Recent Spectroscopic Investigation of Λ-Hypernuclei by the (e,e'K^+) Reaction

-Analysis Status of E01-011 & E05-115-

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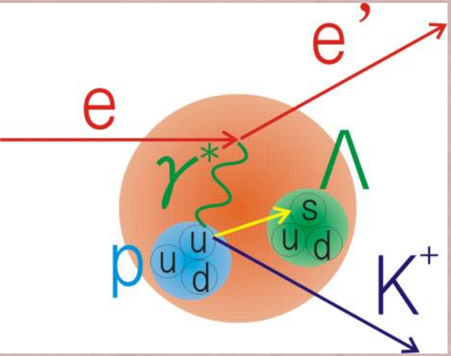
Hampton University

Feb. 21, 2014

Λ HYPERNUCLEAR SPECTROSCOPY VIA (e,e'K$^+$)



Merits of the (e,e'K$^+$) experiment

- ☺ Large momentum transfer
- → Excitation of deeply-bound state
- ☺ p to Λ reaction → Mirror and Neutron-rich hypernuclei
- ☺ Spin-flip/non-flip production
- ☺ High Energy Resolution due to CEBAF beam's quality

2005(E01-011) 2nd Experiment :

$^{7}_{\Lambda}$He $^{12}_{\Lambda}$B, $^{28}_{\Lambda}$Al

- ❖ Newly-constructed **HKS** for K$^+$ side
- ❖ Apply **"Tilt Method"** for e' side

2009(E05-115) 3rd Experiment:

$^{12}_{\Lambda}$B , $^{7}_{\Lambda}$He, $^{10}_{\Lambda}$Be, $^{9}_{\Lambda}$Li and $^{52}_{\Lambda}$V

- ❖ Beam Energy 1.8 →2.344 GeV
- ❖ Brand-new e' spectrometer, HES

Calibration by the elementary process

p(e,e'K$^+$)Λ or Σ: CH_2

CEBAF Bird's-eye photo

INTRODUCTION

Physical Goals:

- To understand YN and YY interactions
- To explore and understand nuclear structure using Λ as a probe
  - **Model the baryonic many body system**
  - **Study the role of Λ in the nuclear medium**

- Shell Model with Λ-N Effective Potential ($p_N s_\Lambda$) for p-shell hypernuclei

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\,\boldsymbol{s}_N\cdot\boldsymbol{s}_\Lambda + V_\Lambda(r)\,\boldsymbol{L}_{N\Lambda}\cdot\boldsymbol{s}_\Lambda + V_N(r)\,\boldsymbol{L}_{N\Lambda}\cdot\boldsymbol{s}_N + V_T(r)\,S_{12}$$

$\bar{V}$ Δ S_Λ S_N T

Radial Integrals
Coefficients of operators

- Additional Contribution: Λ-Σ coupling

Our results with precise B_Λ are important in helping to determine these parameters as well as to explore the full spectroscopy with unseen core states.

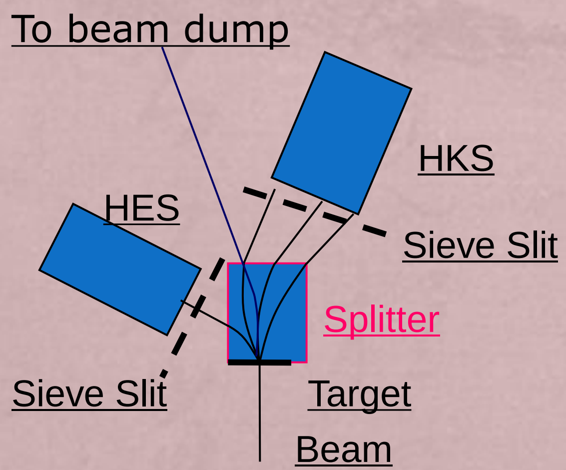
Spectrometer System Calibration

Spectrometer system calibration: key to reach sub-MeV energy resolution

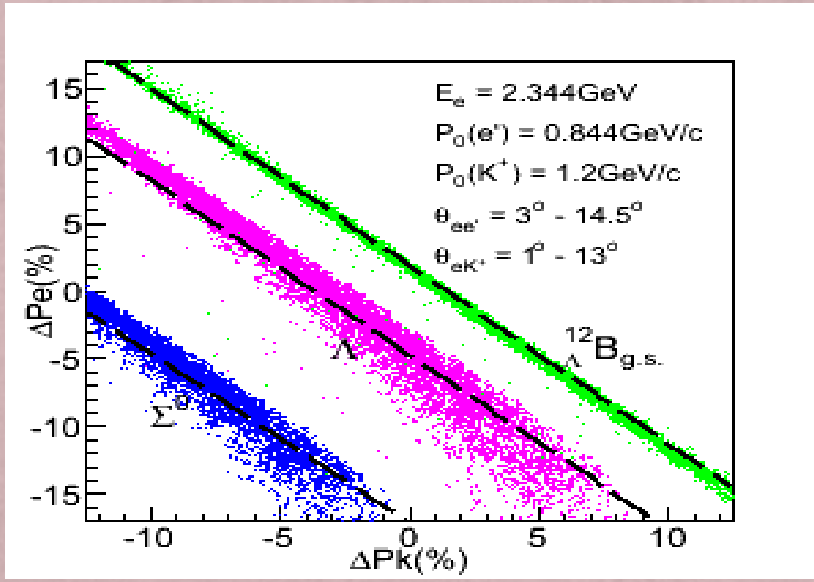
- Common splitter : Separated single arm calibration is impossible
- Technique: 2-arm coupled calibration for both kinematics and optics

Using known masses of Λ, Σ^0 from CH_2 target and identified known hypernuclear bound states ($^{12}_{\Lambda}B$ g.s.) for spectrometer calibration

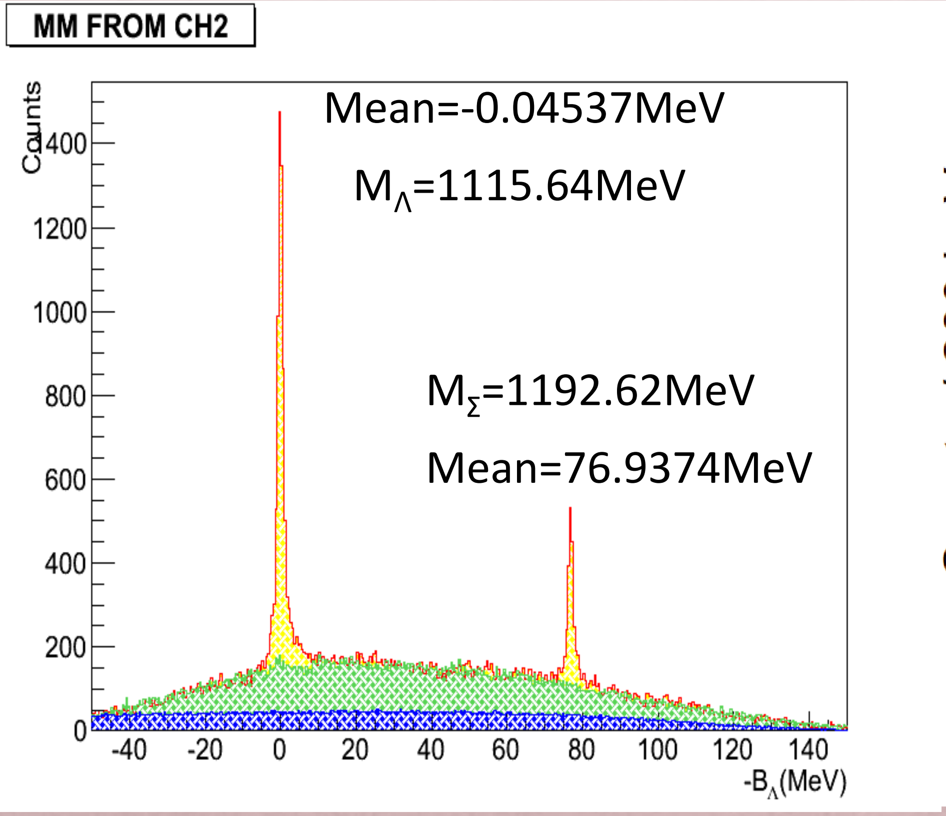
E05-115 spectrometer system

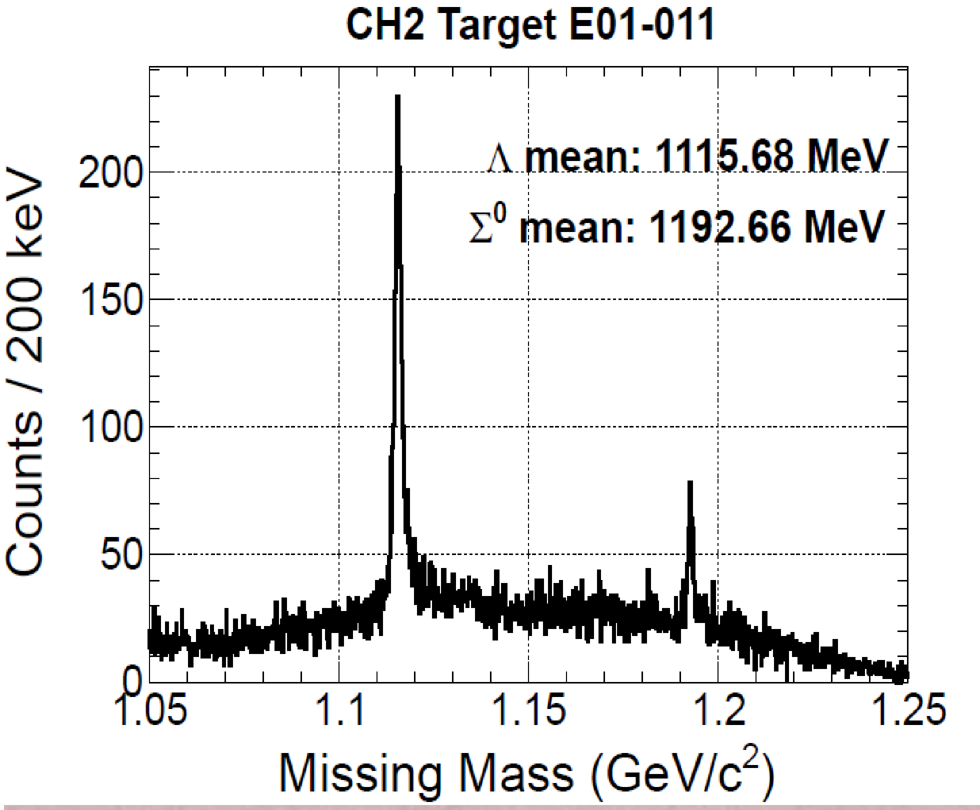


Kinematics coverage



CALIBRATION DATA RESULT



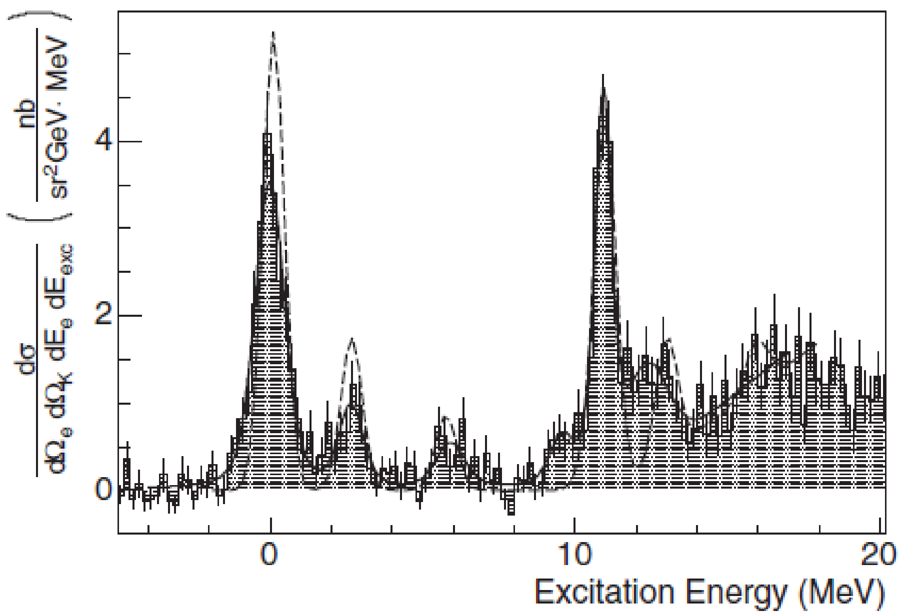


E05-115

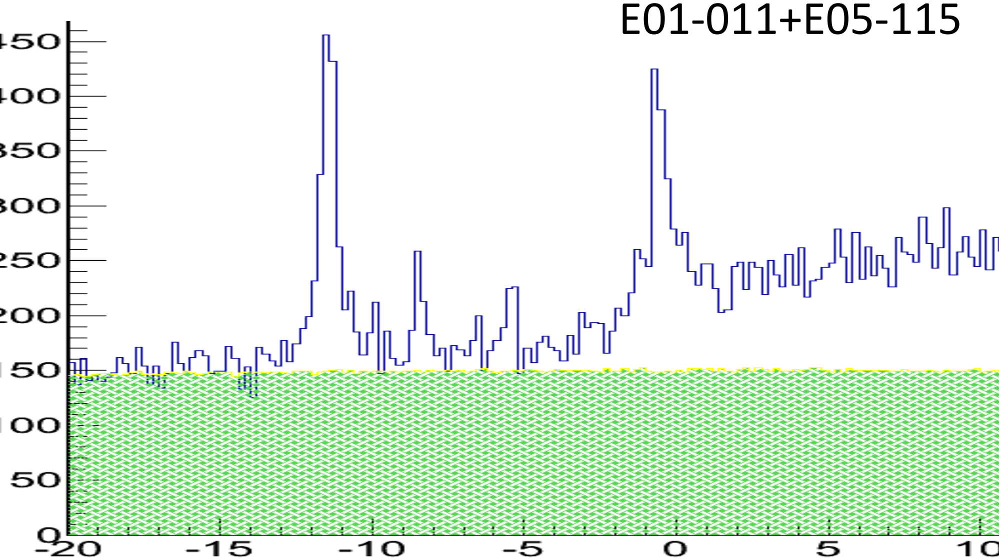
E01-011

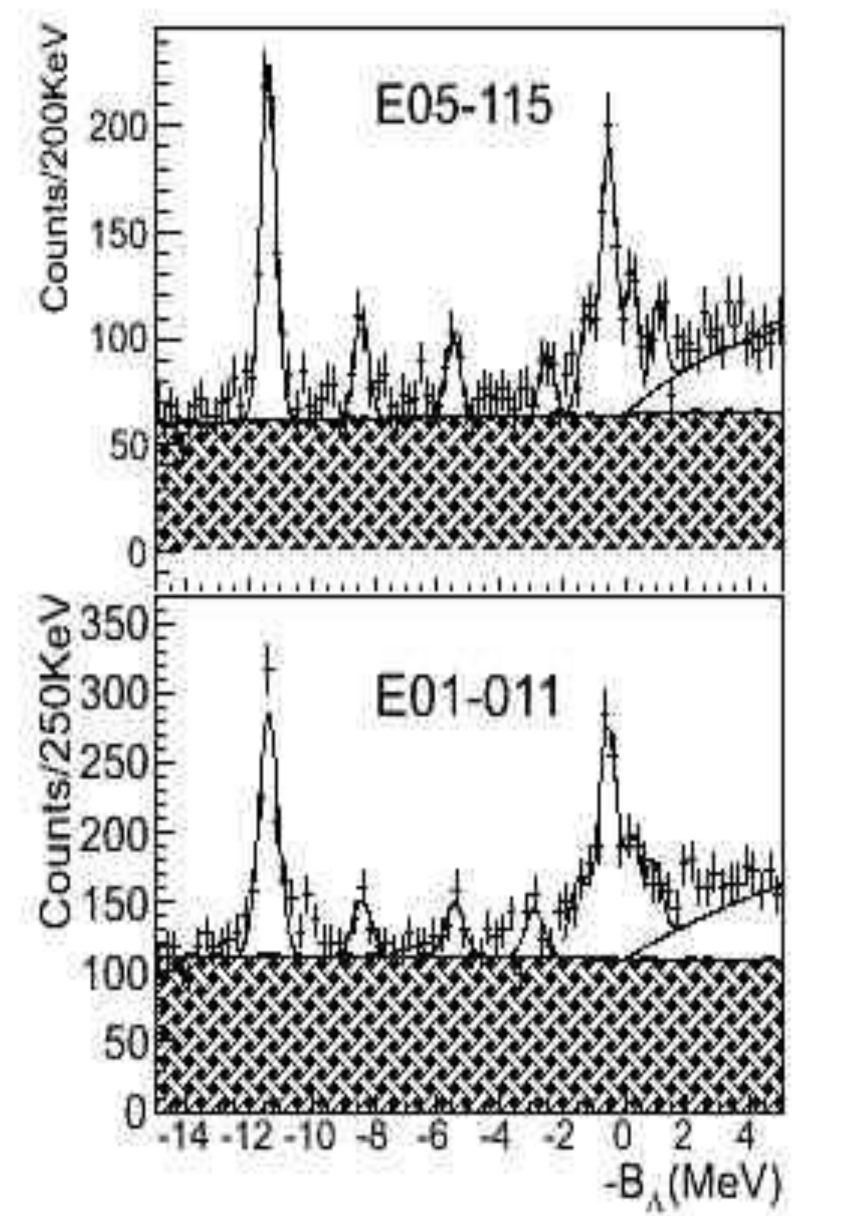
$^{12}_{\Lambda}B$

Phys. Rev. Lett. 99, 052501 (2007) (HallA data)



