7Li	5	22	1	3	+30, -5		+38, -23
12C	2						+37, -23
28Si	5						+38, -23

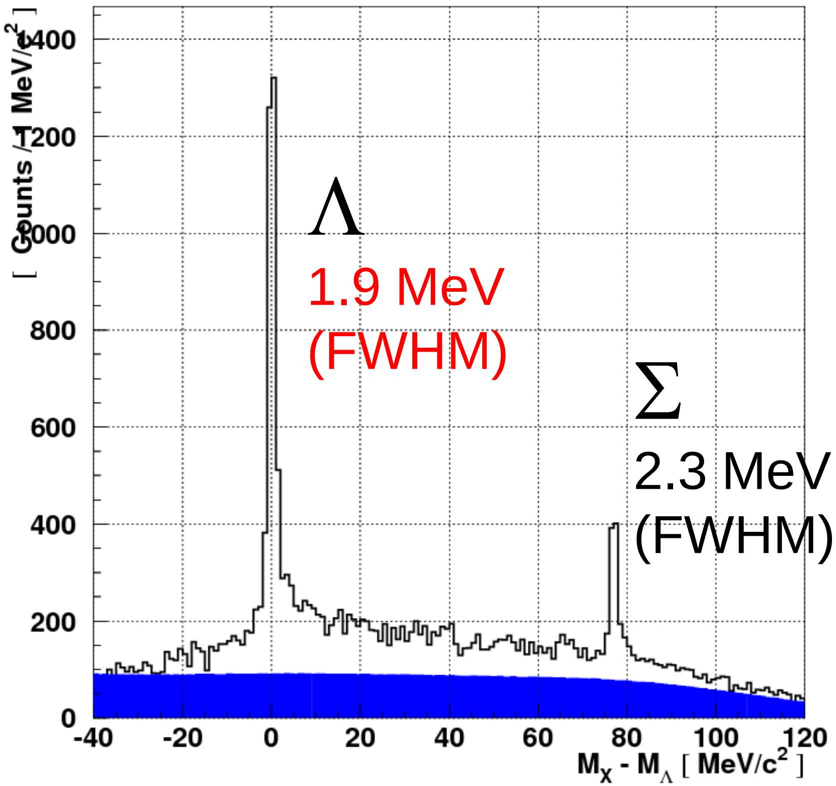
5. Result & Discussion

Λ and Σ spectra (CH2 target)

E01-011

~70 hours

($450\ mg/cm^2$, 1.5 uA)

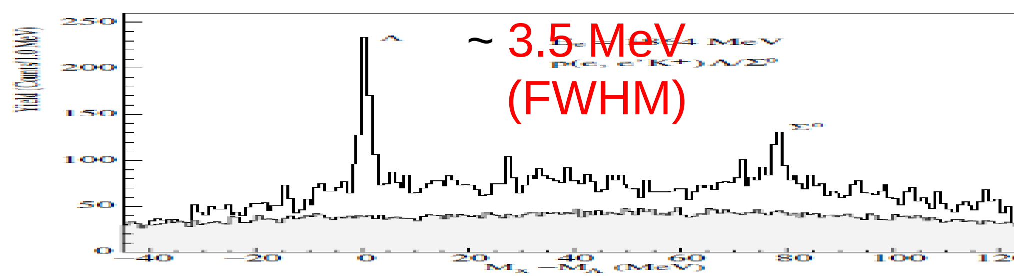


c.f. E89-009, 183 hours

($8.8\ mg/cm^2$, 0.5 or 1.0 uA)

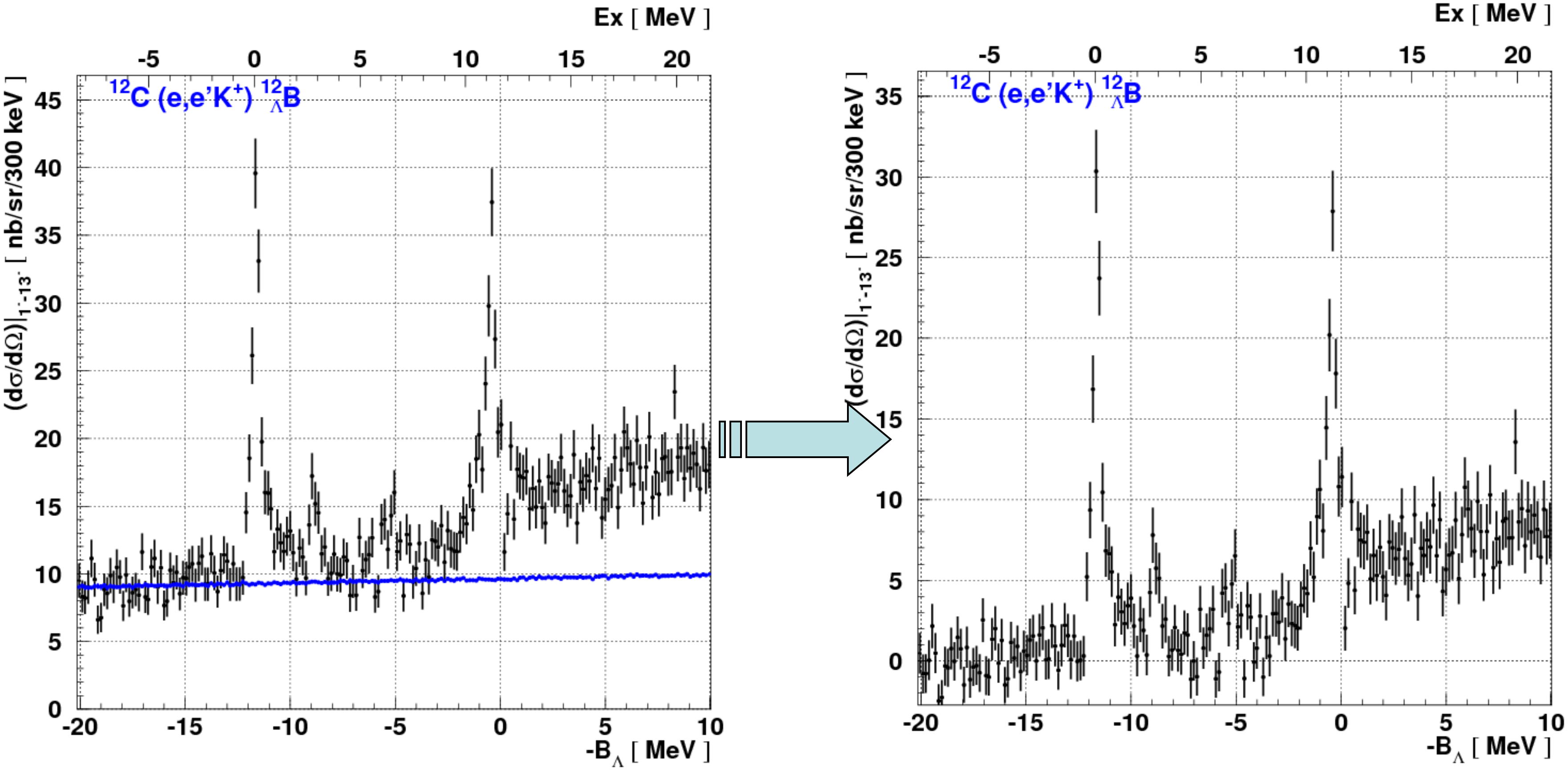
T. Miyoshi *et al.*,

Phy. Rev. Lett. **90**, 232502(2003)

