High Precision Hypernuclear Spectroscopy in JLab: The HKS Experiment

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For HKS collaboration

Hall C January meeting, Jan. 31, 2009

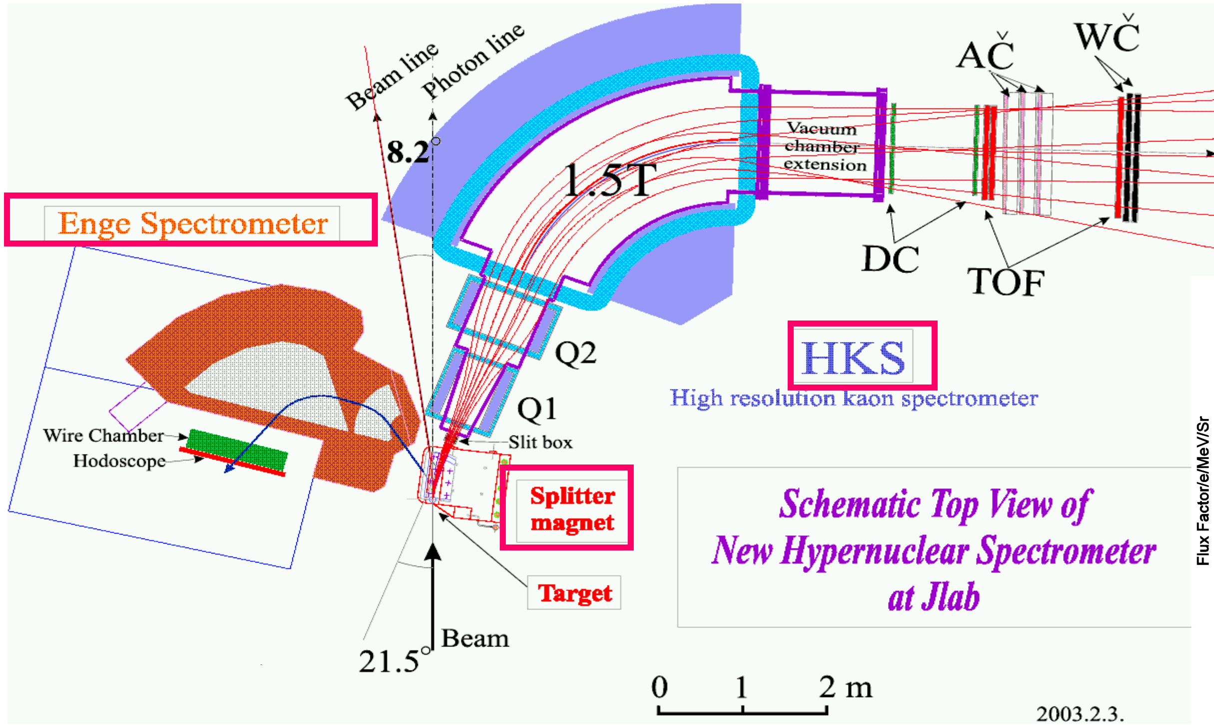
Hypernuclei: Unique Laboratory To Study Hyperon-Nucleon Interaction

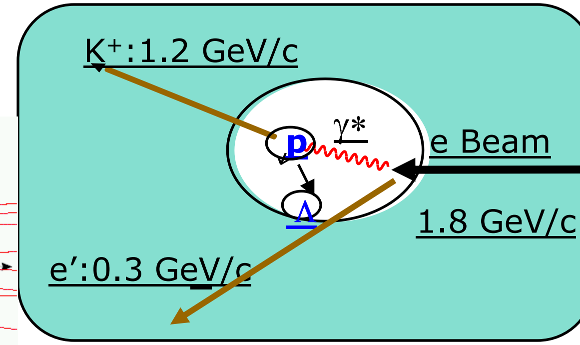
- Hypernuclear Spectroscopy: Probe hyperon-nucleon(YN) effective interaction inside medium
- Understand the role of hyperons in neutron star interior
- Much needed experimental data
  - High resolution hypernuclear spectra beyond p-shell
  - Precise binding energy determination in a wide mass range
  - Produce and study of exotic (highly neutron rich) hypernuclei