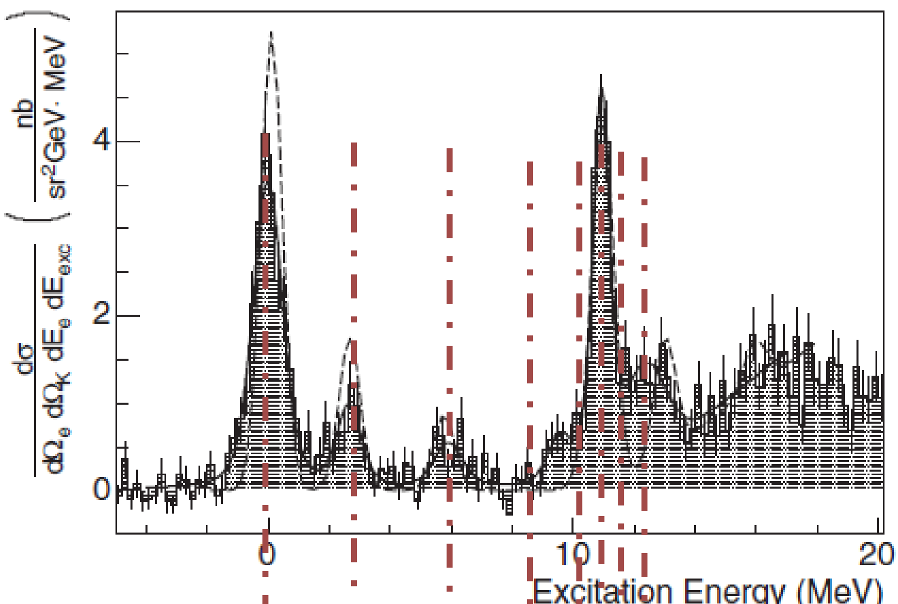
E01-011+E05-115

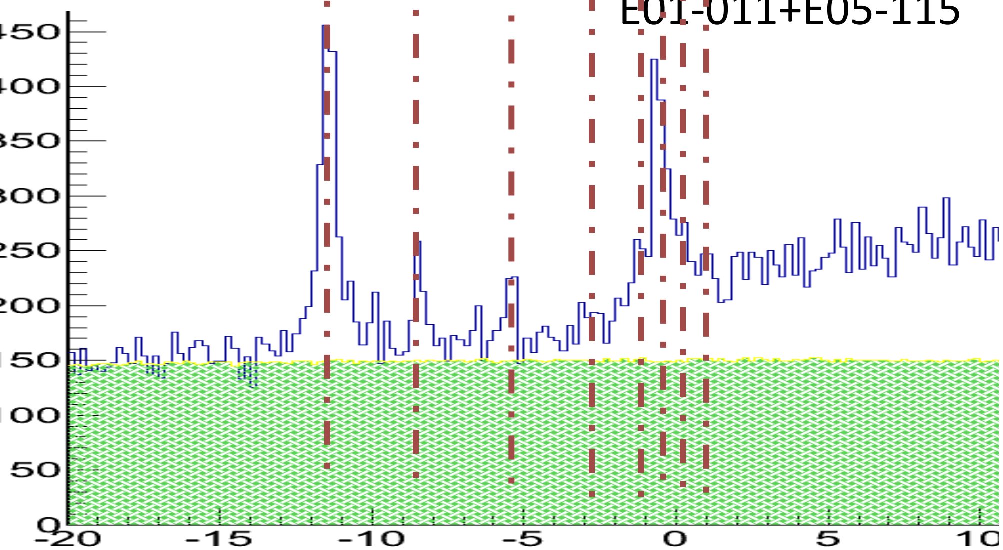


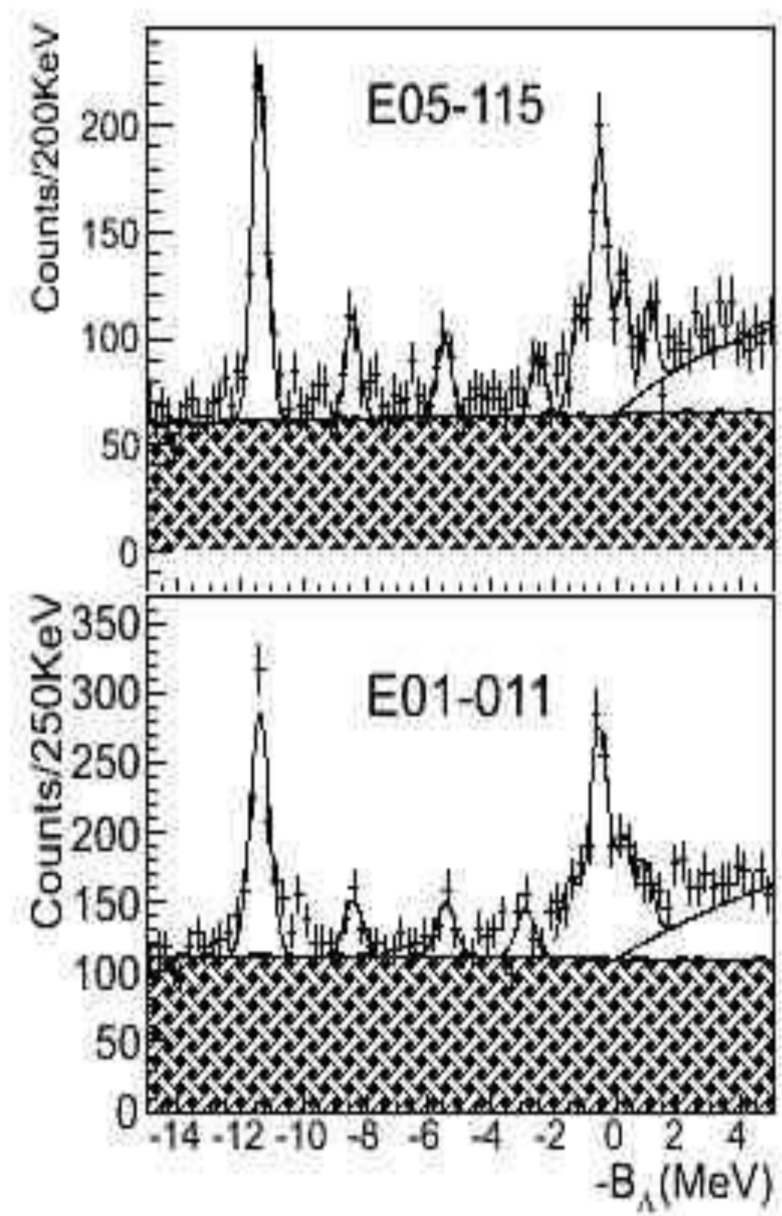


$^{12}{}_{\Lambda}B$

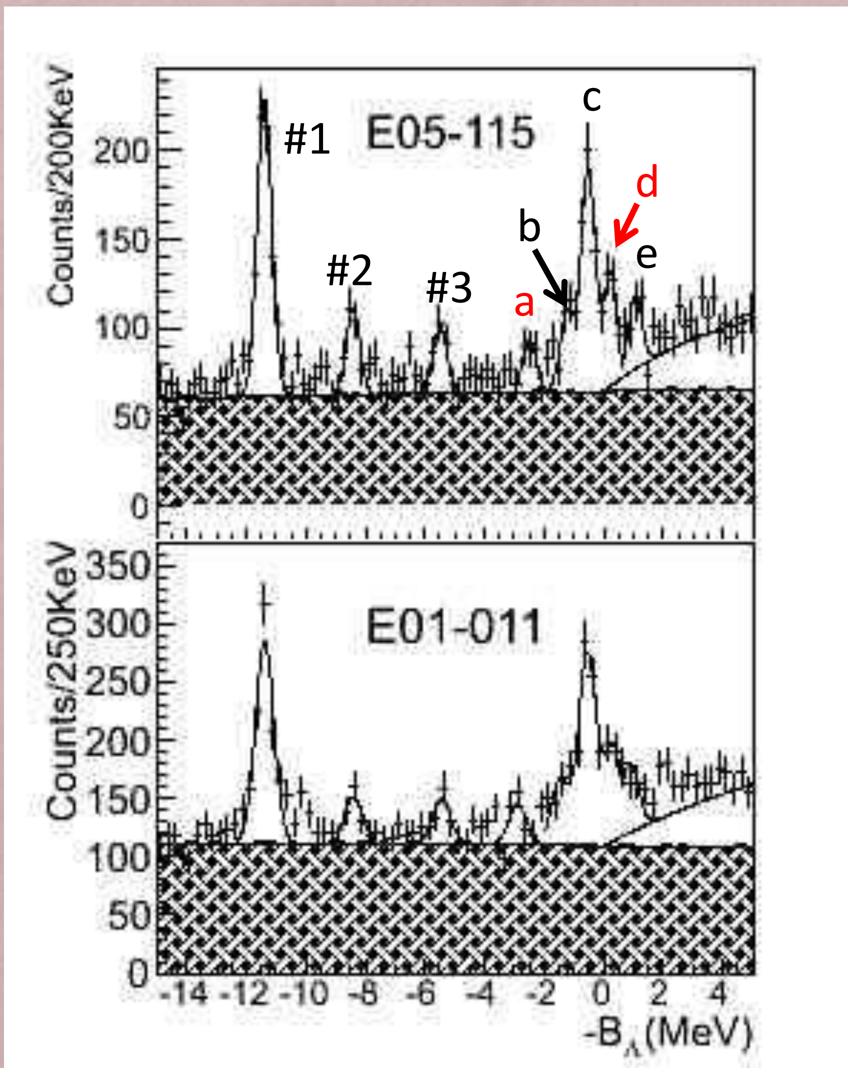
Phys. Rev. Lett. 99, 052501 (2007) (HallA data)



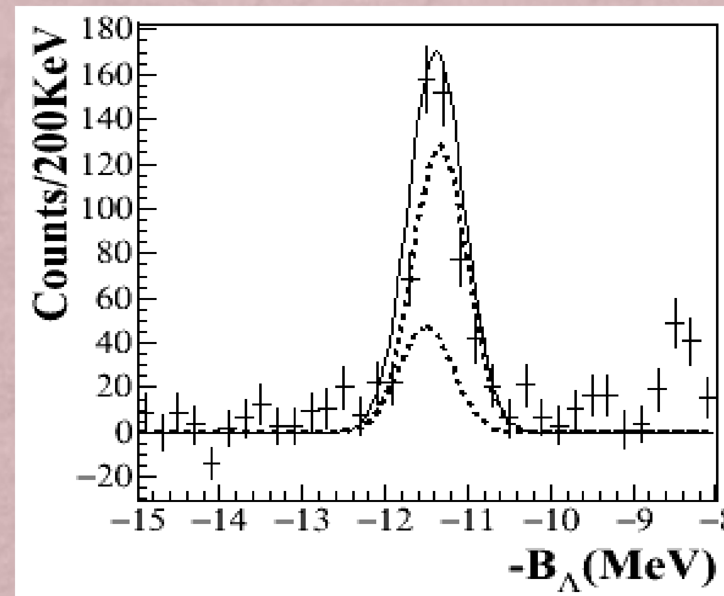




$^{12}{}_{\Lambda}B$

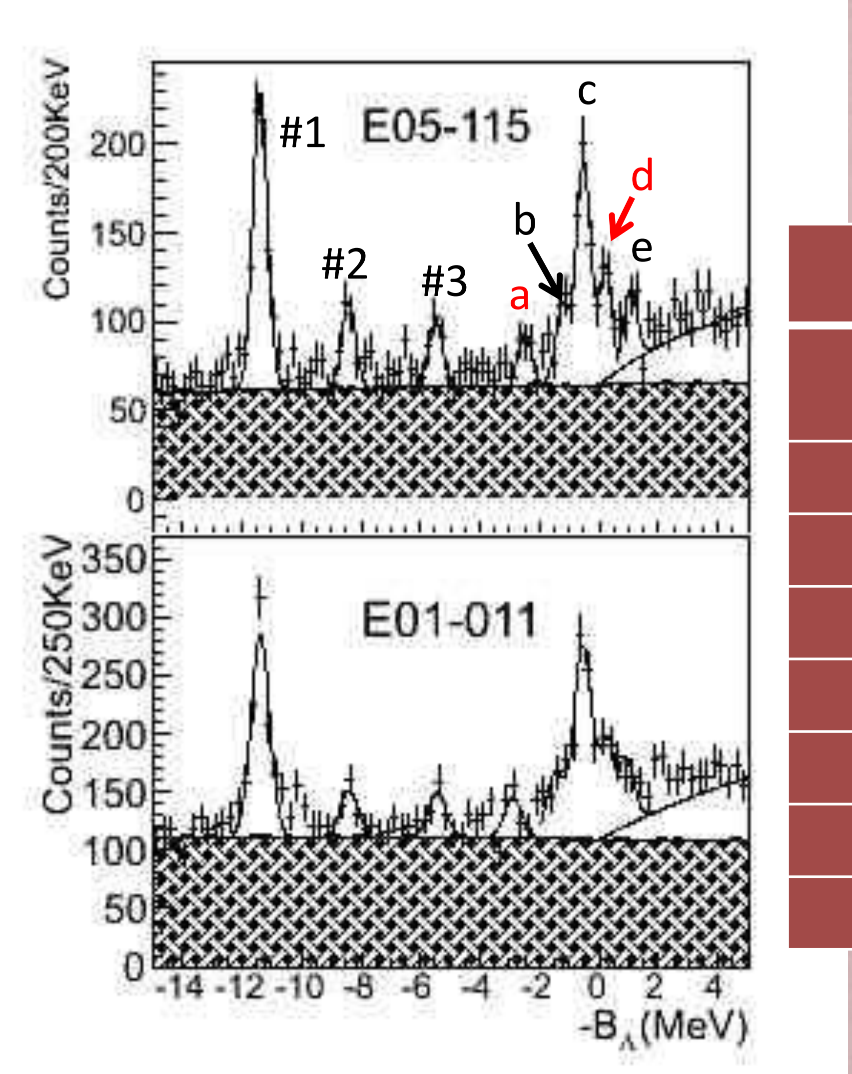


Double gaussian Fitting for $^{12}{}_{\Lambda}B$g.s.



Experiment	Fitting σ (KeV)	Separation (KeV)	ratio
E05-115	231±2	170±21	2.7±1.8
E01-011	300±3	177±21	3.35±1.65

$^{12}_{\Lambda}B$



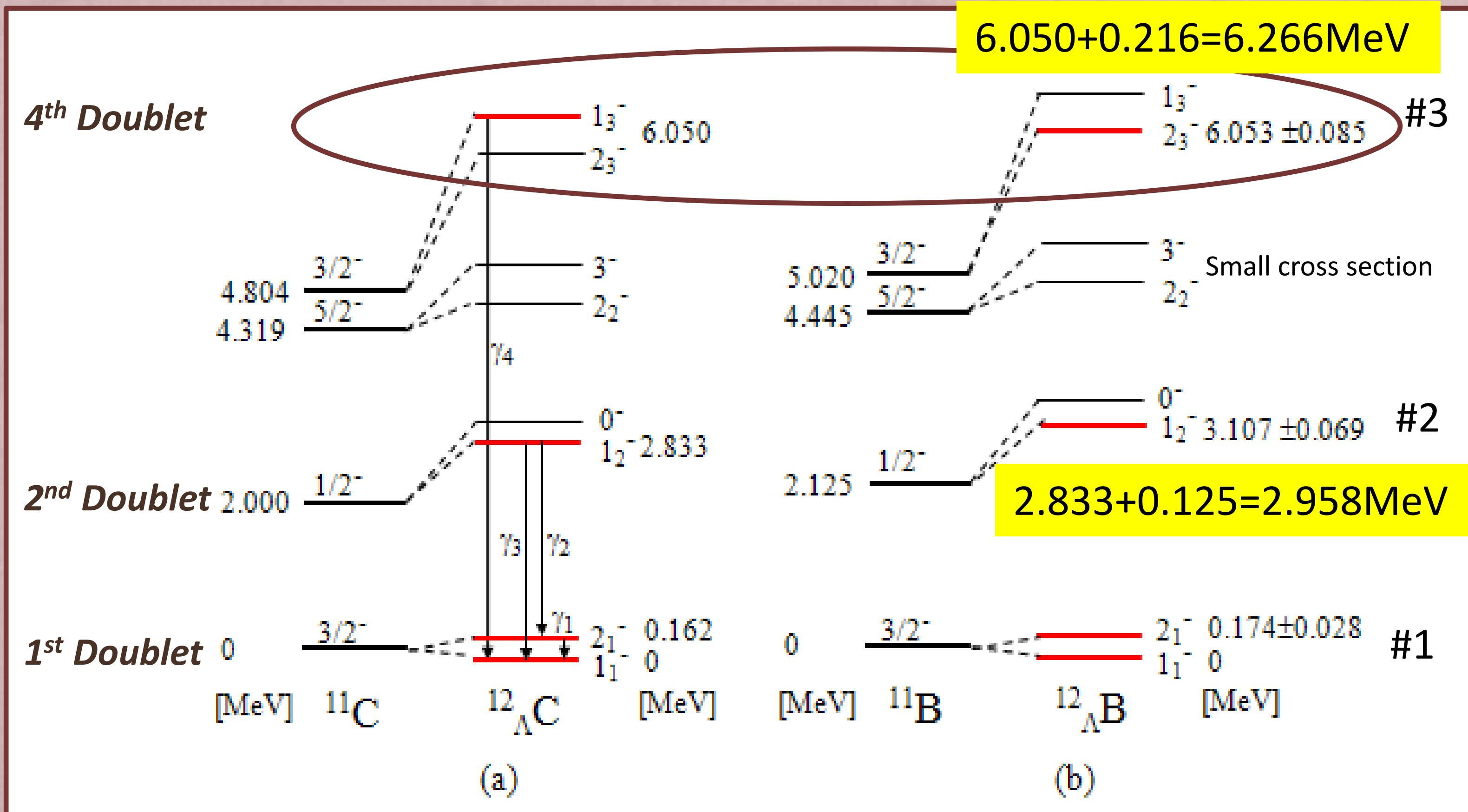
Systematic uncertainty for E05-115 = ±0.11MeV
Systematic uncertainty for E01-011 = ±0.16MeV

Peak	B_Λ (MeV) (E05-115)	B_Λ (MeV) (E01-011)	Average B_Λ (MeV)
#1-1 #1-2	-11.508 ± 0.025 - 11.338 ± 0.025	-11.521 ± 0.031 - 11.344 ± 0.031	-11.515 ± 0.028 - 11.341 ± 0.028
#2	-8.425 ± 0.047	-8.390 ± 0.075	-8.408 ± 0.063
#3	-5.488 ± 0.052	-5.440 ± 0.085	-5.462 ± 0.070
#4	-2.499 ± 0.075	-2.882 ± 0.085	-2.691 ± 0.080
#5	-1.220 ± 0.056	-1.470 ± 0.091	-1.345 ± 0.076
#6	-0.524 ± 0.024	-0.548 ± 0.035	-0.536 ± 0.030
#7	0.223 ± 0.039	0.318 ± 0.085	0.271 ± 0.066
#8	1.047 ± 0.078	0.849 ± 0.101	0.948 ± 0.090

Fixed fitting sigma for E05-115=231KeV
Fixed fitting sigma for E01-011=300KeV

$^{12}{}_{\Lambda}B$

States from Λ in s-shell coupled to the low lying ^{11}B core states



K. Hosomi et al., Nuclear Physics A 914 (2013) 184–188

4th doublet separation: $\Delta E(1_3^- - 2_3^-) \approx 0.213$ ($\pm$0.09stat. $\pm$0.07sys.) MeV

Theory prediction: $\Delta E(1_3^- - 2_3^-) =$ 0.107 MeV(Millener)

$^{12}{}_{\Lambda}B$

States from Λ in p-shell

P_{Λ} means a strong mixing of $P_{3/2\Lambda}$ and $P_{1/2\Lambda}$.