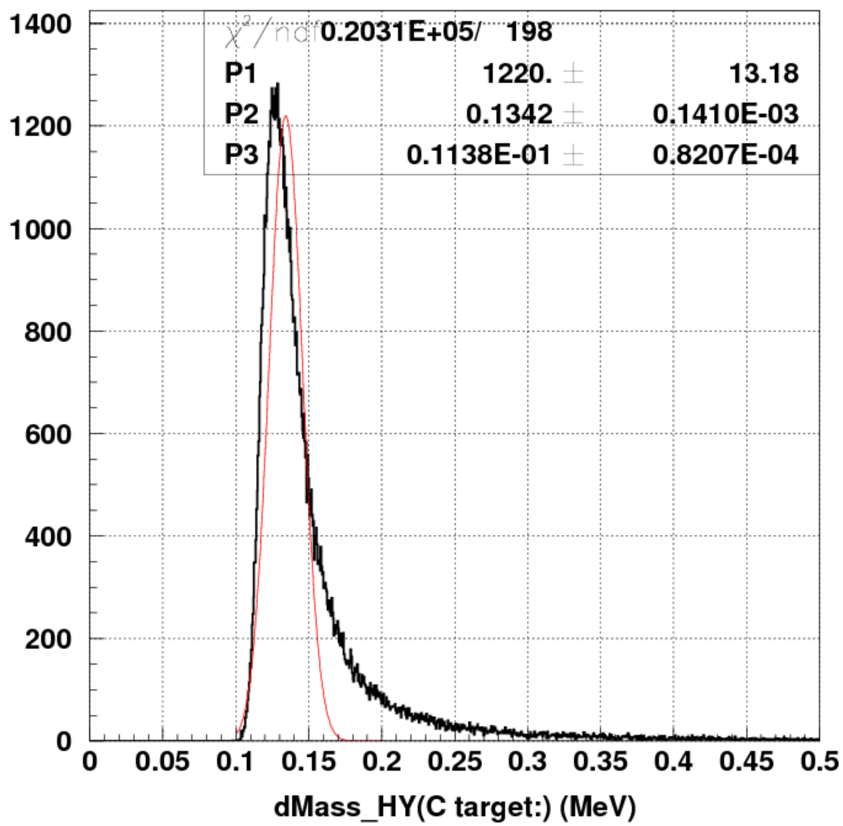


Better resolution and statistics

Background subtraction



Accidental background : polynomial function



GEANT4

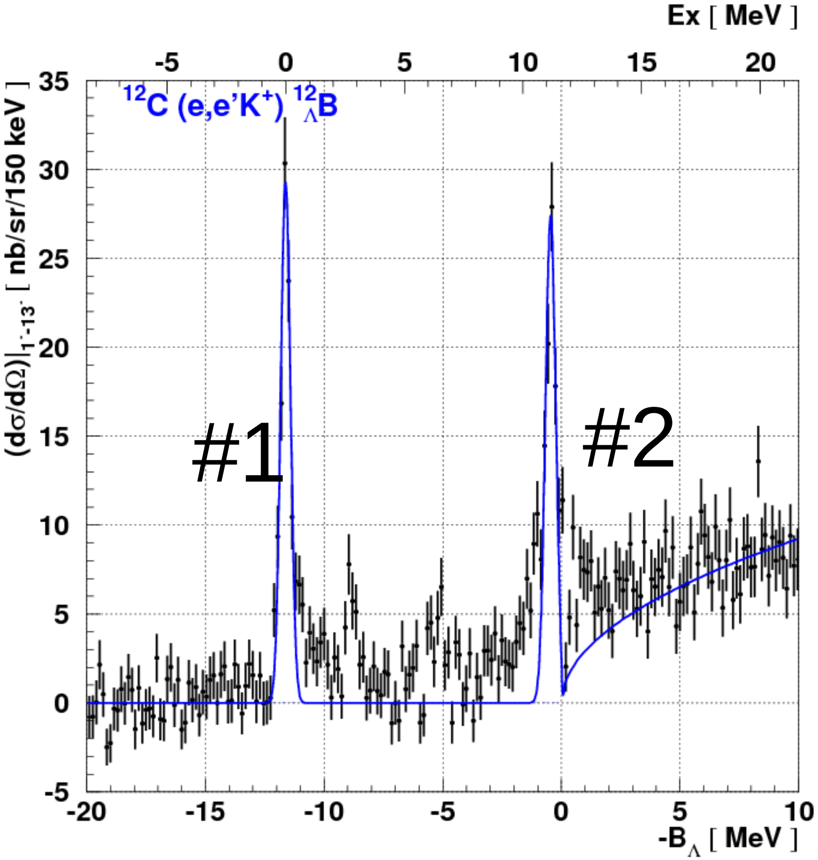
^{12}C 100 mg/cm^2

Effect of simple gaussian fit:

Δ= +20 keV

count difference : -30 %

$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$



Two major peaks

#1 : $[(p_{3/2})^{-1}{}_{p},(s_{1/2})_{\Lambda}]$

#2 : $[(p_{3/2})^{-1}{}_{p},(p_{3/2},p_{1/2})_{\Lambda}]$

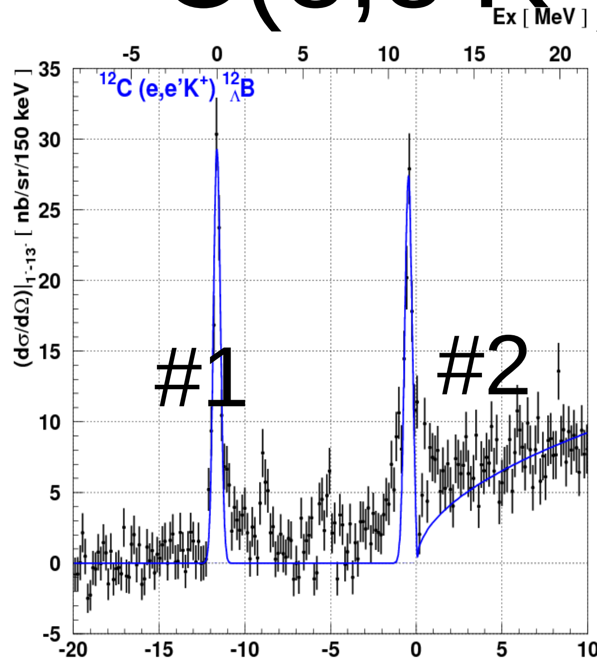
Resolution : ~470 keV (FWHM) for g.s.