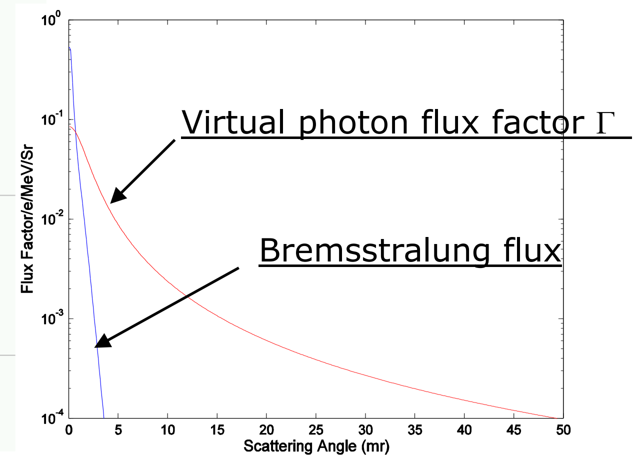
HKS Experimental Goals

- ***JLab HKS experiment: High precision hypernuclear spectroscopy by electroproduction from lower p-shell to medium-heavy mass systems***
  - Electroproduction: $^{A}Z + e \rightarrow {}^{A}_{\Lambda}(Z-1) + e' + K^{+}$
  - Produce $^{7}_{\Lambda}He$, $^{12}_{\Lambda}B$ and $^{28}_{\Lambda}Al$
- ~400 keV energy resolution achievable by utilizing high precision electron beam
- Study of high spin, unnatural parity states complementary to hadronic reactions
- High resolution spectroscopy beyond p-shell-- $^{28}_{\Lambda}Al$
- Possibly resolve spin-doublet splitting
- Neutron rich systems -- $^{7}_{\Lambda}He$

HKS Experimental Setup







- Data taking at JLab Hall C during summer of 2005
- Experimental setup: **Increasing yield and reduce accidental background**
  - Accept very forward angle e’: using Splitter magnet on target
  - Vertically tilt electron spectrometer

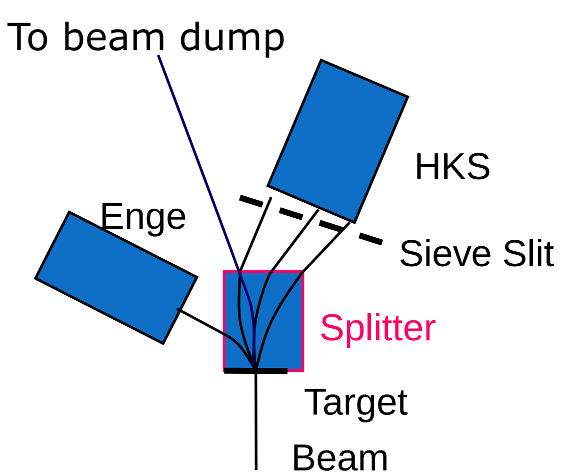
Spectrometer System Calibration

A precise spectrometer system calibration is a challenging task because of the unique optical features of the HKS spectrometer system:

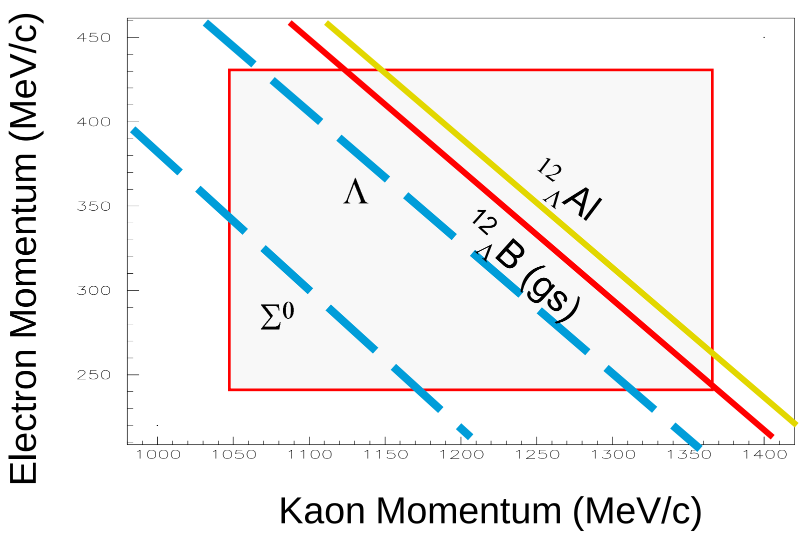
- On-target splitter field couple e’ and K+ arms– only one fixed kinematics setting
- High accidental background in calibration data