M.Iodice, et.al., Phys. Rev. Lett. 99, 052501 (2007)

Peak	Structure	J^{π}	Measured E_x (MeV)	Calculated E_x (MeV)
b	$^{11}B(3/2^-;\ g.s.) \otimes P_{3/2\Lambda}$	2_1^+	10.170 ± 0.081	10.48
	$^{11}B(3/2^-;\ g.s.) \otimes P_{\Lambda}$	1_1^+		10.52
c	$^{11}B(3/2^-;\ g.s.) \otimes P_{1/2\Lambda}$	2_2^+	10.979 ± 0.041	10.98
	$^{11}B(3/2^-;\ g.s.) \otimes P_{3/2\Lambda}$	3_1^+		11.05
e	$^{11}B(1/2^-;\ 2.125) \otimes P_{3/2\Lambda}$	2_3^+	12.463 ± 0.094	12.95
	$^{11}B(1/2^-;\ 2.125) \otimes P_{\Lambda}$	1_3^+		13.05

a	9.009±0.077	*sd shell ^{11}B Core $\otimes S_{\Lambda}$*
d	11.731±0.043	*sd shell ^{11}B Core $\otimes S_{\Lambda}$*

sd shell ^{11}B shell structure: $S^4P^6(sd)$

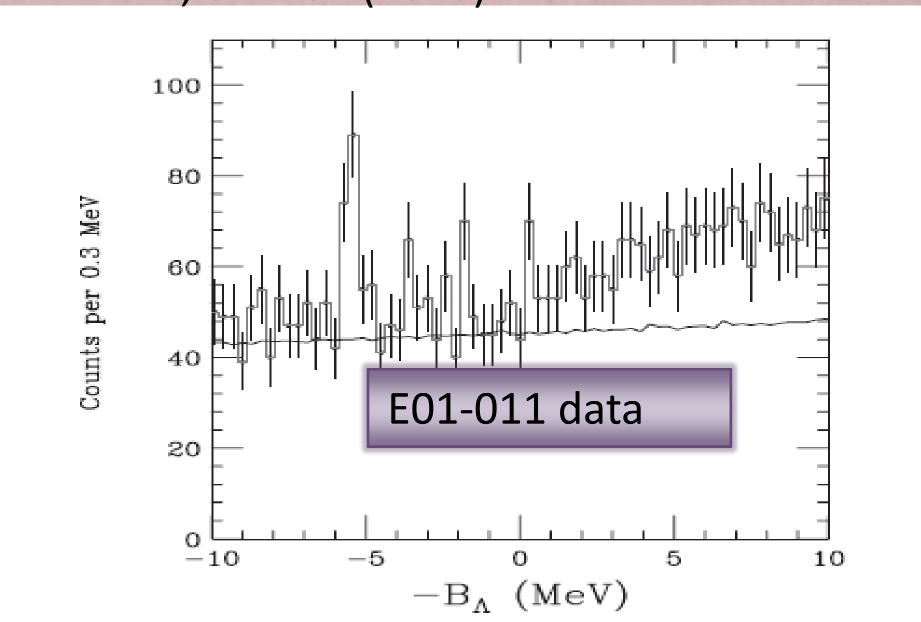
Such unpredicted structures appear to be common in previously measured $^{12}{}_{\Lambda}C$ and $^{12}{}_{\Lambda}B$ spectrum

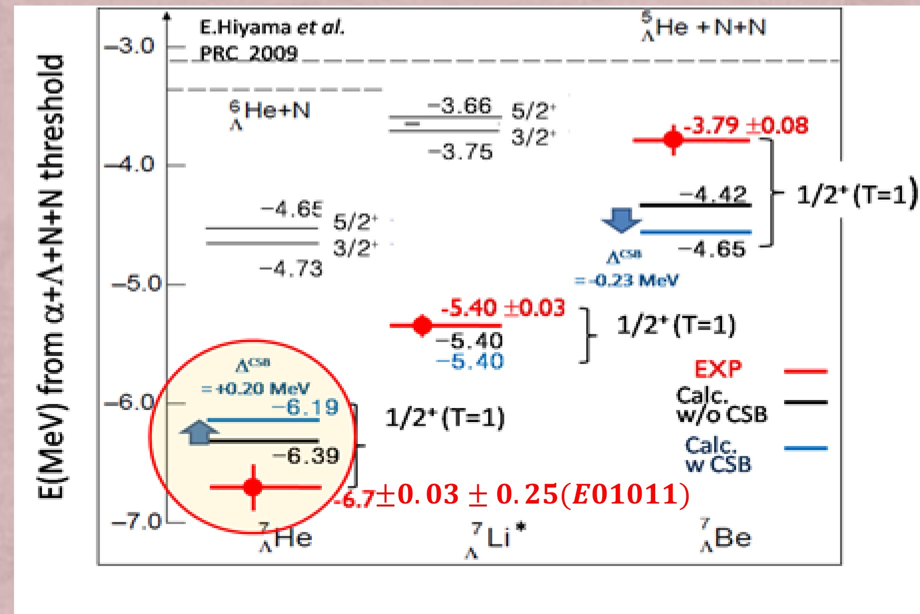
Dr. D.J. **MILLENER says:**

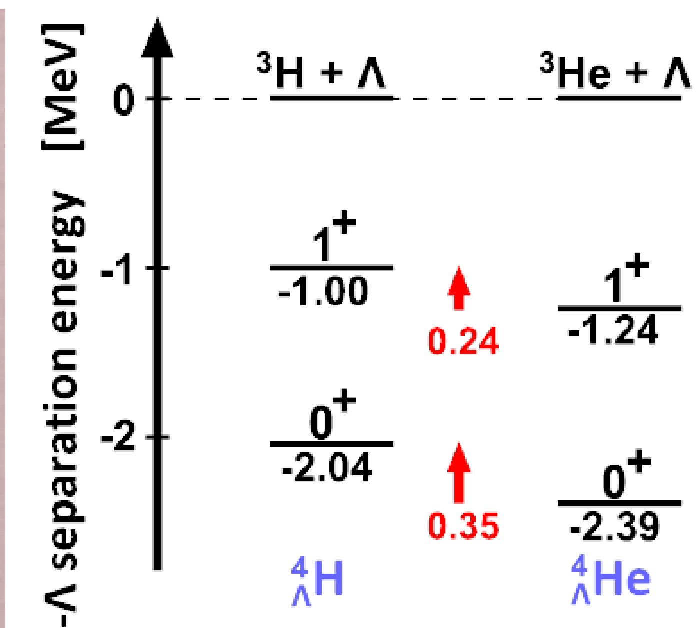
Thus, hypernuclear states based the 9.873 and 11.60-MeV states (^{11}B $1\hbar\omega$ shell state) are the best candidates for **the two extra peaks** that you see. **One day, I will do the shell-model calculation.**

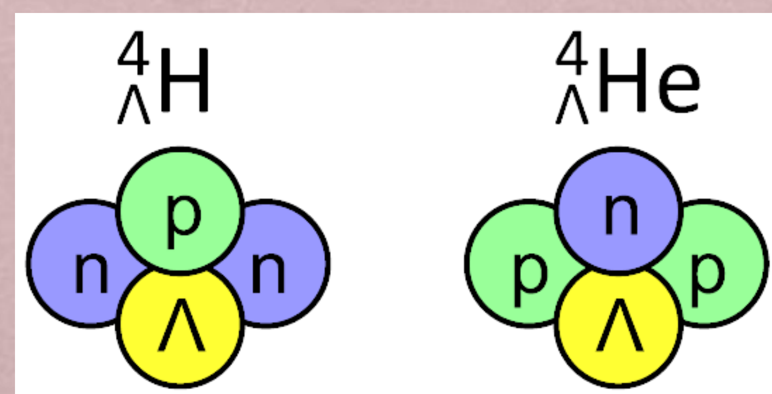
$^{7}_{\Lambda}$He

PRL 110, 012502 (2013)



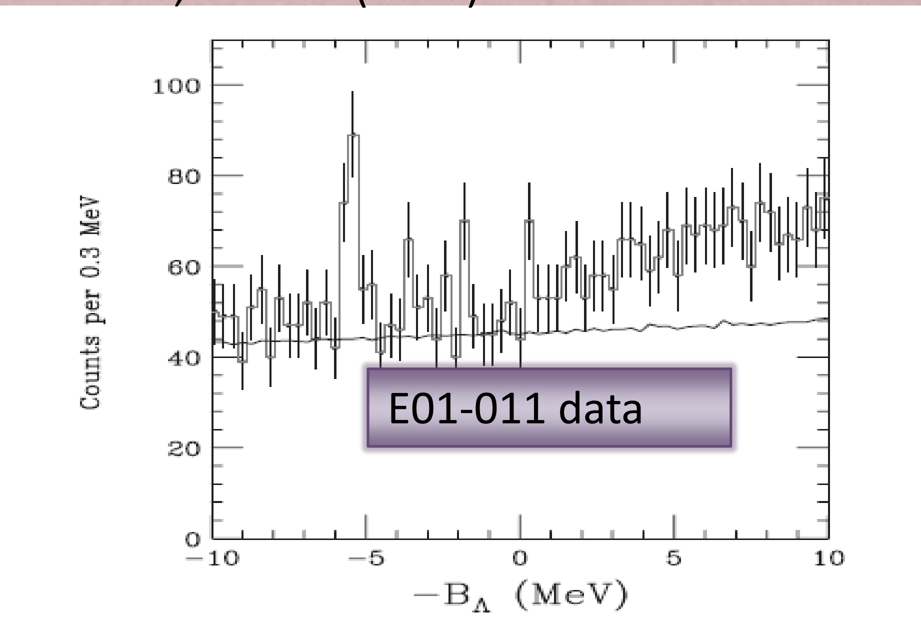


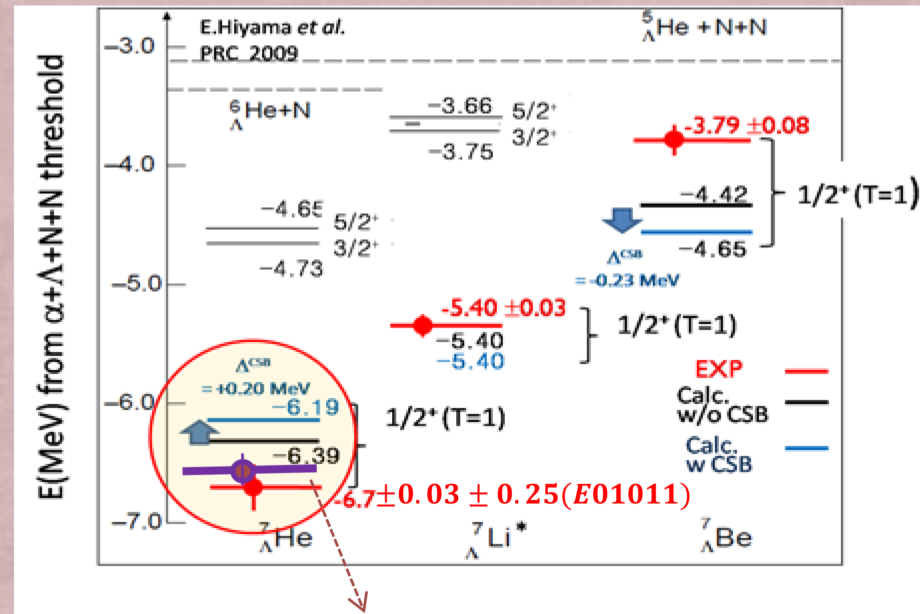




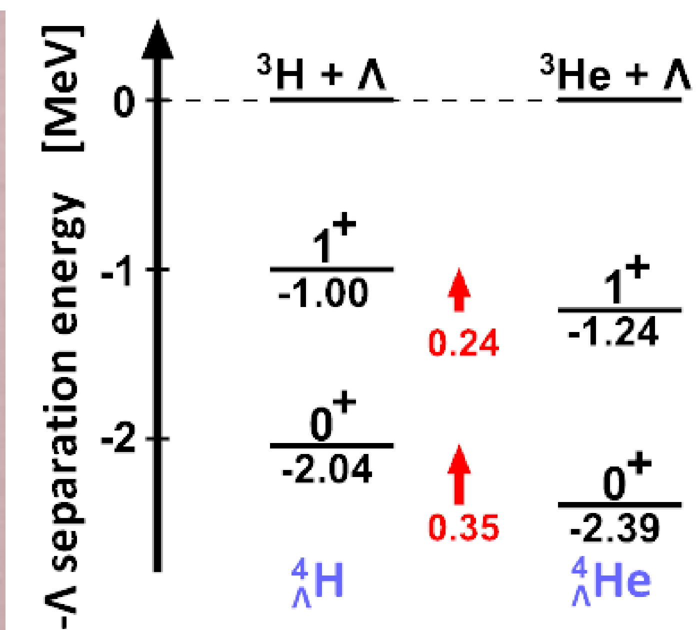
${}^{7}_{\Lambda}He$

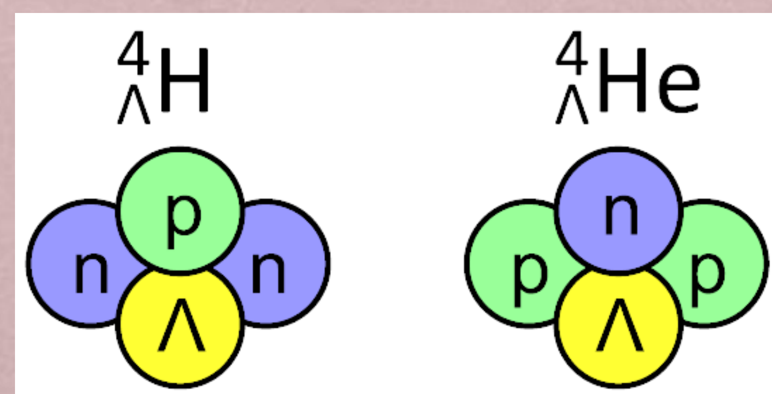
PRL 110, 012502 (2013)