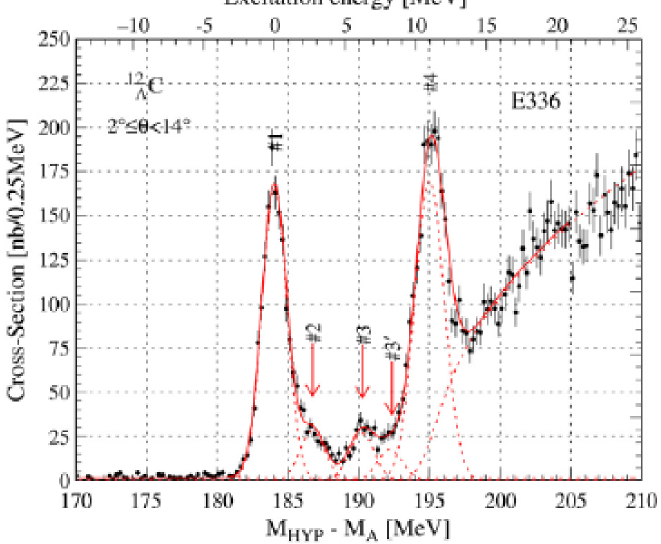
Data taking : ~30 hours w/ 30 μA

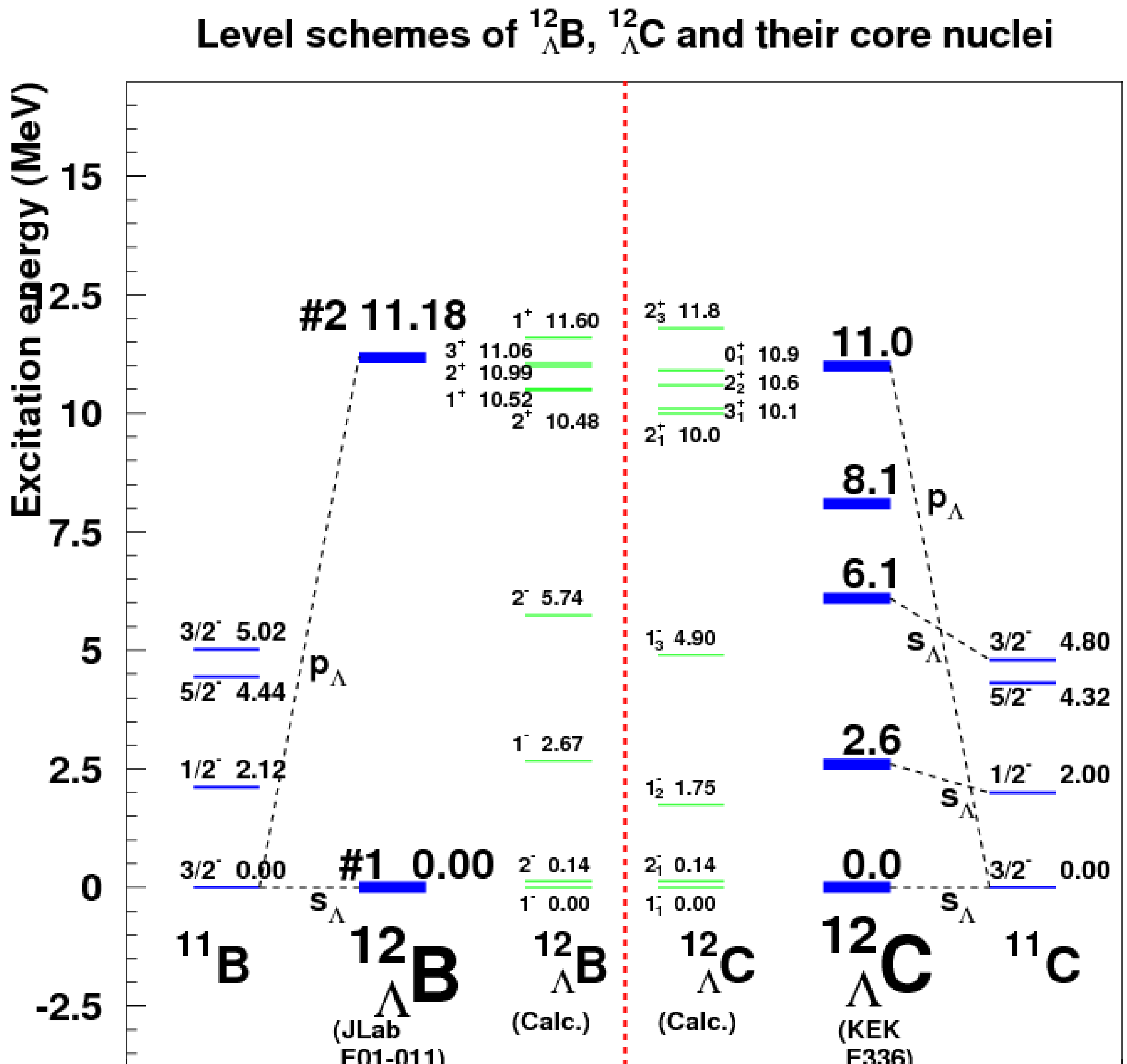
Fitting Result

Peak No.	$-B_{\Lambda}$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	Ex [MeV] $\pm$ (stat.) $\pm$ (sys.)	FWHM [MeV]	$\overline{(d\sigma/d\Omega)}|_{1^\circ-13^\circ}$ [nb/sr] $\pm$ (stat.) $\pm$ (sys.)	
# 1	$-11.63 \pm 0.01 \pm 0.10$	0	0.47 ± 0.07	$97 \pm 3.9\ ^{+22}_{-25}$	(126)
# 2	$-0.45 \pm 0.01 \pm 0.10$	$11.18 \pm 0.01 \pm 0.10$	0.51 ± 0.07	$100 \pm 3.8\ ^{+30}_{-30}$	(130)

$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$, $^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$

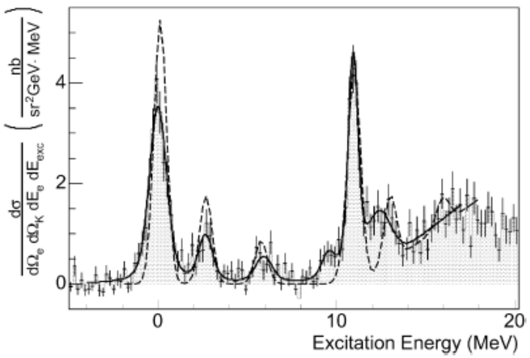






$^{12}C(e,e'K^+)^{12}_{\Lambda}B$

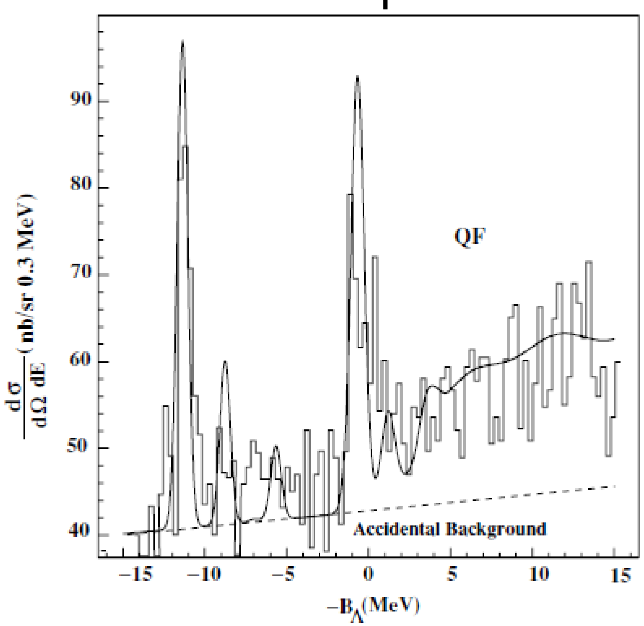
Hall-A spectrum

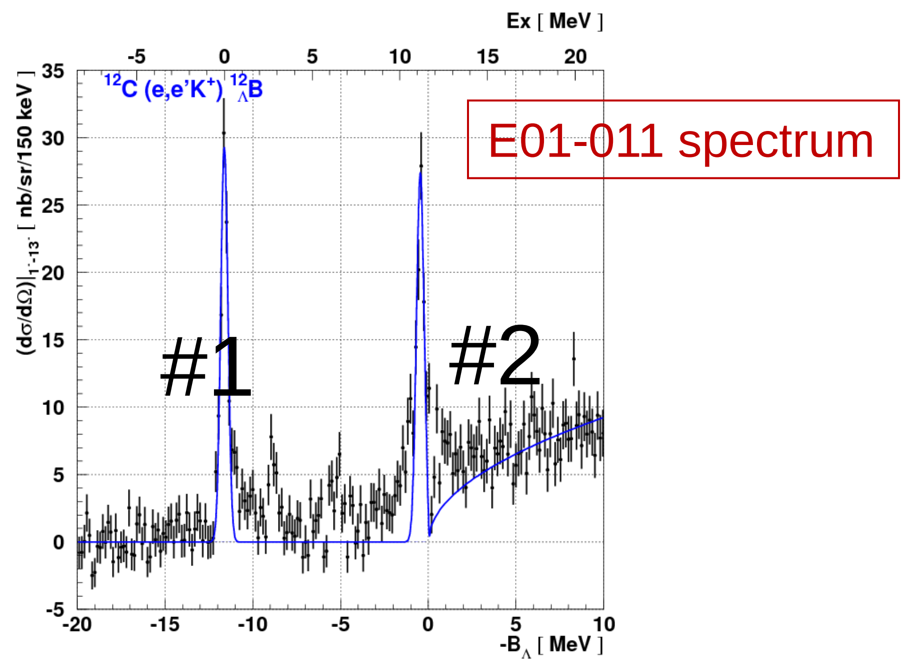


	s_Λ		p_Λ	
Experiment	$Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	Width [MeV] $\pm$ (stat.)	$Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	Width [MeV] $\pm$ (stat.)
E01-011	0 $(-11.63 \pm 0.01 \pm 0.10)$	0.47 ± 0.07	$11.18 \pm 0.01 \pm 0.10$ $(-0.45 \pm 0.01 \pm 0.10)$	0.51 ± 0.07
E89-009 [27, 28, 59]	0 (-11.52 ± 0.35)	0.75	(-0.49 ± 0.16)	N/A
E94-107 [58]	0	1.15 ± 0.18	10.93 ± 0.03	0.67 ± 0.15