Using known masses of Λ, Σ^0 from CH2 target and identified hypernuclear bound states for spectrometer calibration

HKS spectrometer system



Kinematics coverage



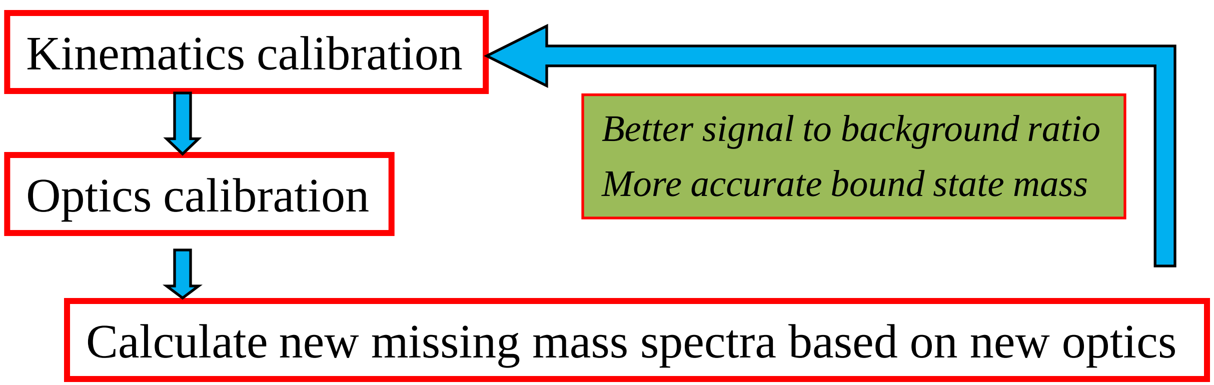
Spectrometer System Calibration Strategy

- Kinematics calibration: utilizing well known masses of Λ, Σ^0 produced from CH2. essential to determine binding energy level to a precision ~100 keV
- Spectrometer optics calibration: directly minimize Chisquare w.r.t reconstruction matrix M by an Nonlinear Least Square method

$$\chi^2 = \sum_i w_i (m_i^{cal} - m_i^{exp})^2 p_i = f(X_{fp} \mid M)$$

- Iteration

Iteration procedure for spectrometer calibration



Kinematics Calibration

- Correct kinematics determined by minimizing Λ and Σ^0 width χ^2

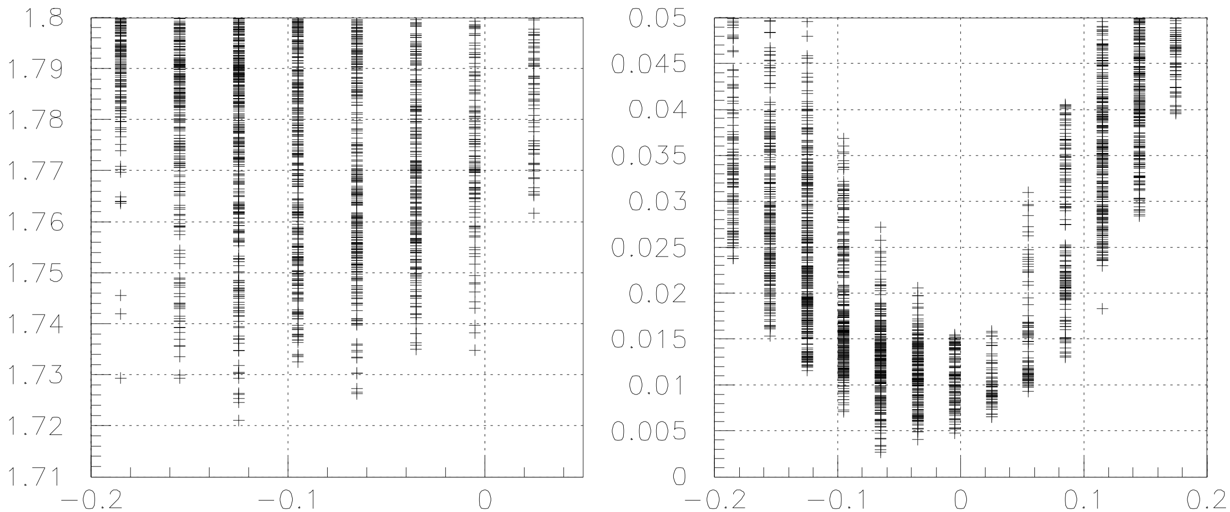
$$\chi^2_{CH2-wid} = 2\sigma^2_\Lambda + \sigma^2_\Sigma$$