E05-115 with 4 time more statistics and better precision





$^{7}_{\Lambda}He$

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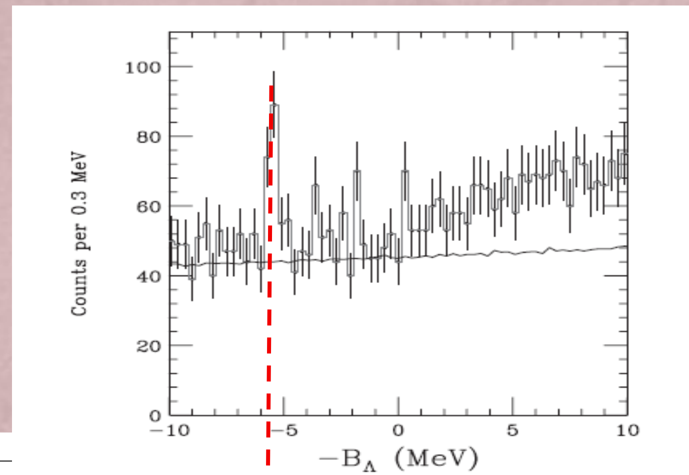
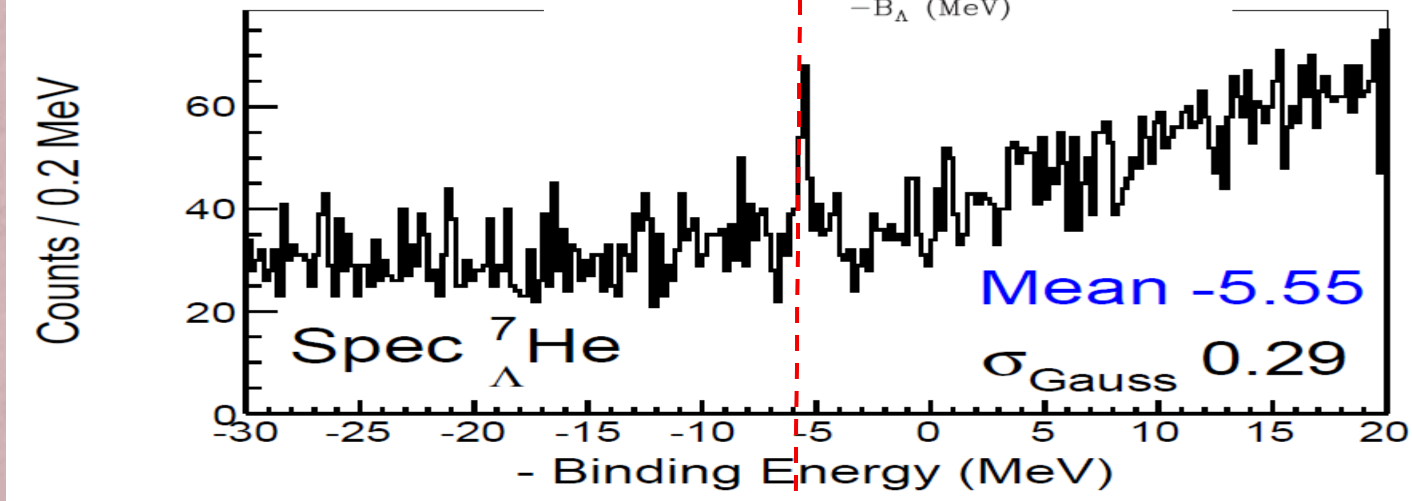
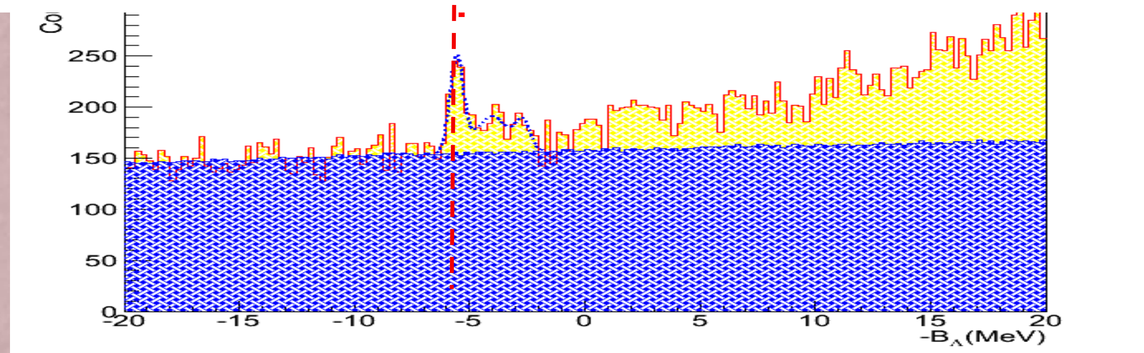


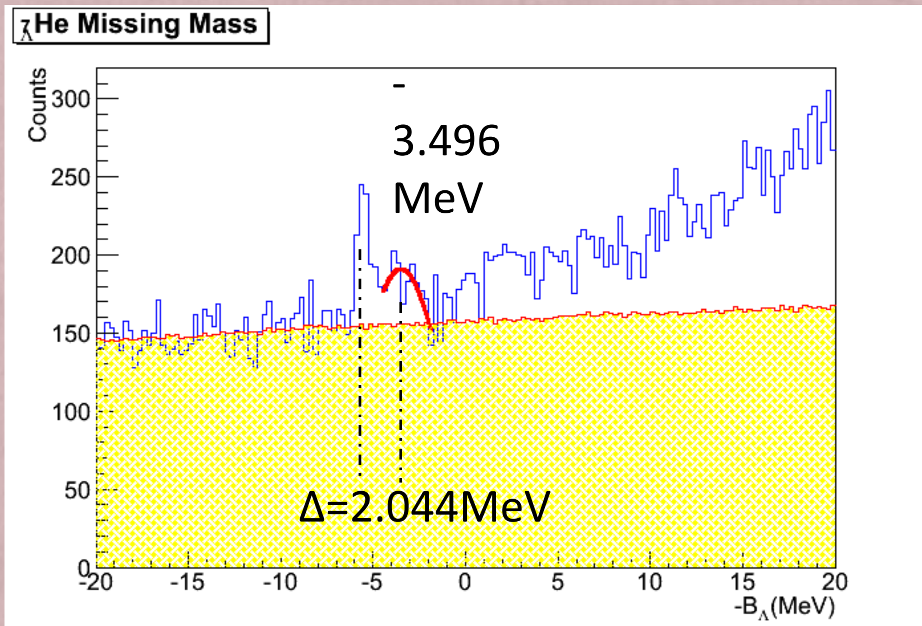
E01-011 reanalyzed

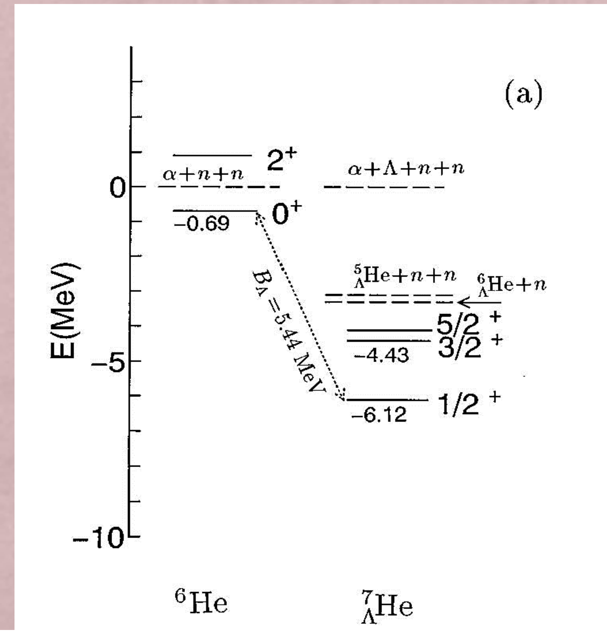


E05-115



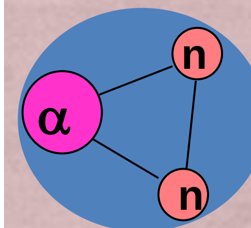
$^{7}_{\Lambda}$He

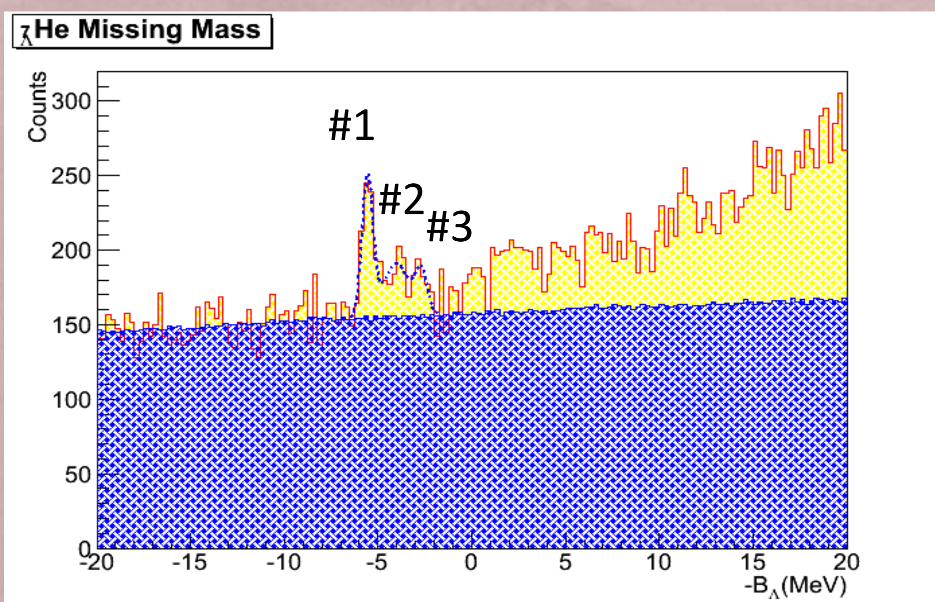




E. Hiyama, et al., PRC53 2078 (1996)

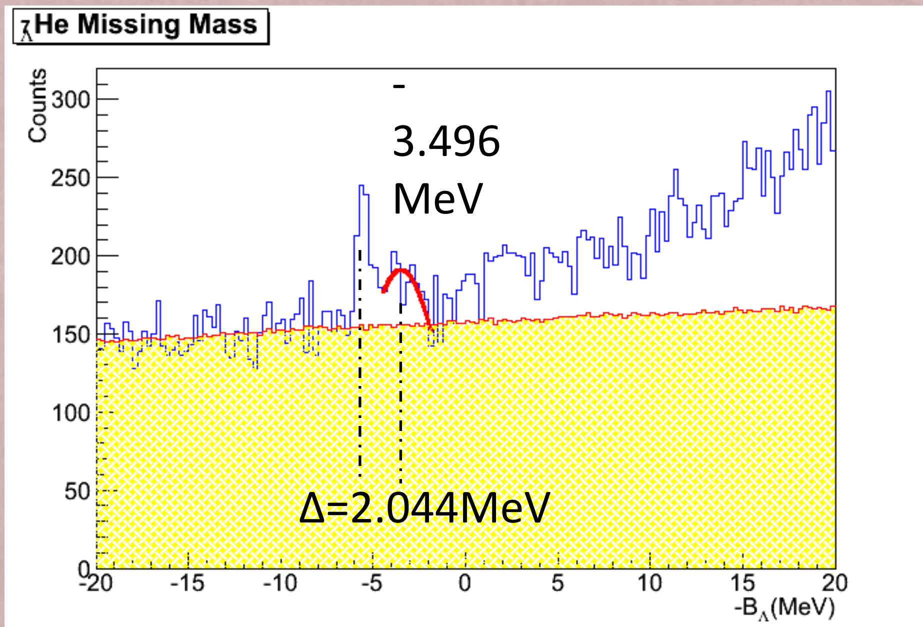
^{6}He core

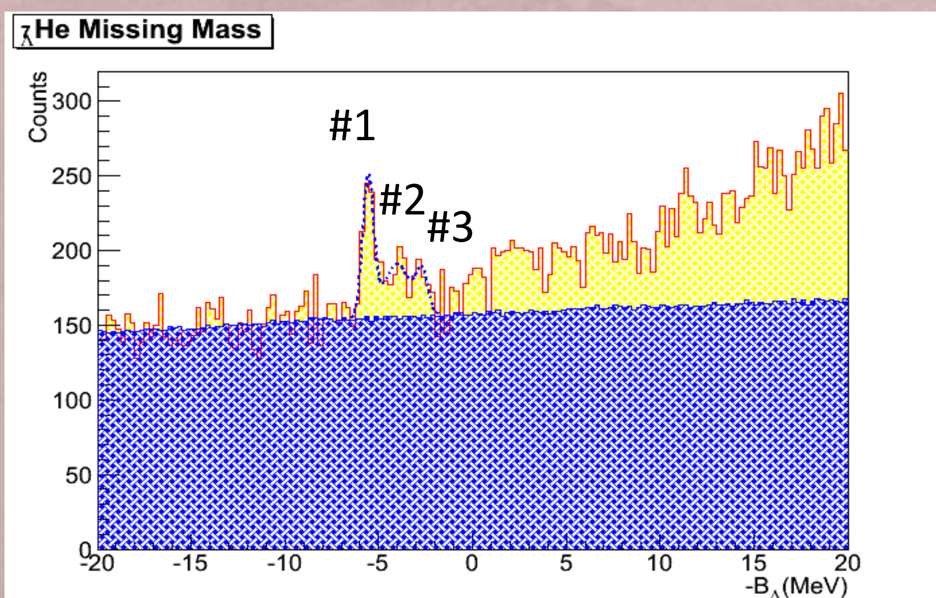


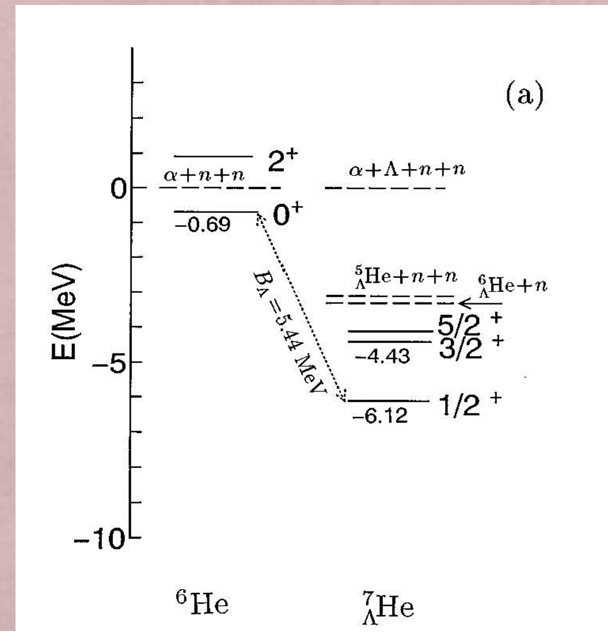


peak	Mean(MeV)	σ(KeV)
1	-5.54	253
2	-4.01	379
3	-2.97	375

$^{7}_{\Lambda}$He

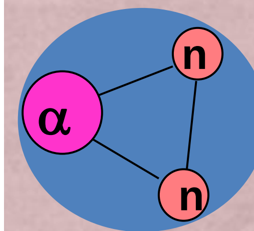






E. Hiyama, et al., PRC53 2078 (1996)

^{6}He core



peak	Mean(MeV)	σ(KeV)
1	-5.54	253
2	-4.01	379
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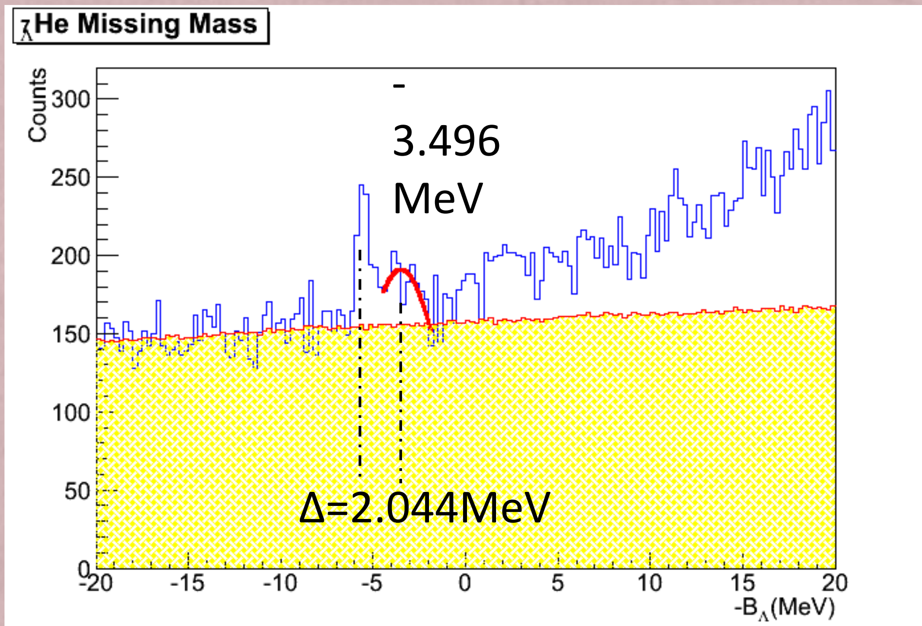
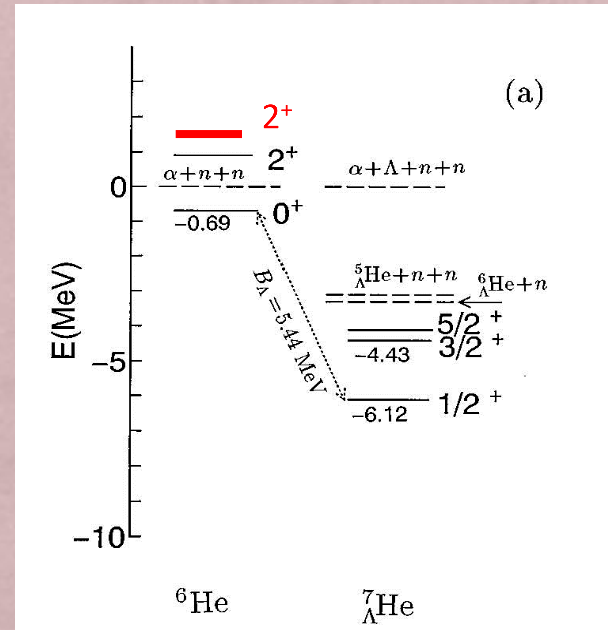
ΔE_{Λ} ~ 130keV