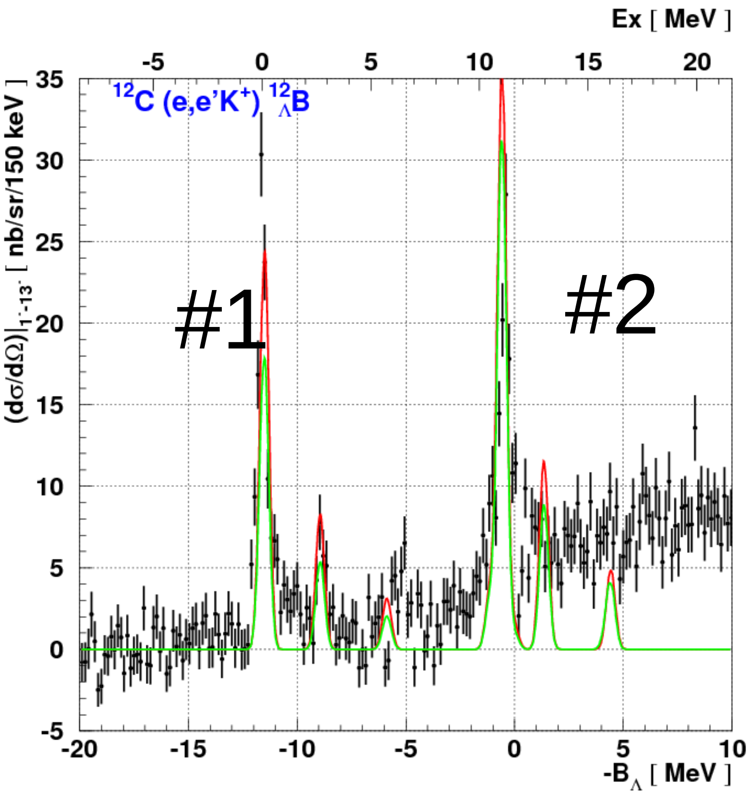
Table 5.4: Comparison of excitation energies and widths of $^{12}_{\Lambda}B$.

E89-009 spectrum





$^{12}C(e,e'K^+)^{12}{}_\Lambda B$



Red : calculation with SLA
Green : calculation with KMAID

Theory by Sotona *et. al.*
($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

J^π	Ex [MeV]	Cross section [nb/sr]	
		SLA	KMAID
1^-	0	19.7	20.7
2^-	0.14	65.7	43.0
2^+	10.99	48.3	38.0
3^+	11.06	75.3	68.5

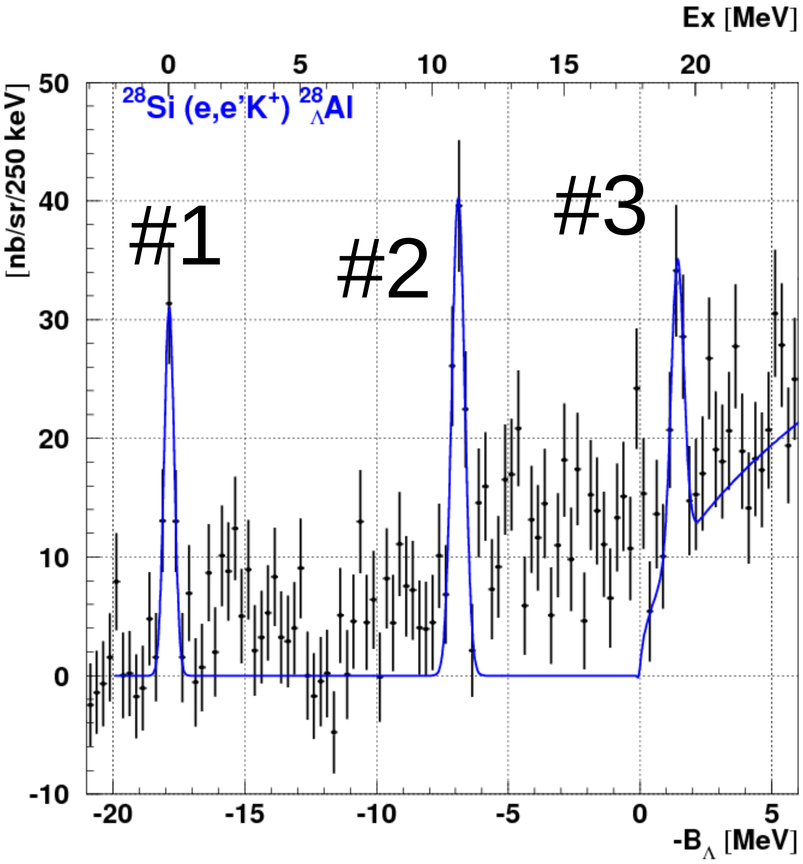
Result

ID	Ex [MeV]	Cross section [nb/sr]	Cross section (Calc., SLA) [nb/sr]	
#1	0	97 ± 3.9 (*stat.*) +29,-22 (*sys.*)	85.4 ($1^- + 2^-$)	(126)
#2	11.18 ± 0.01 (*stat.*) ±0.10 (*sys.*)	100 ± 3.8 (*stat.*) +30, -30 (*sys.*)	123.6 ($2^+ + 3^+$)	(130)

$^{12}C(e,e'K^{+})^{12}{}_{\Lambda}B$

- Two major peaks ; #1:$[(p_{3/2})^{-1}{}_{p},(s_{1/2})_{\Lambda}]$,
  #2:$[(p_{3/2})^{-1}{}_{p},(p_{3/2},p_{1/2})_{\Lambda}]$
  - Consistent $-B_{\Lambda}$ with previous exp.
  - Different width for g.s. with E94-107 data
  - Ex and cross sections : agree with shell model calculation
- Best resolution of 470 keV (FWHM) for g.s.