Using position χ^2 as a constraint:

$$\chi^2_{CH2-pos} = 2(m^{fit}_\Lambda - m^{PDG}_\Lambda - \Delta m_\Lambda)^2 + (m^{fit}_\Sigma - m^{PDG}_\Sigma - \Delta m_\Sigma)^2$$

- Searching minimum χ^2 by a kinematics scan on offsets of beam energy, K and e' central momentum.

Dependence of χ^2_{wid} and χ^2_{pos} on kinematics offset V_{kin}



$$V_{kin} = \Delta E_b - \Delta P^0_K - \Delta P^0_E$$

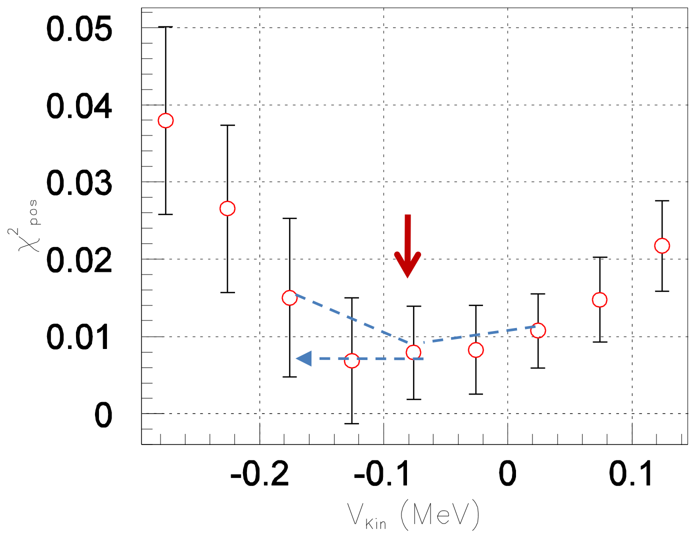
Systematic Error From Kinematics Calibration

1. uncertainty of the kinematics point obtained by the calibration: 0.102 MeV/c

$$\sigma_{\chi^2} = 0.006 \rightarrow \sigma_{V_{kin}} = 0.102 \text{ MeV/c}$$

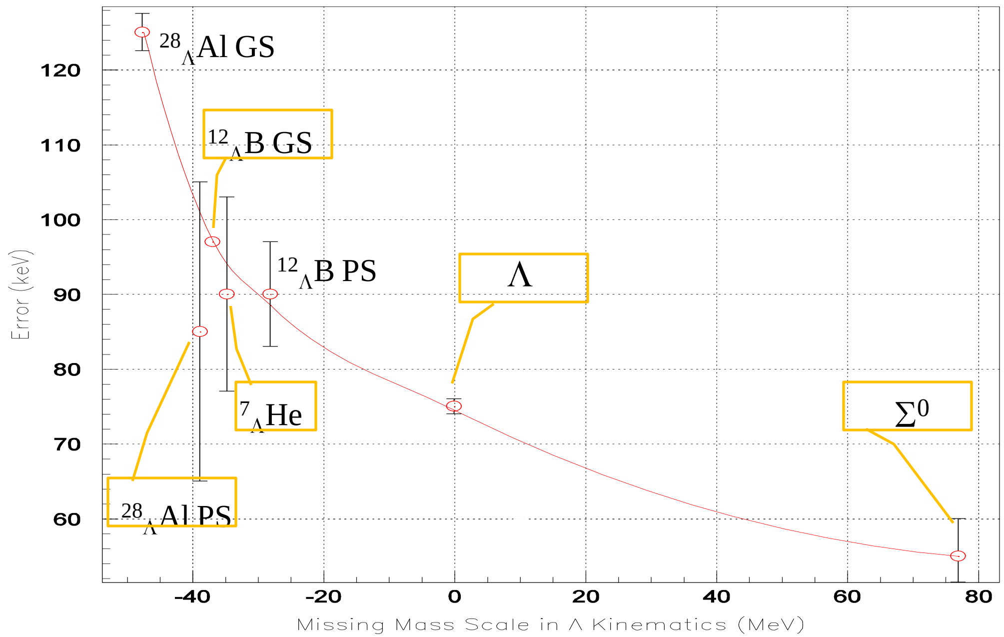
2. systematic errors of hypernuclear bound states binding energy are the shifts in binding energy resulting from the kinematics uncertainty