$\frac{3^+}{2} / \frac{5^+}{2}$

$^{7}_{\Lambda}He$





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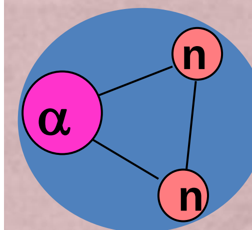
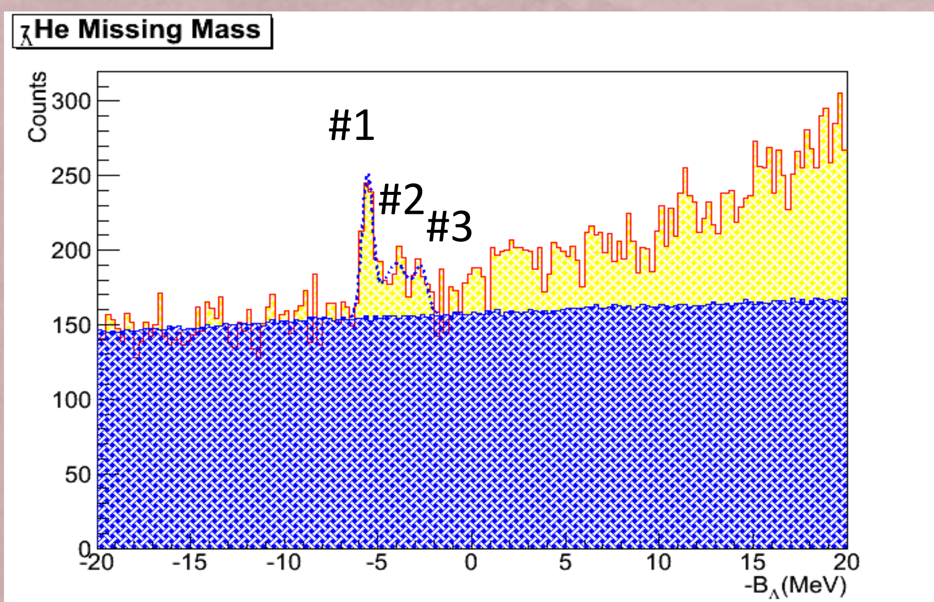
^{6}He core





peak	Mean(MeV)	σ(KeV)
1	-5.54	253
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3	-2.97	375

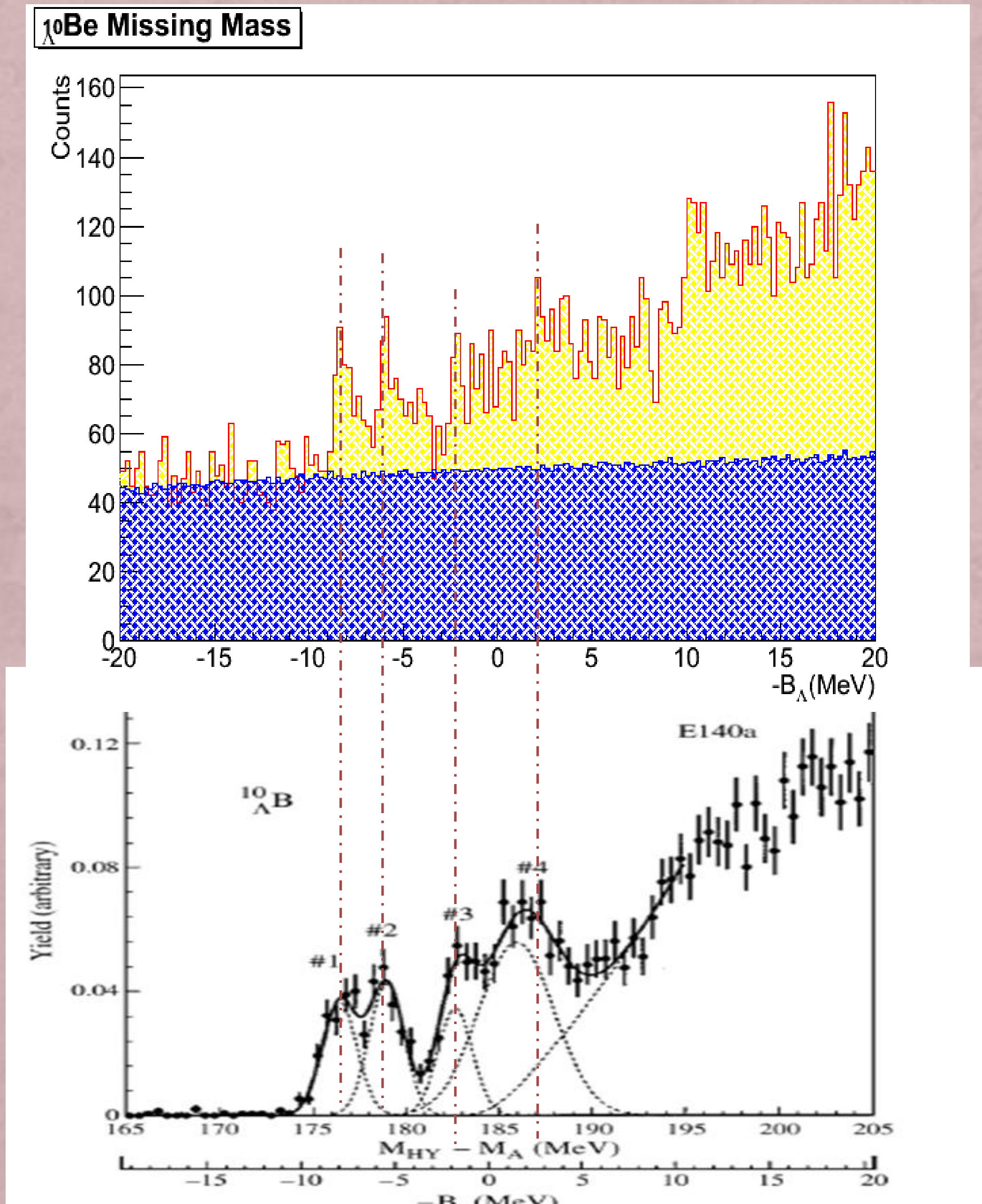
ΔE_Λ ~ 130keV

$\frac{3^+}{2} / \frac{5^+}{2}$

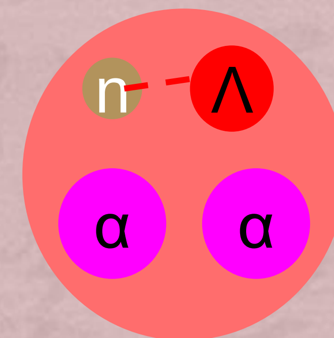
A resonance state

Possibility : Additional 2^+ core state

PRELIMINARY RESULT – $^{10}_{\Lambda}Be$

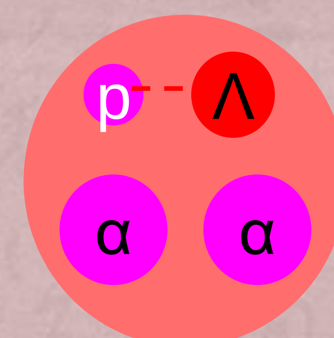


E05-115



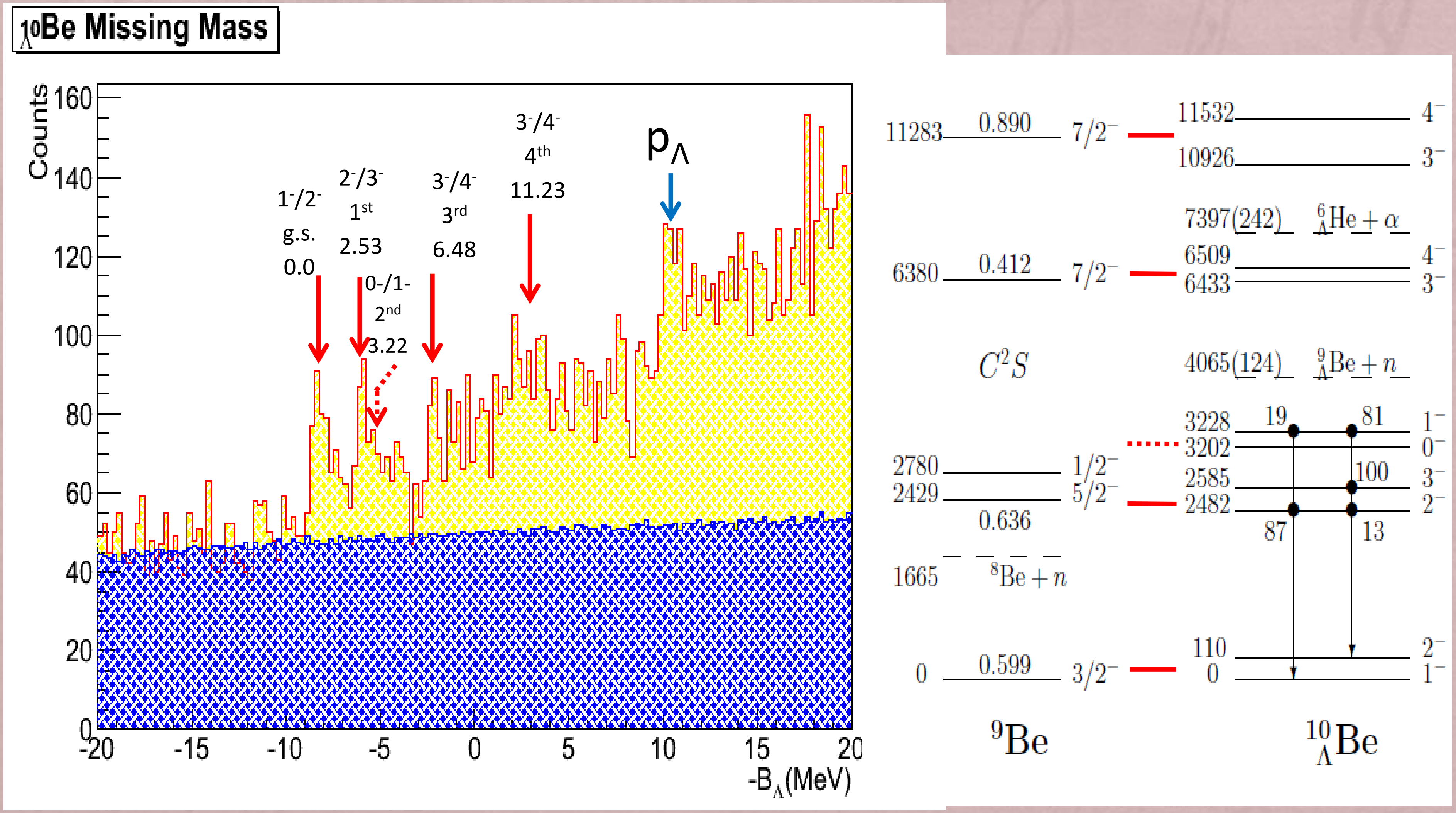
$^{10}_{\Lambda}Be$

KEK-E140a
$^{10}{}_{\Lambda}B$



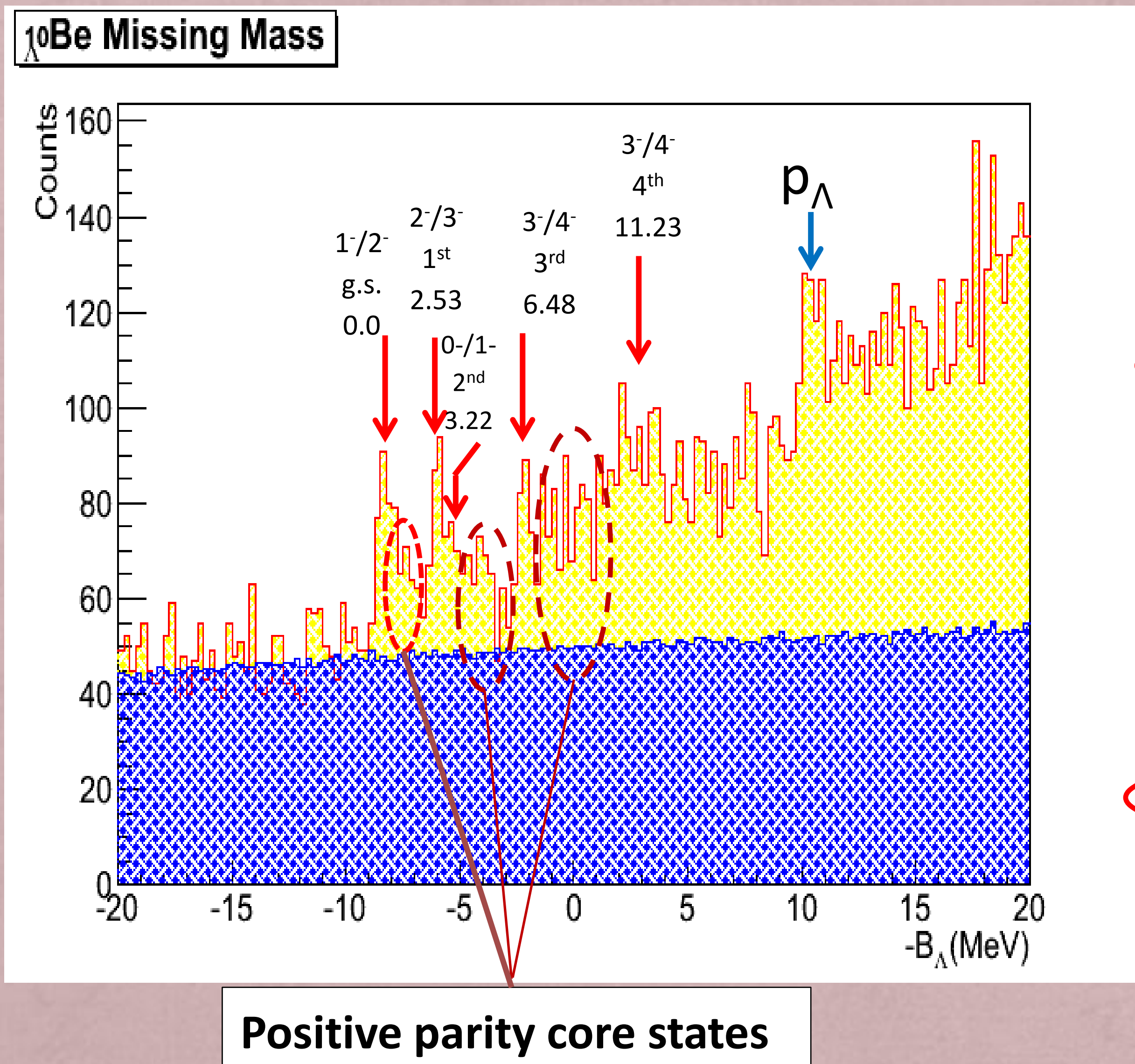
$^{10}_{\Lambda}B$

PRELIMINARY RESULT – $^{10}_{\Lambda}Be$



Calculated by D.J. Millener

PRELIMINARY RESULT – $^{10}{}_{\Lambda}$Be

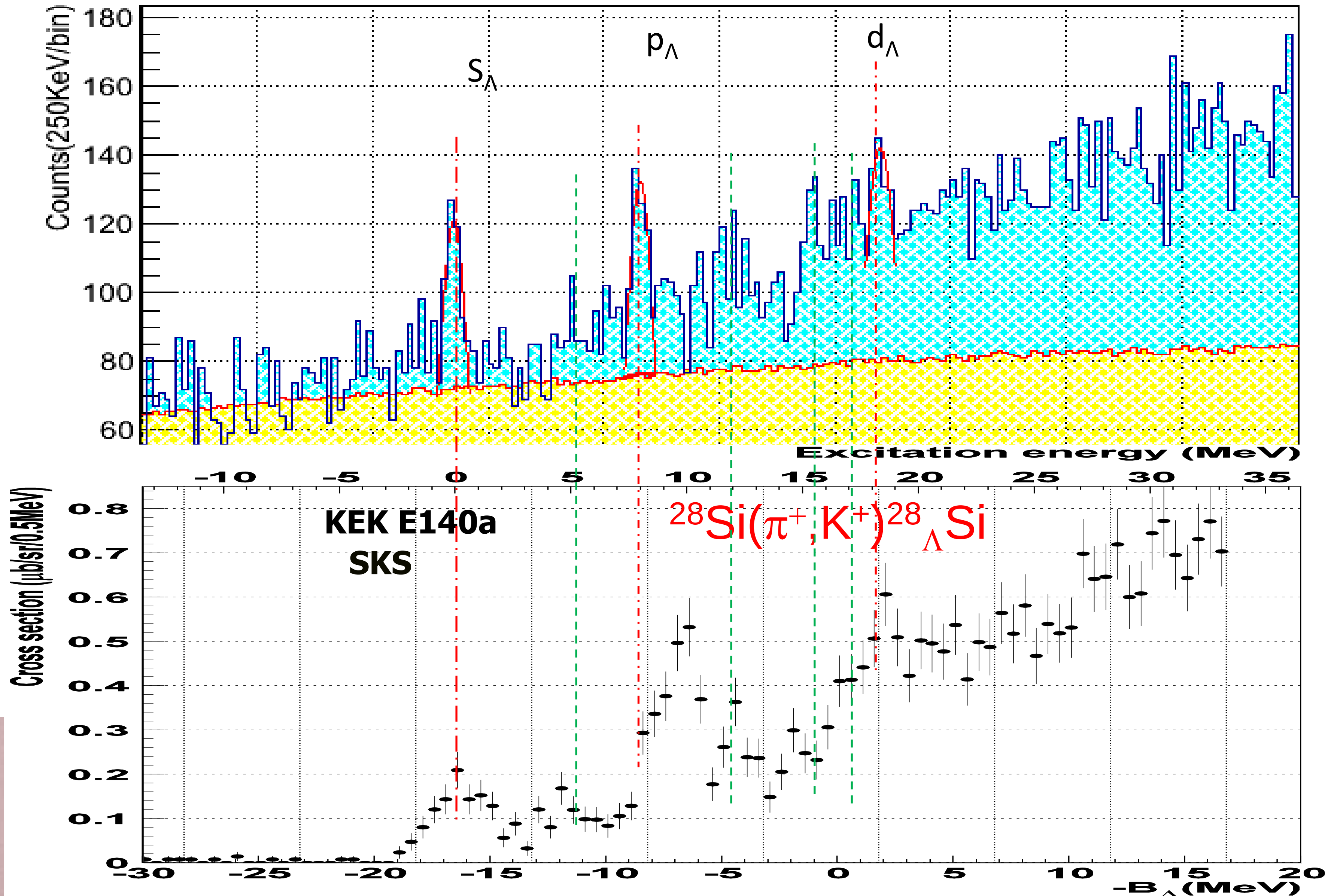


Mirror states ($T = \frac{1}{2}$) in $A = 9$ nuclei[a]