$^{28}Si(e,e'K^+)^{28}{}_{\Lambda}Al$



Three major peaks

#1 : $[(d_{5/2})^{-1}_p,(s_{1/2})_{\Lambda}]$

#2 : $[(d_{5/2})^{-1}_p,(p_{3/2},p_{1/2})_{\Lambda}]$

#3 : $[(d_{5/2})^{-1}_p,(d_{5/2},d_{3/2})_{\Lambda}]$

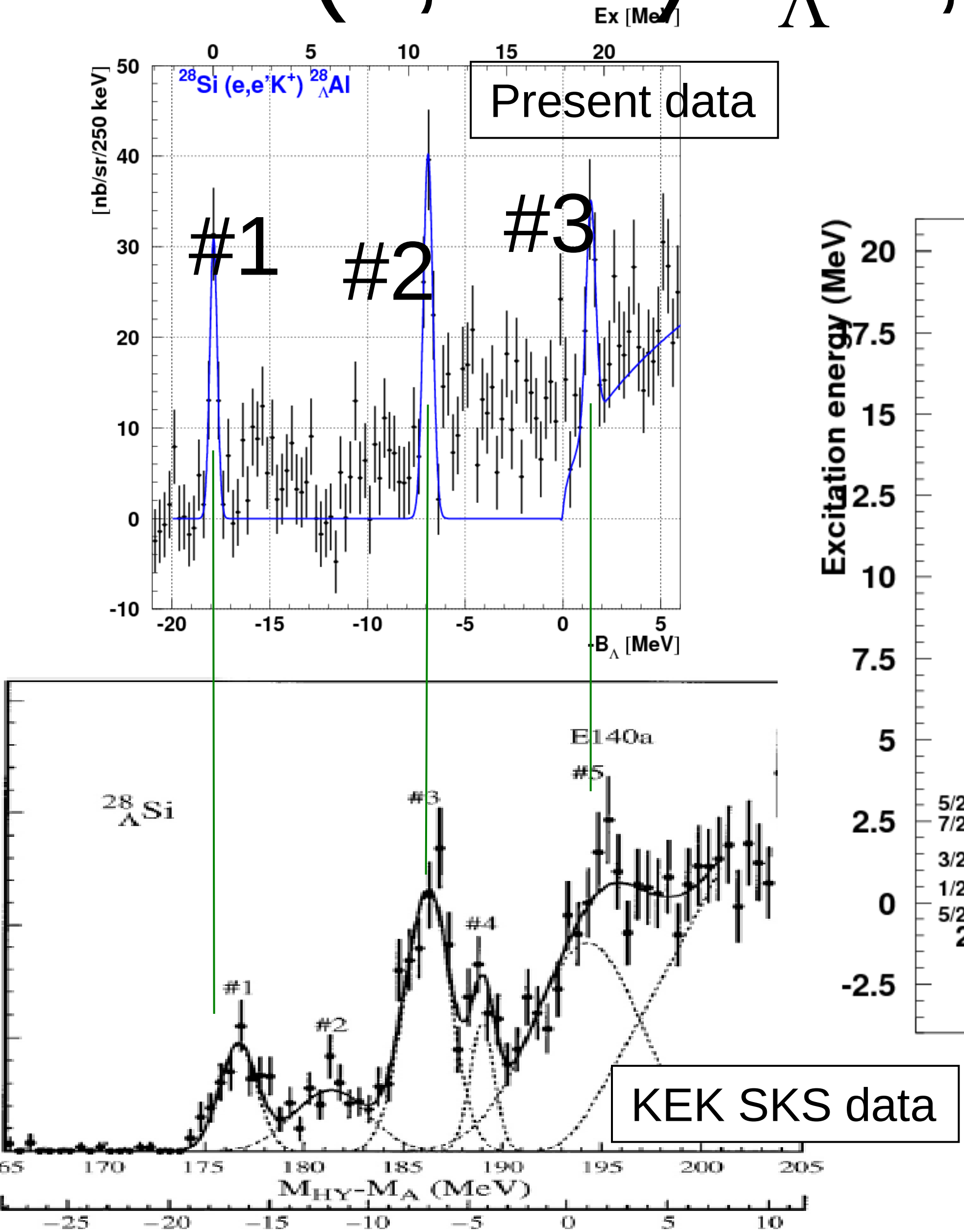
Resolution : ~450 keV (FWHM) for g.s.

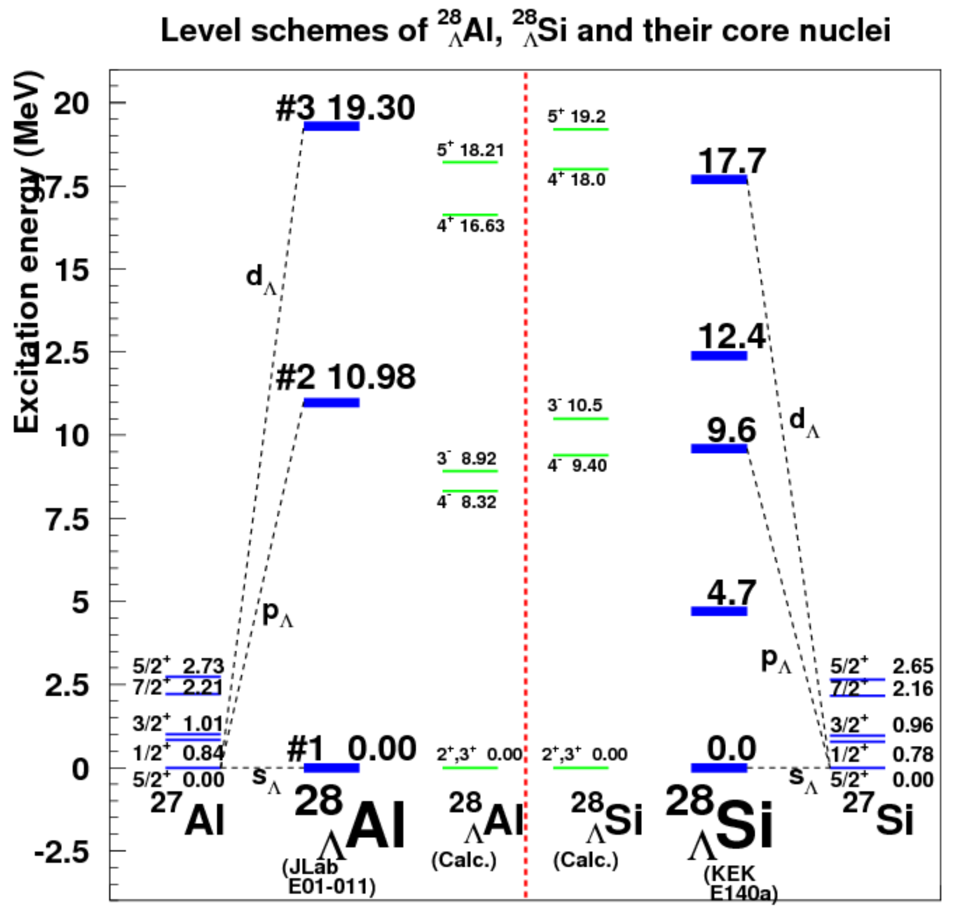
Data taking : ~30 hours w/ 30 μA

Fitting Result

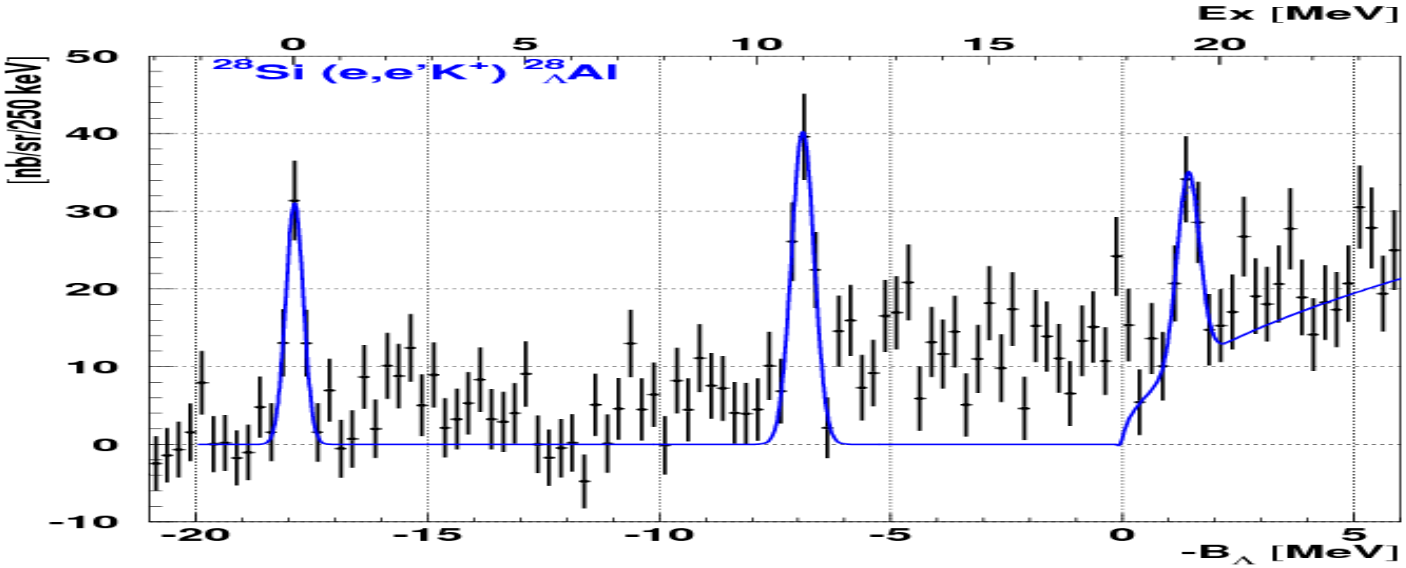
Peak No.	$-B_\Lambda$ [MeV] ± (stat.) ± (sys.)	Ex [MeV] ± (stat.) ± (sys.)	FWHM [MeV]	$\overline{(d\sigma/d\Omega)}\|_{1^\circ-13^\circ}$ [nb/sr] ± (stat.) ± (sys.)	
# 1	−17.88 ± 0.02 ± 0.30	0	0.45 ± 0.07	$60 \pm 5.0\ ^{+27}_{-18}$	(78)
# 2	−6.90 ± 0.02 ± 0.30	10.98 ± 0.02 ± 0.30	0.55 ± 0.07	$94 \pm 6.0\ ^{+43}_{-28}$	(122)
# 3	1.42 ± 0.03 ± 0.30	19.30 ± 0.03 ± 0.30	0.56 ± 0.07	$59 \pm 6.7\ ^{+55}_{-18}$	(77)

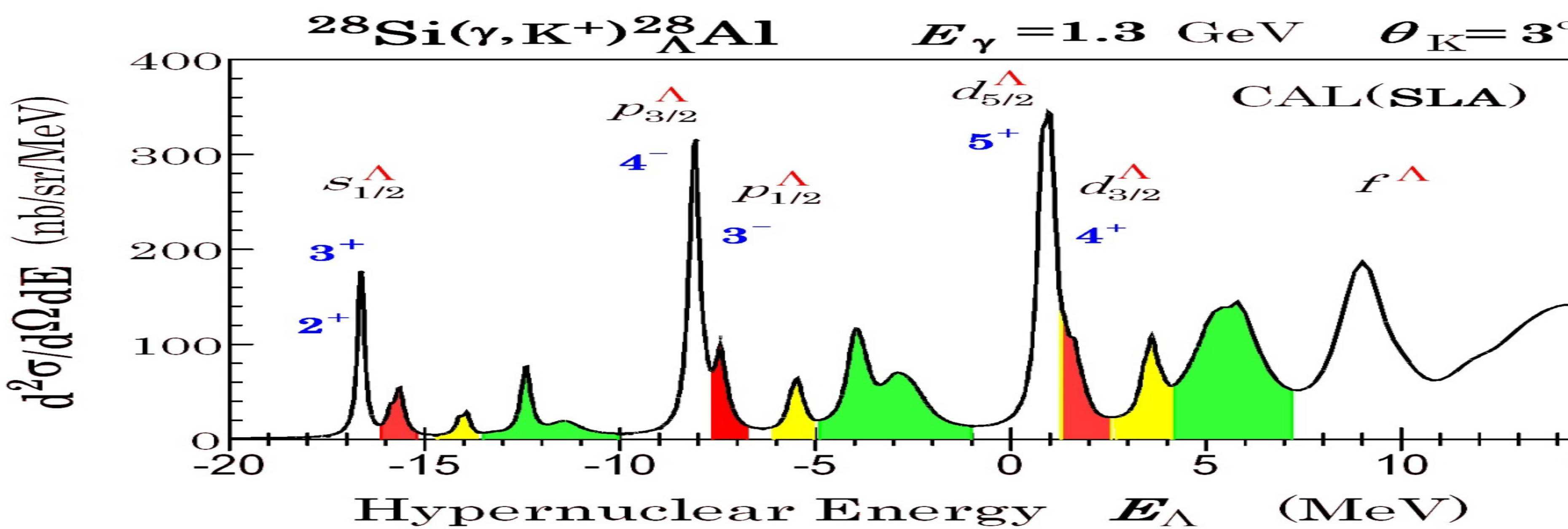
$^{28}Si(e,e'K^+)^{28}{}_{\Lambda}Al$, $^{28}Si(\pi^+,K^+)^{28}{}_{\Lambda}Si$



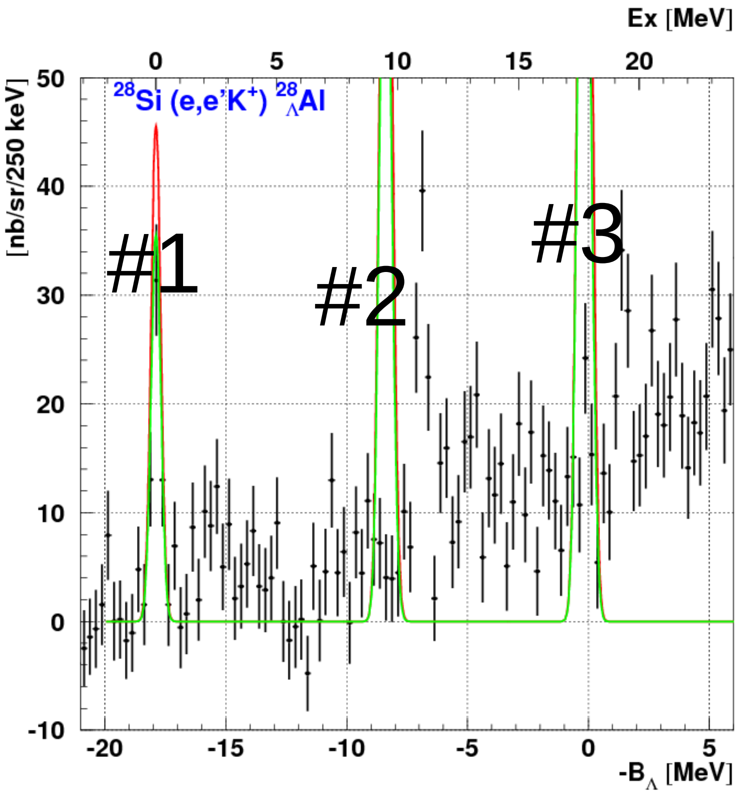


Comparison with shell-model calculation





$^{28}Si(e,e'K^+)^{28}{}_{\Lambda}Al$



Red : calculation with SLA

Green : calculation with KMAID

Theory by Sotona *et. al.*
(1.3 < Eγ < 1.6 GeV, 1 < θ_K < 13 deg.)

J^{π}	Ex [MeV]	Cross section [nb/sr]	
		SLA	KMAID
$2^+,3^+$	0	92.1	71.76
4^- 3^-	9.42 9.67	134.9 91.3	117.5 58.5
4^+ 5^+	17.6 17.9	148.4 139.1	135.1 89.9

Result

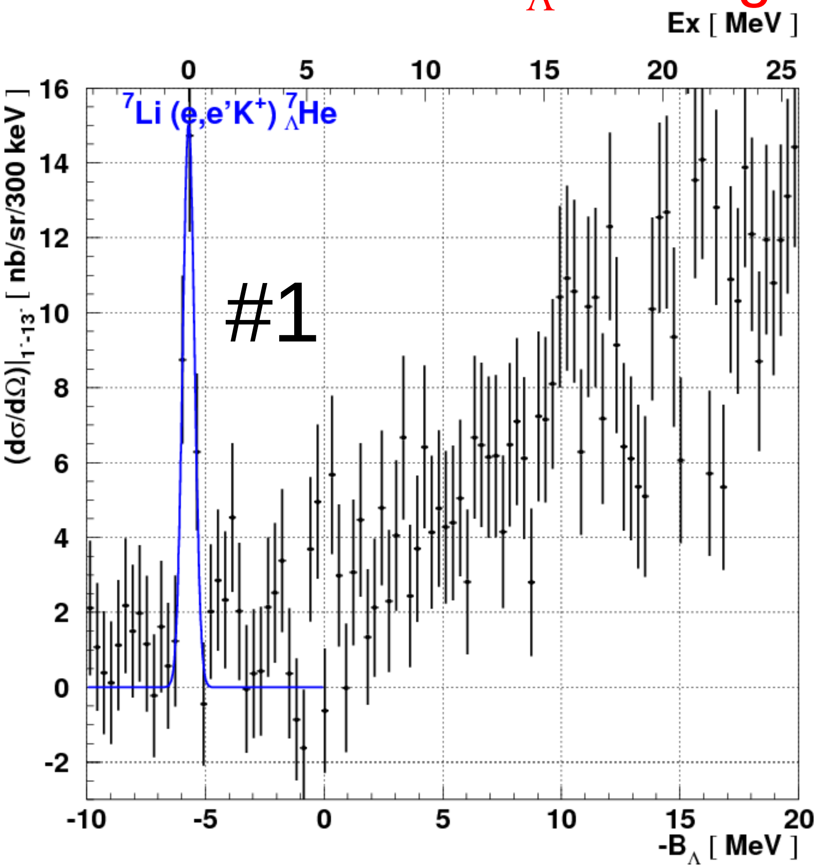
ID	Ex [MeV]	Cross section [nb/sr]	Cross section (Calc. SLA) [nb/sr]	
#1	0	60±5.0 (*stat.*) +27, -18 (*sys.*)	92.1 ($2^+ + 3^+$)	(78)
#2	10.98±0.02 (*stat.*) ±0.30 (*sys.*)	94±6.0 (*stat.*) +43, -28 (*sys.*)	226.2 ($4^- + 3^-$)	(122)
#3	19.30±0.03 (*stat.*) ±0.30 (*sys.*)	59±6.7 (*stat.*) +55, -18(*sys.*)	287.5 ($4^+ + 5^+$)	(77)