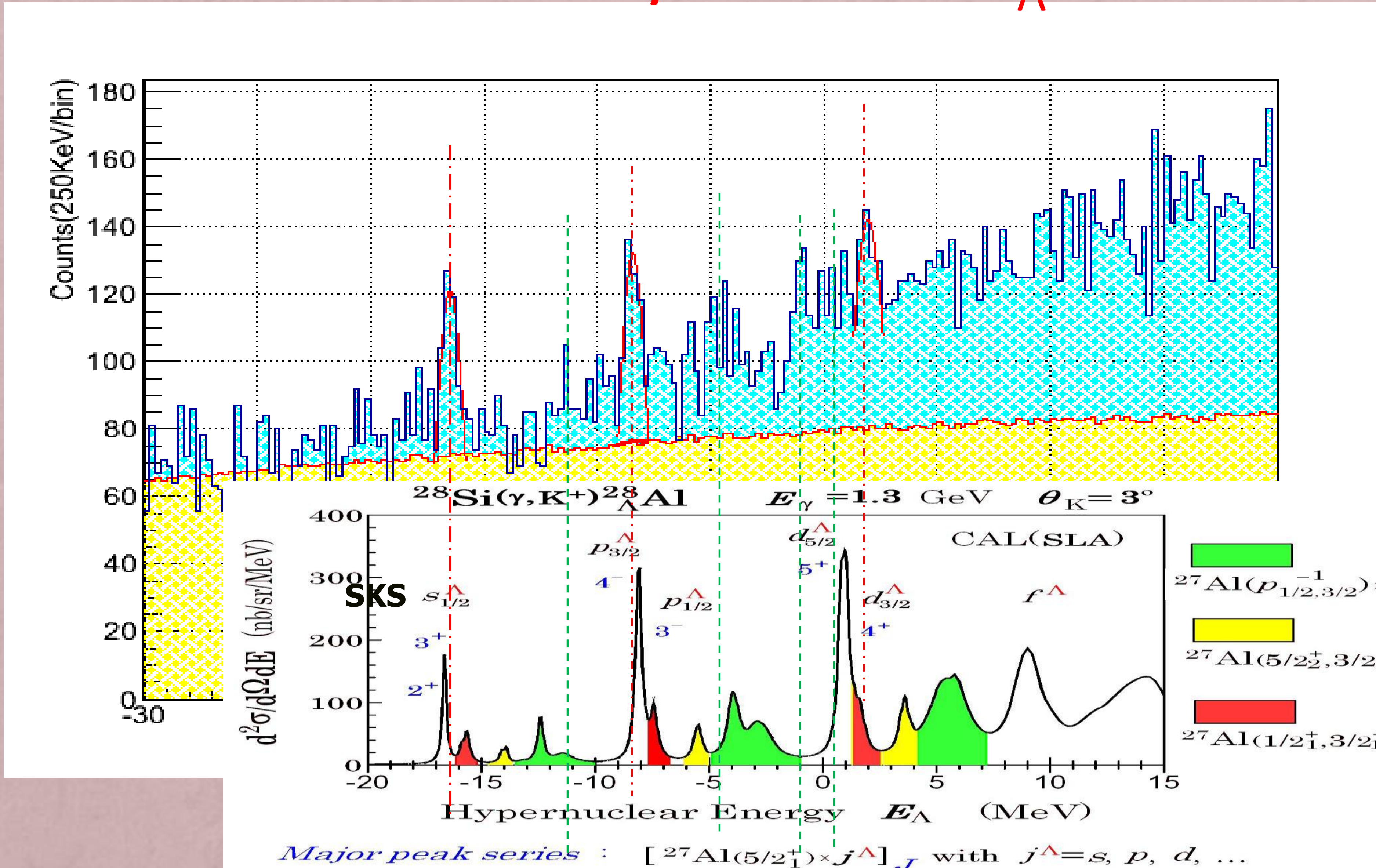
^{9}Be

E_x (MeV)	J^{π}
0	$\frac{3}{2}^-$
1.684	$\frac{1}{2}^+$
2.429	$\frac{5}{2}^-$
2.78	$\frac{1}{2}^-$
3.049	$\frac{5}{2}^+$
4.704	$(\frac{3}{2})^+$
5.59	$(\frac{3}{2}^-)$
6.38[d]	$\frac{7}{2}^-$
6.76	$\frac{9}{2}^+$
7.94	$(\frac{5}{2}^-)$
11.283	$(\frac{7}{2}^-)$
11.81	$\frac{5}{2}^-$

Preliminary Status – $^{28}{}_{\Lambda}Al$



Preliminary Status – $^{28}{}_{\Lambda}$Al



SUMMARY

- Our systematic calibration is almost completed;
- The precise level structure of p-shell Λ hypernuclei ($^{7}_{\Lambda}He$, $^{10}_{\Lambda}Be$, and $^{12}_{\Lambda}B$) are evidential and encouraging;
- There is stronger evidence for sd-shell nuclei from spectroscopy of $^{12}_{\Lambda}B$ and $^{28}_{\Lambda}Al$;
- $^{52}_{\Lambda}V$ spectroscopy is coming soon.

BACK UP

CALIBRATION PROCEDURE

$$MM = f(E_{beam}, P_k, xt'_{k'}, yt'_k, P_{e'}, xt'_{e'}, yt'_{e'}) = f(Ebeam_0 + \Delta E_{beam0}, P_{k0} + \Delta P_{k0}, xt'_k, yt'_k, P_{e'0} + \Delta P_{e'0}, xt'_{e'}, yt'_{e'})$$

$$P = P0(1+\delta/100)$$

$$\begin{pmatrix} xt' \\ yt' \\ \delta \end{pmatrix} = (M) \begin{pmatrix} xf \\ xf' \\ yf \\ yf' \end{pmatrix} = \begin{pmatrix} M\_angle \\ M\_momentum \end{pmatrix} \begin{pmatrix} xf \\ xf' \\ yf \\ yf' \end{pmatrix}$$

- ❖ Field Map Correction → Real Optics
  - ✓ Agreement between Simulation data and Real SS data
  - ✓ Independence of invariant mass to reconstructed kinematical parameters. (Λ&Σ; P,xt',yt')

Initial Matrices

- ❖ Mathematical optimization by **Nonlinear Least Chi^2 fitting**

  a. Central kinematics scan (m_Λ,m_Σ,$\Delta m_{\Lambda\Sigma}$)

  b. Angular matrices (m_Λ,m_Σ,σ)

  c. Momentum matrices ($^{12}{}_\Lambda$Bgs)

  d. Iteration

Kinematics of the E05-115 Experiment

Electron beam

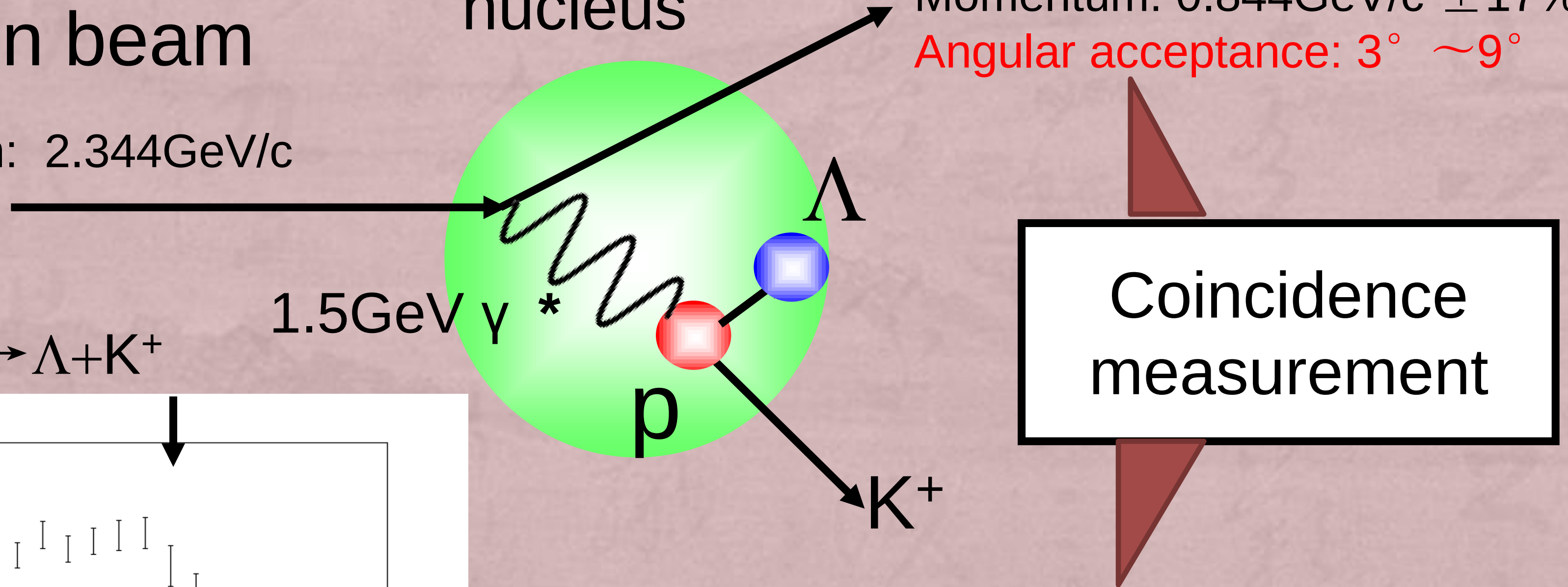
Momentum: 2.344GeV/c

Target nucleus

Scattered electron

Momentum: 0.844GeV/c ±17%

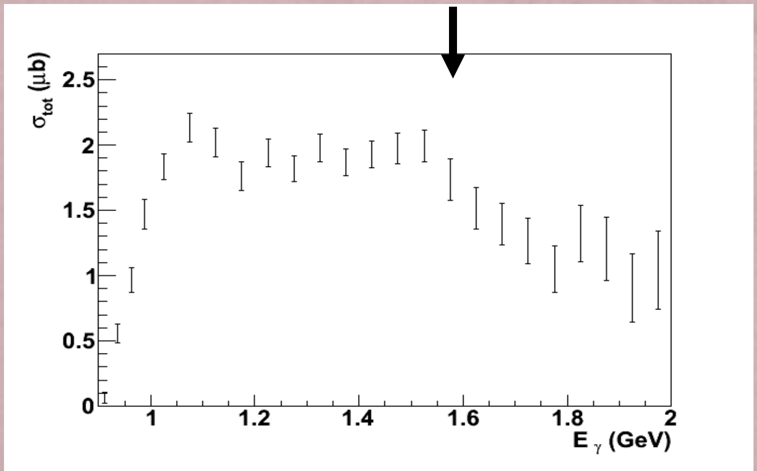
Angular acceptance: 3° ～9°



Momentum: 1.2GeV/c ±12.5%

Angular acceptance : 1° ～13°

$\gamma + p \rightarrow \Lambda + K^+$



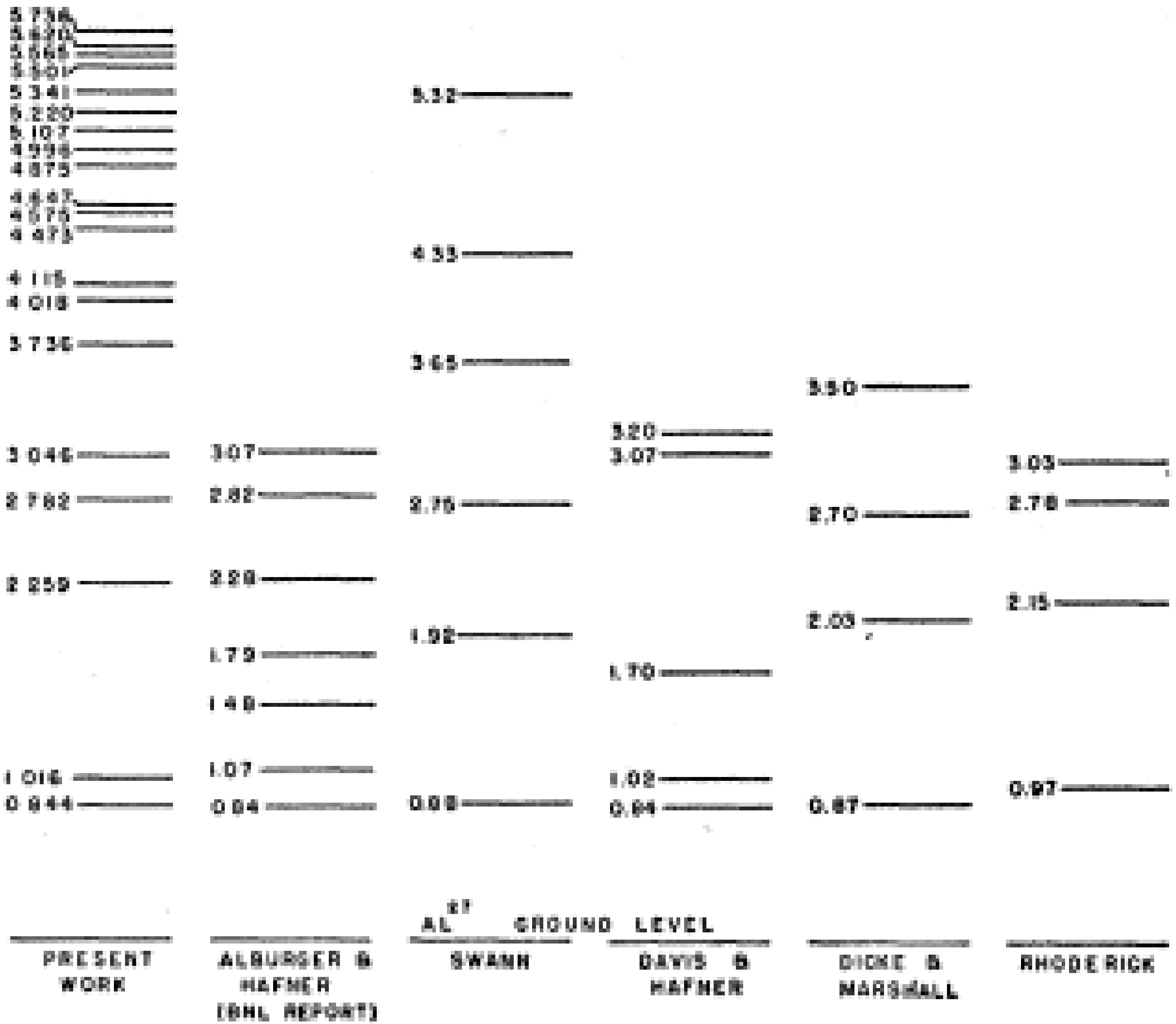
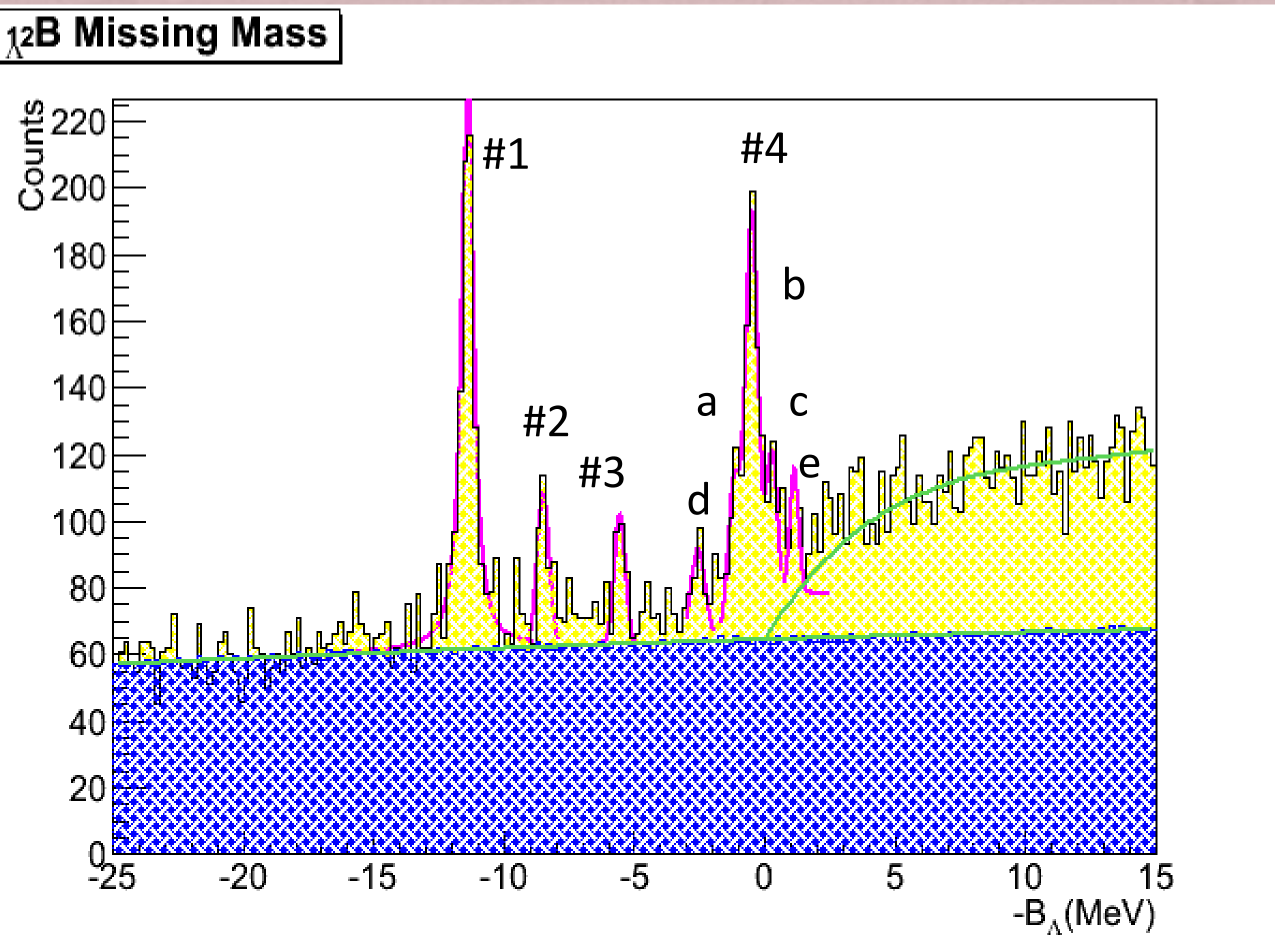
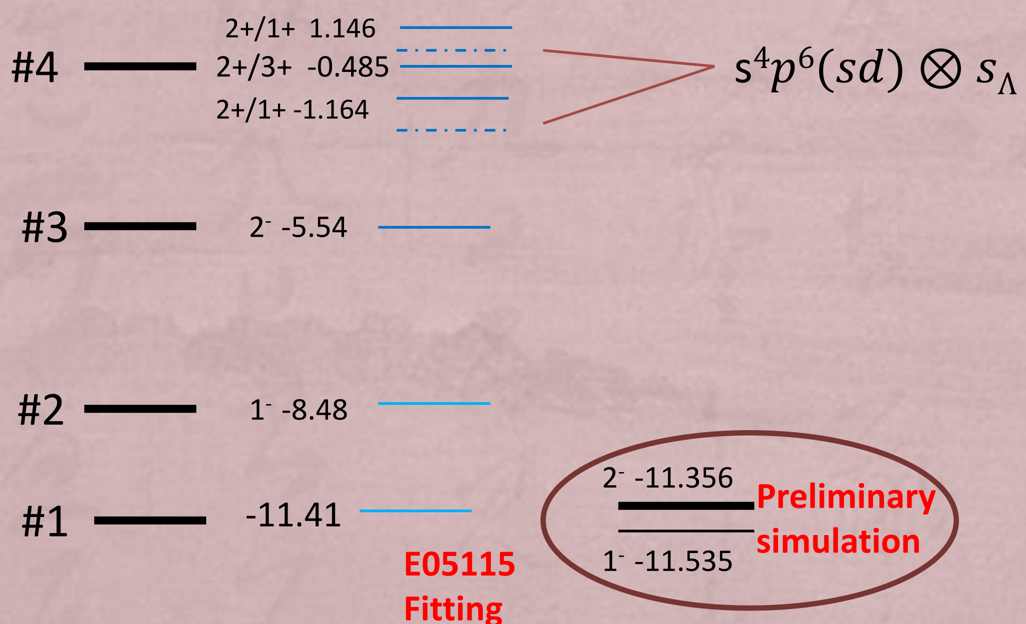