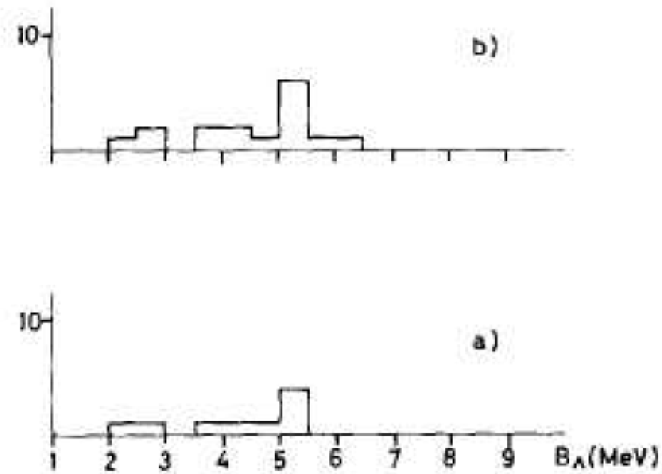
$^{28}Si(e,e'K^+)^{28}_{\Lambda}Al$

- First sd-shell hypernuclear spectroscopy by $(e,e'K^+)$
- Three major peaks ; #1:$[(d_{5/2})^{-1}_{p},(s_{1/2})_{\Lambda}]$,
  #2:$[(d_{5/2})^{-1}_{p},(p_{3/2},p_{1/2})_{\Lambda}]$
  #3:$[(d_{5/2})^{-1}_{p},(d_{5/2},d_{3/2})_{\Lambda}]$
  - Deeper $-B_{\Lambda}$ for g.s. than $^{28}_{\Lambda}Si$ and shell model calculation
  - Wider energy spacing between #1 and #2 than calc.
  - Narrower energy spacing between #2 and #3 than calc.
  - Smaller cross sections than calc.

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

Observation of $^{7}_{\Lambda}He$ w/ good statistics



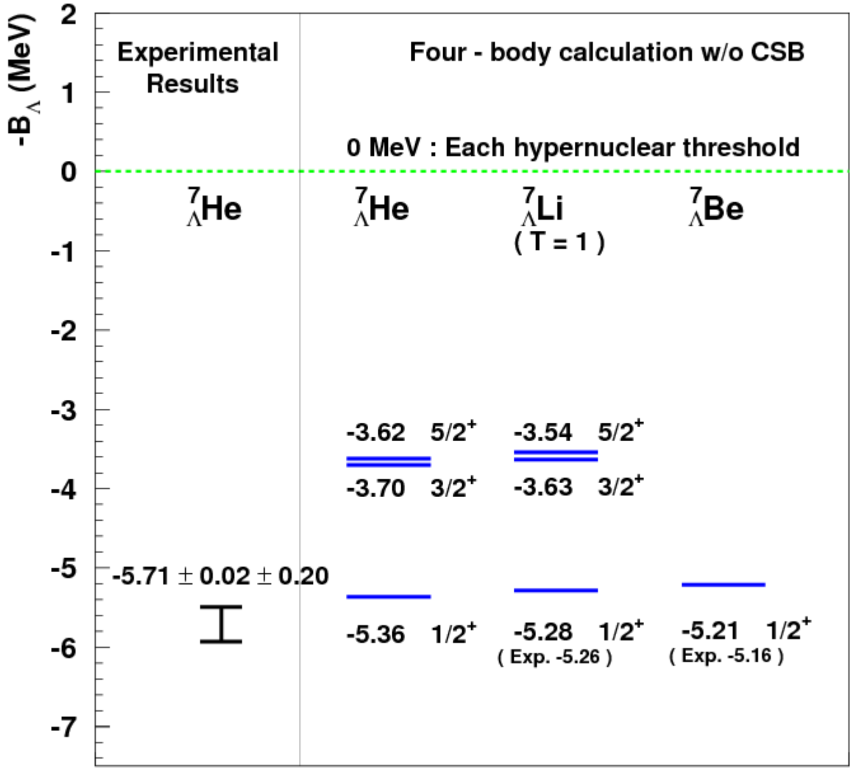


Fitting Result

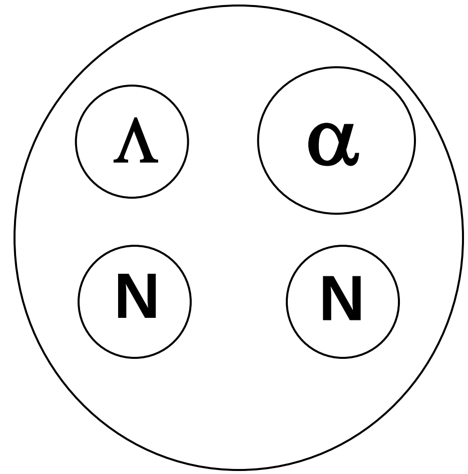
Peak No.	$-B_{\Lambda}$ [MeV] ± (stat.) ± (sys.)	Ex [MeV] ± (stat.) ± (sys.)	FWHM [MeV]	$(d\sigma/d\Omega)|_{1^{\circ}-13^{\circ}}$ [nb/sr] ± (stat.) ± (sys.)
# 1	$-5.71 \pm 0.02 \pm 0.20$	0	0.48 ± 0.07	$31 \pm 2.8\ ^{+11.8}_{-9.3}$

CSB effect by cluster model

E.Hiyama *et al.*
PRC80,054321(2009)



Four-body cluster model

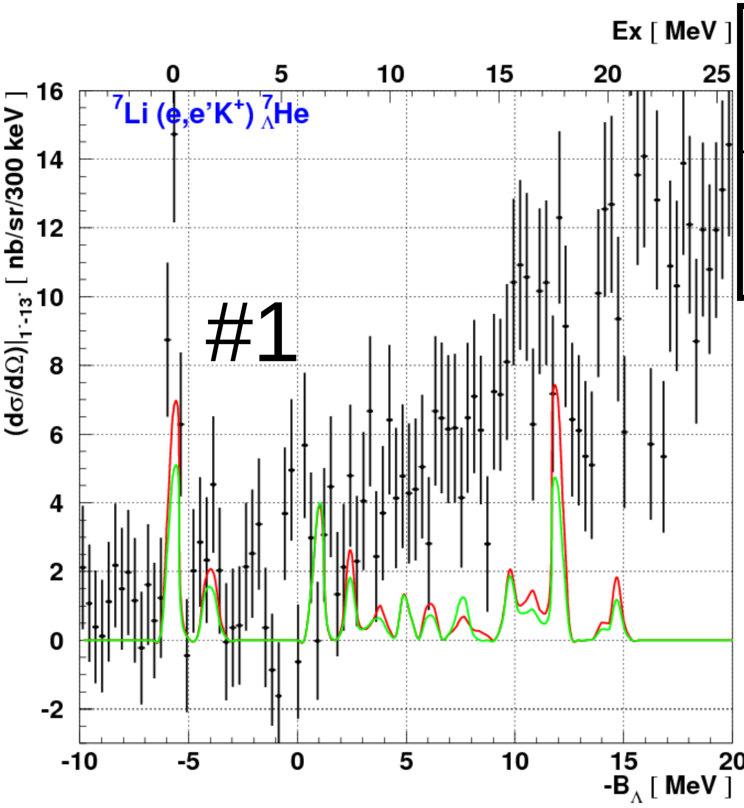


Phenomenological potential

$$V_{\Lambda N}^{CSB}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{even,CSB} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda \cdot \sigma_N}^{even,CSB}\right)e^{-\beta_{even} r^2} + \frac{1-P_r}{2}\left(v_0^{odd,CSB} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda \cdot \sigma_N}^{odd,CSB}\right)e^{-\beta_{odd} r^2}\right],$$