FIG. 2. Energy level scheme for Al^{27}.

$^{12}_{\Lambda}B$

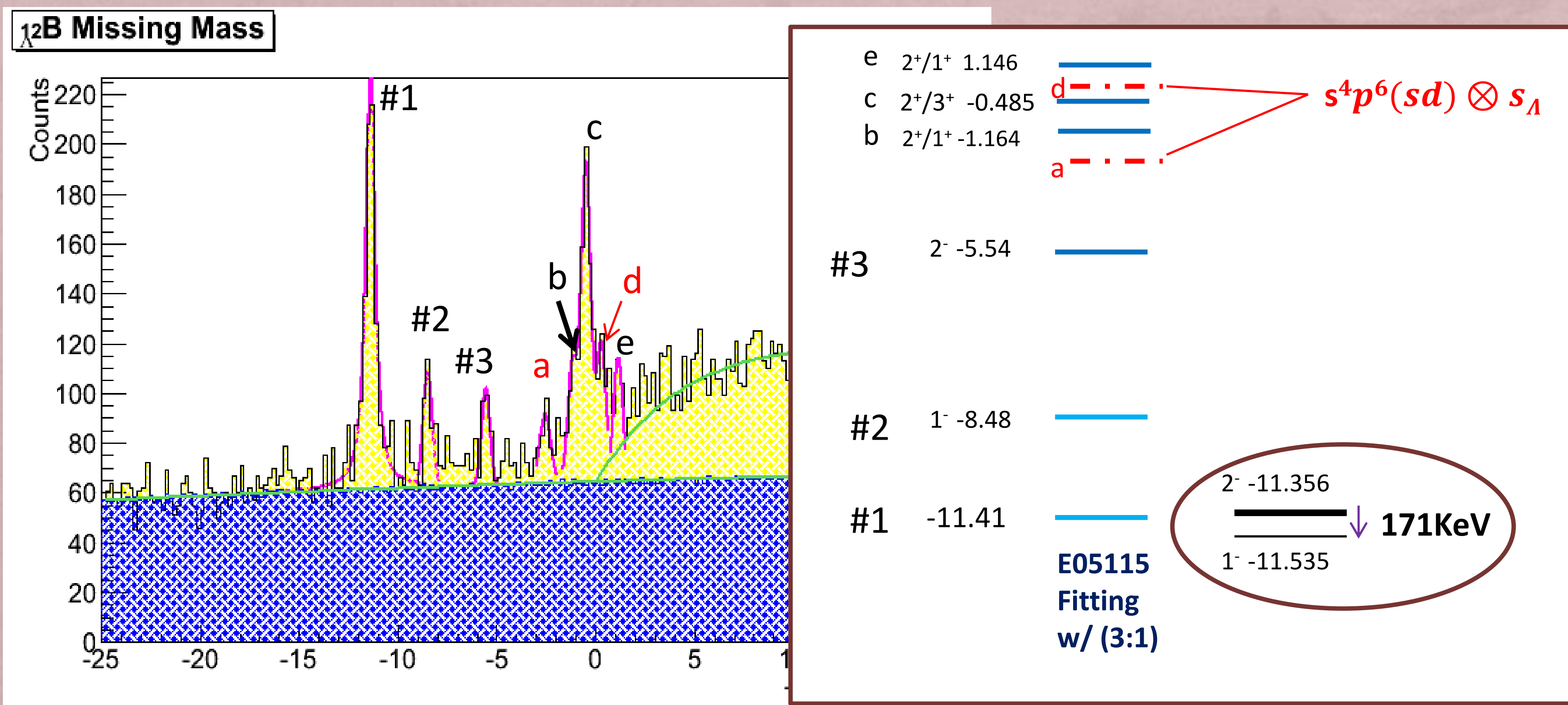


peak		Mean(MeV)	σ(KeV)
1		-11.41	265
2		-8.48	231
3		-5.54	210
4	a	-1.164	240
	b	-0.485	
	c	0.295	
	d	-2.539	281
	e	1.146	172



<table>
<tr><th colspan="2">peak</th><th>Mean(MeV)</th><th>σ(KeV)</th></tr>
<tr><td colspan="2">1</td><td>-11.41</td><td>265</td></tr>
<tr><td colspan="2">2</td><td>-8.48</td><td>231</td></tr>
<tr><td colspan="2">3</td><td>-5.54</td><td>210</td></tr>
<tr><td rowspan="5">4</td><td>a</td><td>-1.164</td><td rowspan="3">240</td></tr>
<tr><td>b</td><td>-0.485</td></tr>
<tr><td>c</td><td>0.295</td></tr>
<tr><td>d</td><td>-2.539</td><td>281</td></tr>
<tr><td>e</td><td>1.146</td><td>234</td></tr>
</table>

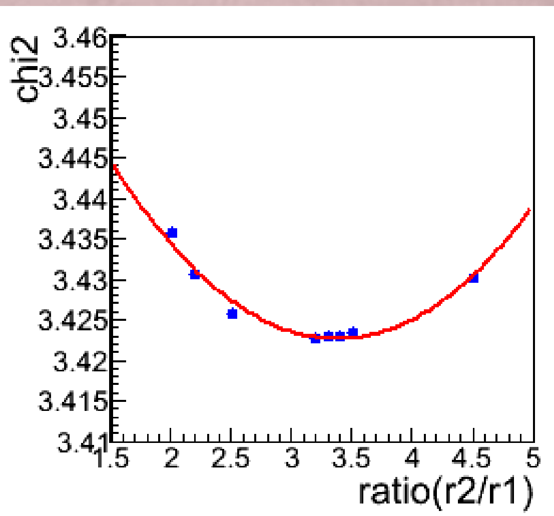
$^{12}{}_{\Lambda}B$

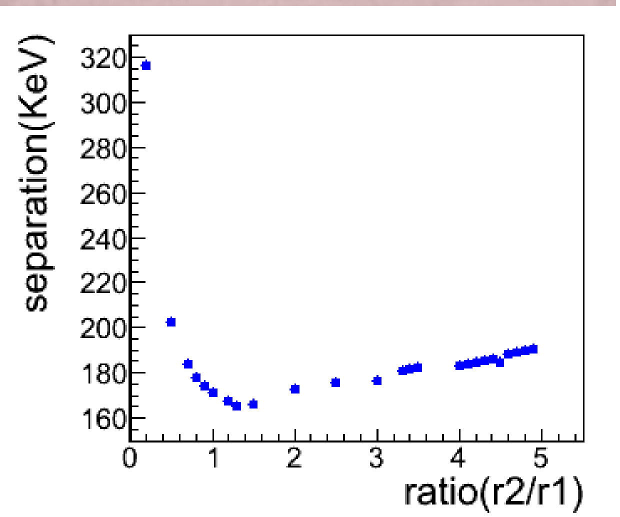


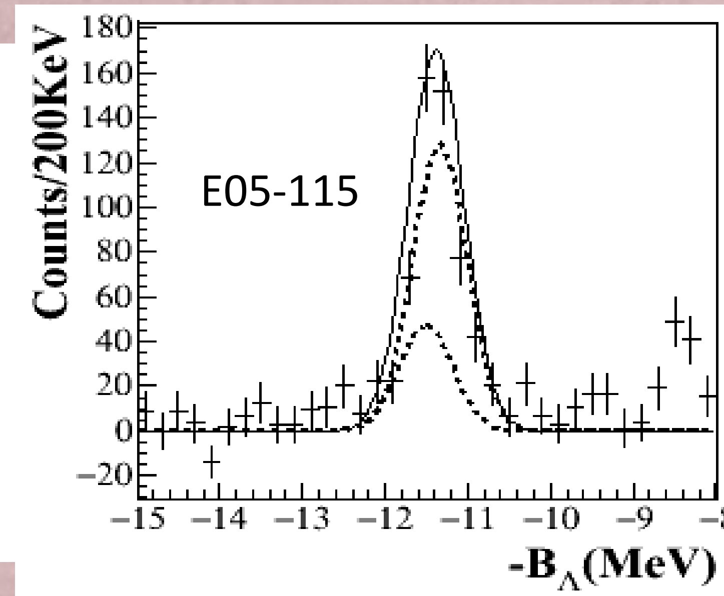
Λ12B Missing Mass
Counts
#1
#2
#3
a
b
c
d
e
e 2+/1+ 1.146
c 2+/3+ -0.485
b 2+/1+ -1.164
d
a
$s^4p^6(sd) \otimes s_\Lambda$
#3 2- -5.54
#2 1- -8.48
#1 -11.41
2- -11.356
171KeV
1- -11.535
E05115
Fitting
w/ (3:1)

Peak	B_Λ (MeV) (E05-115)	B_Λ (MeV) (E01-011)	Average B_Λ (MeV)	Cross section (nb/sr) (E05-115)	Cross section (nb/sr) (E01-011)
#1-1 **#1-2**	-11.508 ± 0.025 -11.338 ± 0.025	-11.521 ± 0.031 -11.344 ± 0.031	-11.515 ± 0.028 -11.341 ± 0.028	83.0 ± 3.0	101.0 ± 4.2
#2	-8.425 ± 0.047	-8.390 ± 0.075	-8.408 ± 0.063	19.1 ± 4.7	33.5 ± 6.0
#3	-5.488 ± 0.052	-5.440 ± 0.085	-5.462 ± 0.070	18.0 ± 4.6	26.0 ± 5.4
#4	-2.499 ± 0.075	-2.882 ± 0.085	-2.691 ± 0.080	16.2 ± 4.8	20.5 ± 5.0
#5	-1.220 ± 0.056	-1.470 ± 0.091	-1.345 ± 0.076	28.7 ± 6.2	31.5 ± 6.3
#6	-0.524 ± 0.024	-0.548 ± 0.035	-0.536 ± 0.030	75.7 ± 12.1	87.7 ± 11.5
#7	0.223 ± 0.039	0.318 ± 0.085	0.271 ± 0.066	39.0 ± 7.7	46.3 ± 16.4
#8	1.047 ± 0.078	0.849 ± 0.101	0.948 ± 0.090	27.8 ± 5.8	28.5 ± 10.8

$^{12}{}_{\Lambda}B$







Double gaussian Fitting for $^{12}{}_{\Lambda}$Bg.s. from 2009 data

σ= 229 – 233 KeV σ_average = 231KeV

Separation_1^{-} /2^{-} = 149 – 191 KeV Separation_1^{-} /2^{-} _average = 170 KeV

Ratio(2^{-} /1^{-}) = 0.9 – 4.5 Ratio(2^{-} /1^{-})_average = 2.7

Double gaussian Fitting for $^{12}{}_{\Lambda}$Bg.s. from 2005 data

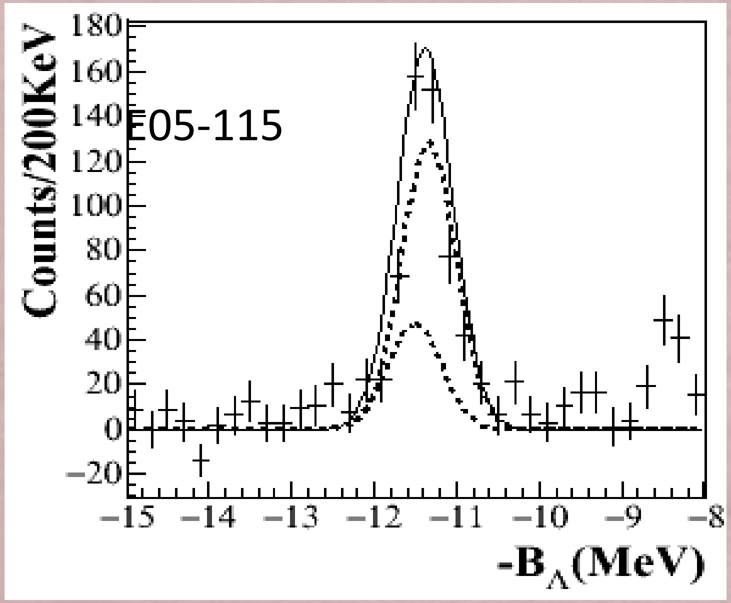
σ= 297 – 303 KeV σ_average = 300KeV

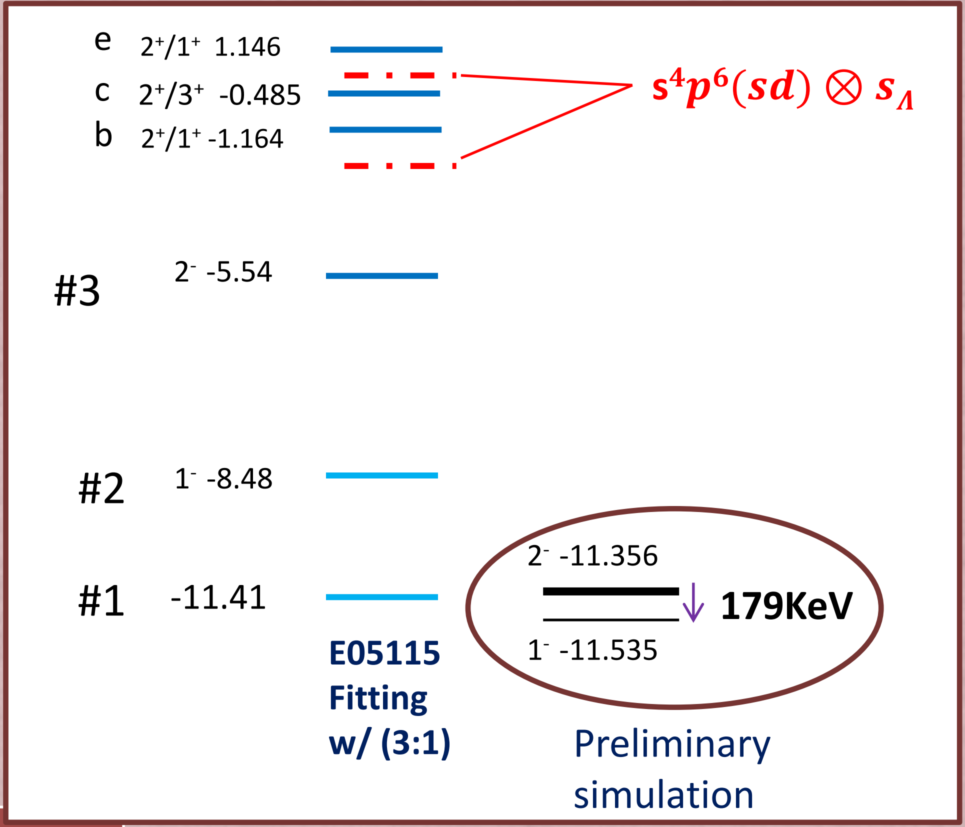
Separation_1^{-} /2^{-} = 156 – 185 KeV Separation_1^{-} /2^{-} _average = 177 KeV

Ratio(2^{-} /1^{-}) = 1.7 – 5.5 Ratio(2^{-} /1^{-})_average = 3.35

$^{12}{}_{\Lambda}B$

Double gaussian Fitting for $^{12}{}_{\Lambda}$Bg.s.

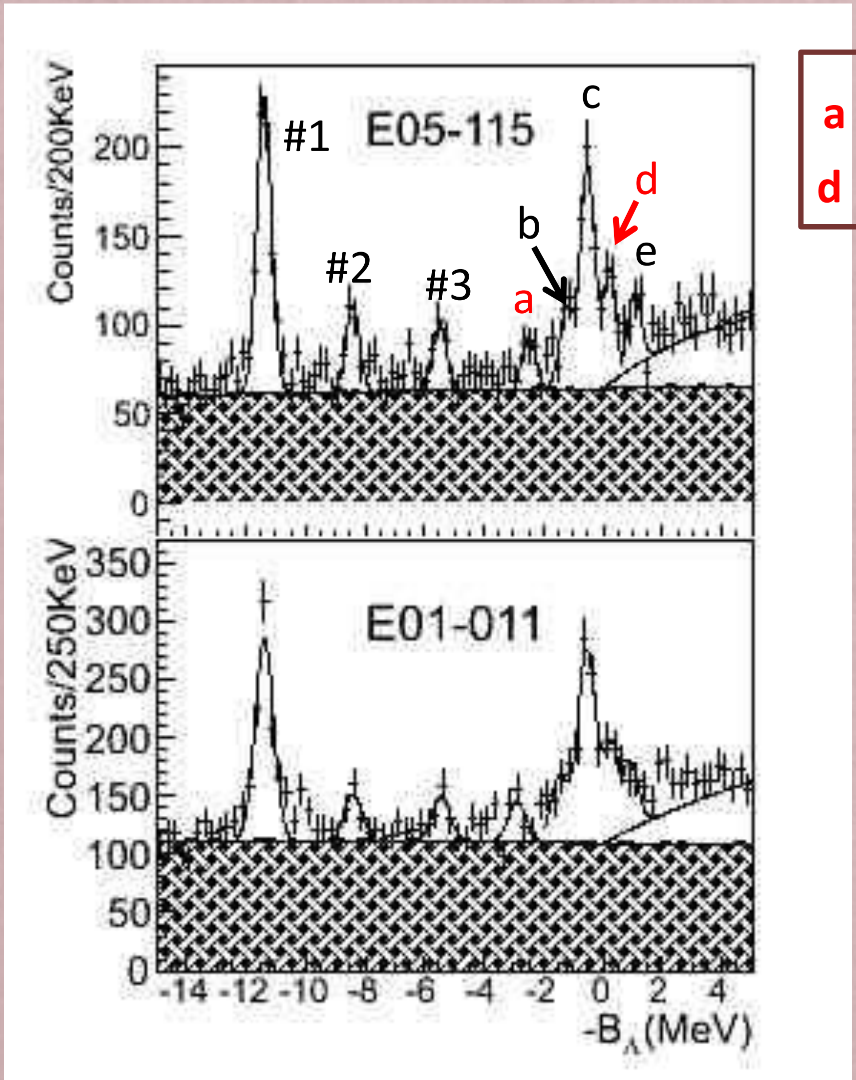




Experiment	Fitting σ (KeV)	Separation (KeV)	ratio
E05-115	231±2	170±21	2.7±1.8
E01-011	300±3	177±21	3.35±1.65

$^{12}{}_{\Lambda}B$

States from Λ in p-shell



a	9.009±0.077	*SD shell ^{11}B Core $\otimes S_{\Lambda}$*
d	11.731±0.043	*SD shell ^{11}B Core $\otimes S_{\Lambda}$*

From $1\hbar\omega$ calculation, the sd-shell core has three bands:
(1) 7.286(5/2+) and 7.978(3/2+);
(2) 9.272(5/2+) and 9.873(3/2+); and
(3) 11.60(5/2+)

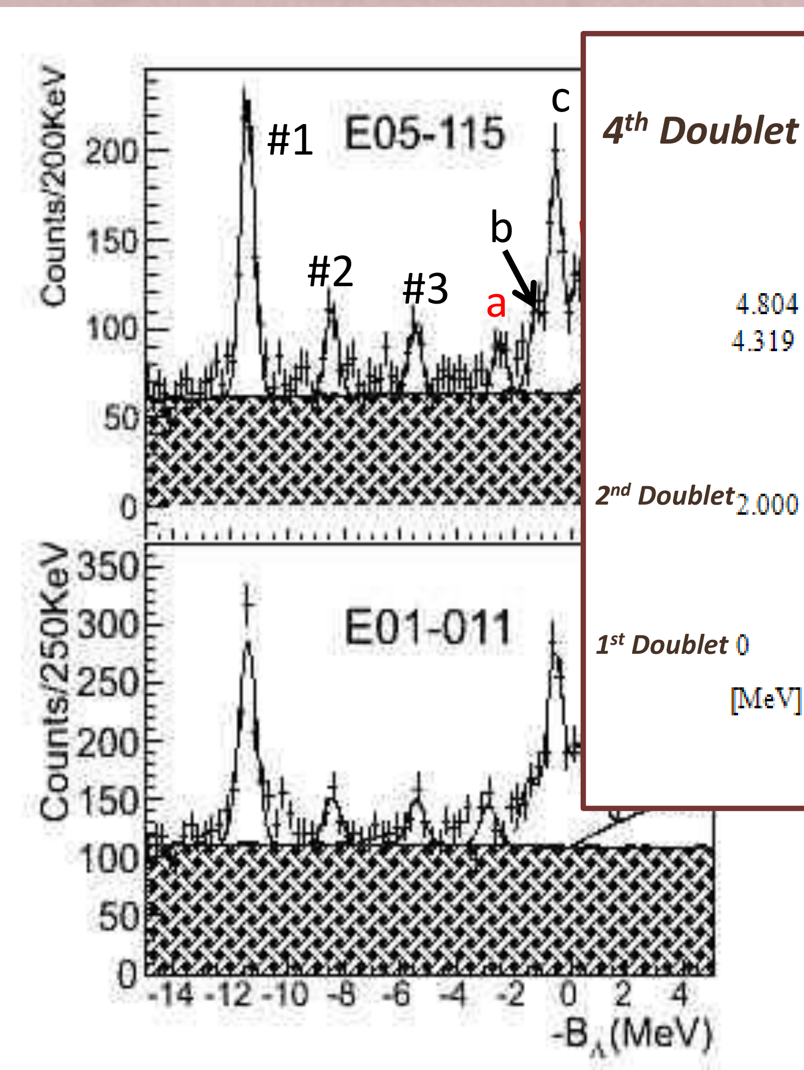
sd shell ^{11}B shell structure: $S^4P^6(sd)$

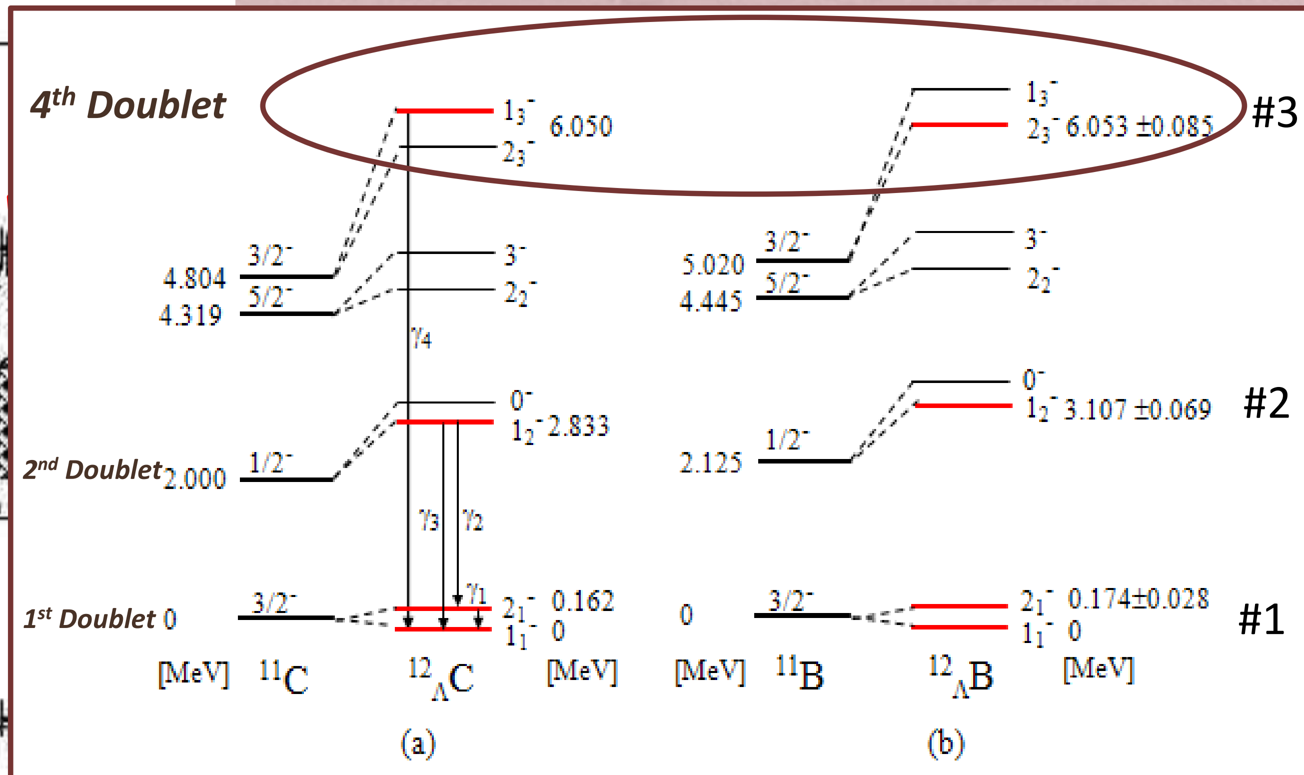
Such unpredicted structures appear to be common in previously measured $^{12}{}_{\Lambda}C$ and $^{12}{}_{\Lambda}B$ spectrum

Peak	Average B_Λ (MeV)	Average E_x (MeV)	Structure	J^π	Cross section (nb/sr) (E01-011)	Cross section (nb/sr) (Theory Estimate)
#1-1 #1-2	-11.515 ± 0.028 -11.341 ± 0.028	0.000 0.174 ± 0.028	$^{11}B(3/2^-; g.s.) \otimes s_{1/2\Lambda}$ $^{11}B(3/2^-; g.s.) \otimes s_{1/2\Lambda}$	1_1^- 2_1^-	101.0 ± 4.2	99.8
#2	-8.408 ± 0.063	3.107 ± 0.069	$^{11}B(1/2^-; 2.125) \otimes s_{1/2\Lambda}$ $^{11}B(1/2^-; 2.125) \otimes s_{1/2\Lambda}$	1_2 0^-	33.5 ± 6.0	32.8
#3	-5.462 ± 0.070	6.053 ± 0.085	$^{11}B(3/2^-; g.s.) \otimes s_{1/2\Lambda}$ $^{11}B(3/2^-; g.s.) \otimes s_{1/2\Lambda}$	1_1^- 2_1^-	26.0 ± 5.4	12.4 4.0
#4	-2.691 ± 0.080	8.824 ± 0.085			20.5 ± 5.0	
#5	-1.345 ± 0.076	10.170 ± 0.081	$^{11}B(3/2^-; g.s.) \otimes p_{3/2\Lambda}$ $^{11}B(3/2^-; g.s.) \otimes p_{\Lambda}$	2_1^+ 1_1^+	31.5 ± 6.3	5.1 2.6
#6	-0.536 ± 0.030	10.979 ± 0.041	$^{11}B(3/2^-; g.s.) \otimes p_{1/2\Lambda}$ $^{11}B(3/2^-; g.s.) \otimes p_{3/2\Lambda}$	2_2^+ 3_1^+	87.7 ± 11.5	30.5 46.7
#7	0.271 ± 0.066	11.786 ± 0.072			46.3 ± 16.4	
#8	0.948 ± 0.090	12.463 ± 0.094	$^{11}B(1/2^-; 2.125) \otimes p_{3/2\Lambda}$ $^{11}B(1/2^-; 2.125) \otimes p_{\Lambda}$	2_3^+ 1_3^+	28.5 ± 10.8	19.4 5.8

$^{12}_{\Lambda}B$

States from Λ in s-shell coupled to the low lying ^{11}B core states





4th doublet separation: $\Delta E(1_3^- - 2_3^-) \approx$ 0.213 (±0.09stat. ±0.07sys.) MeV

Theory prediction: $\Delta E(1_3^- - 2_3^-) =$ 0.107 MeV(Millener)

TABLE 11.4

Energy levels of ^{11}B

E_x (MeV ± keV)	$J^\pi; T$	τ_m (fsec) [a]) or $\Gamma_{c\,m}$ (keV)	Decay	Reactions
0	$\frac{3}{2}^-; \frac{1}{2}$	stable	—	1, 2, 6 → 8, 12 → 17, 21 → 25, 28, 30 → 63
2.124693 ± 0.027	$\frac{1}{2}^-$	$\tau_m = 5.5 \pm 0.4$	γ	1, 6 → 8, 12 → 17, 21 → 23, 28, 30, 31, 33, 34, 37, 38, 41, 46, 48 → 55, 57 → 63
4.44489 ± 0.50	$\frac{5}{2}^-$	1.18 ± 0.04	γ	1, 2, 6 → 8, 12 → 14, 17, 21 → 23, 25, 27, 28, 30, 31, 33, 34, 37, 38, 41, 49, 51 → 54, 58 → 63

5.02031 ± 0.30	$\frac{3}{2}^-$	0.34 ± 0.01	γ	1, 6→8, 13, 14, 21→23, 25, 28, 30, 31, 33, 34, 37, 38, 49, 50, 52→54, 58→61, 63
6.7429 ± 1.8	$\frac{7}{2}^-$	22 ± 5	γ	1, 2, 6, 13, 14, 17, 21→23, 25, 27, 30, 34, 37, 38, 49, 52, 53, 55, 58, 59, 60, 62, 63
6.79180 ± 0.30	$\frac{1}{2}^+$	1.7 ± 0.2	γ	1, 2, 6, 13, 14, 21→23, 28, 30, 34, 38, 41, 52, 53, 55, 63
7.28551 ± 0.43	$\frac{5}{2}^+$	0.57 ± 0.04	γ	1, 2, 6, 12→14, 21→23, 28, 30, 34, 53, 63
7.97784 ± 0.42	$\frac{3}{2}^+$	0.57 ± 0.06	γ	1, 2, 13, 21, 22, 28, 30, 34
8.5603 ± 1.8	$\leqslant \frac{5}{2}^-$	0.70 ± 0.07	γ	1, 12, 13, 21, 22, 30, 31, 34, 59
8.9202 ± 2.0	$\frac{5}{2}^-$	$\Gamma = 4.37 \pm 0.02$ eV	γ, α	1, 2, 12, 13, 17, 21, 22, 25, 26, 30, 31, 34, 58, 59
9.1850 ± 2.0	$\frac{7}{2}^+$	$1.9^{+1.5}_{-1.1}$ eV	γ, α	1, 2, 13, 21, 22, 26, 34, 61
9.2744 ± 2	$\frac{5}{2}^+$	4	γ, α	1, 2, 13, 21, 22, 34, 61
9.876 ± 8	$\frac{3}{2}^+$	110 ± 15	α	5, 13, 28
10.26 ± 15	$\frac{3}{2}^-$	165 ± 25	γ, α	2, 5, 13
10.33 ± 11	$\frac{5}{2}^-$	110 ± 20	γ, α	2, 5, 13, 22, 34
10.597 ± 9	$\frac{7}{2}^+$	100 ± 20	γ, α	2, 5, 13, 18, 20, 34
10.96 ± 50	$\frac{5}{2}^-$	4500	α	5
11.265 ± 17	$\frac{9}{2}^+$	110 ± 20	α	5, 13
11.444 ± 19		103 ± 20	α	5, 13
11.589 ± 26	$\frac{5}{2}^+$	170 ± 30	n, α	3, 5, 13, 18, 20, 34
11.886 ± 17	$\frac{5}{2}^-$	200 ± 20	n, α	3, 5, 13, 18, 20
12.0 ± 200	$\frac{7}{2}^+$	≈ 1000	n, α	5, 18, 20