$-B_\Lambda$= -5.36 w/o CSB
-5.16 w/ CSB

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$



Red : calculation with SLA
Green : calculation with KMAID

Result

ID	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]
#1	-5.71±0.02 (*stat.*) ±0.20 (*sys.*)	31±2.8 (*stat.*) +11.8,-9.3 (*sys.*)

(40)

Theory by Sotona *et. al.* (Cross section)
by Hiyama *et. al.* ($-B_{\Lambda}$: w/o CSB)
($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

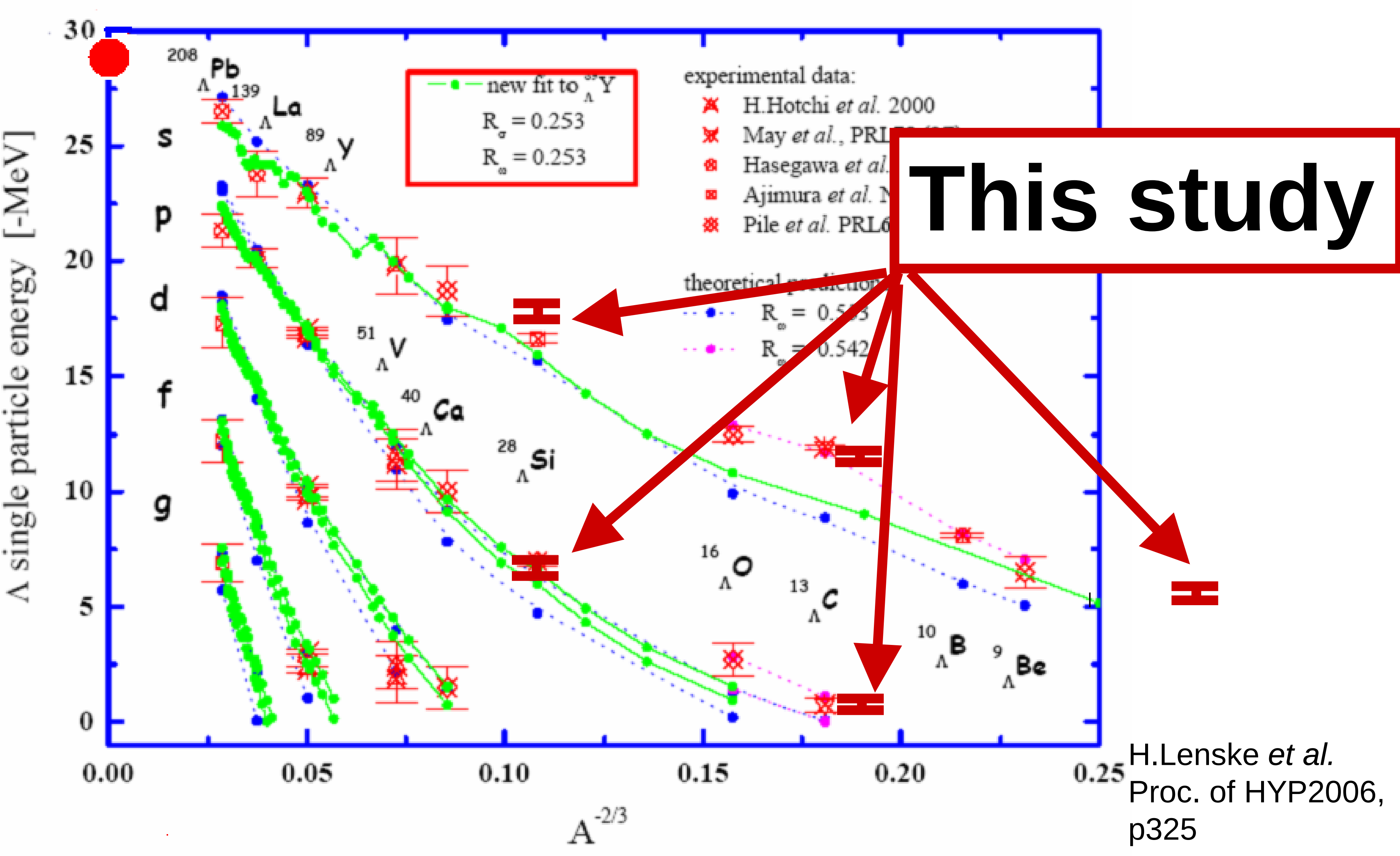
J^{π}	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]	
		SLA	KMAID
$1/2^{+}$	-5.36	13.2	9.7

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

- High statistics spectroscopy
- $-B_{\Lambda}=-5.71\pm0.02$ (stat.) ±0.20 (sys.) for g.s.
  - Cluster model calculation
    - $-B_{\Lambda}=-5.36$ MeV (w/o CSB)
    - $-B_{\Lambda}=-5.16$ MeV (w/ CSB)
- Cross section : larger than shell model calc.

End

Λ single particle energies



H.Lenske *et al.*
Proc. of HYP2006, p325

Summary

- 2^{nd} Generation hypernuclear spectroscopy

  @JLab Hall C : **HKS** and **tilt method**

  ➔ High resolution and high statics hypernuclear spectroscopy w/ wide mass region

  □ $^{28}{}_{\Lambda}$Al : First sd-shell hypernucleus by (e,e'K^{+})

  Three major peak : $[(d5/2)_p^{-1} s_\Lambda, p_\Lambda, d_\Lambda]$

  ($-B_\Lambda$ for g.s. : -17.88 ± 0.02(stat.)± 0.30(sys.) MeV)

  Gateway to heavier hypernucleus

  □ $^{12}{}_{\Lambda}$B : Best energy resolution of 480 keV (FWHM) for g.s.

  □ $^{7}{}_{\Lambda}$He : First high statistics spectroscopy

  Binding energy of -5.71 ± 0.02(stat.)± 0.20(sys.) MeV for g.s.

	2004 ～ 2005	2005	2009	2009 ～
	E94-107	**E01-011**	**E05-115**	**Mainz**
E_γ (GeV)	2.2	1.5	1.5	1.05
W (GeV)	2.2	1.9	1.9	1.67
Q^2 $(GeV/c)^2$	0.07	0.01	0.01	0.05
E_{beam} (GeV)	4.02/3.78/3.66	1.85	2.34	1.50
$P_{e'}$ (GeV/c)	1.8/1.57/1.44	0.35	0.84	0.455
$\theta_{e'}$ (deg)	6	3.7 ～ 5.7	3 ～ 9	15.5
P_{K+} (GeV/c)	1.96	1.2	1.2	0.466
θ_{K+} (deg)	6	1 ～ 13	1 ～ 13	31.4

Count, S/N

Peak ID	# of peak [counts]	# of BG(3σ) [counts]	S/N	Sys. Err. (Contami. -%)	Sys. Err. (Loss +%)
${}^{7}_{\Lambda}$He:#1	120	230	0.52	30	30
${}^{12}_{\Lambda}$B:#1	630	561	1.12	5	30
${}^{12}_{\Lambda}$B:#2	695	706	0.98	20	30
${}^{28}_{\Lambda}$Al:#1	145	360	0.40	40	30
${}^{28}_{\Lambda}$Al:#2	240	516	0.47	40	30
${}^{28}_{\Lambda}$Al:#3	77	545	0.14	90	30