χ^2_{pos} vs. kinematics offset V_{kin}



$$V_{kin} = \Delta E_b - \Delta P^0_K - \Delta P^0_E$$

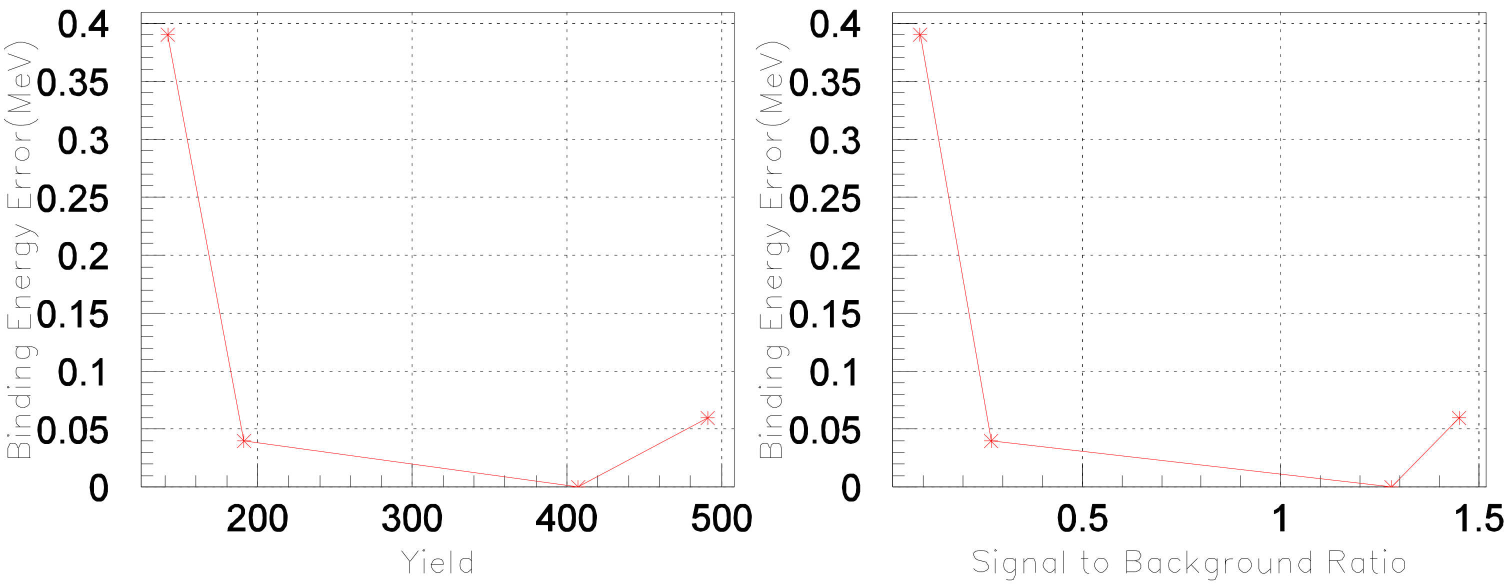
Binding energy errors vs. binding energy calculated under p(e,e'k) kinematics.



Systematic Error from Optical Calibration

- The systematic errors from optical calibration procedure are estimated based on the blind analysis result from simulated data
- The error depends on S/N ratio in missing mass spectrum

Binding energy error from optical calibration vs. S/N ratio in blind analysis



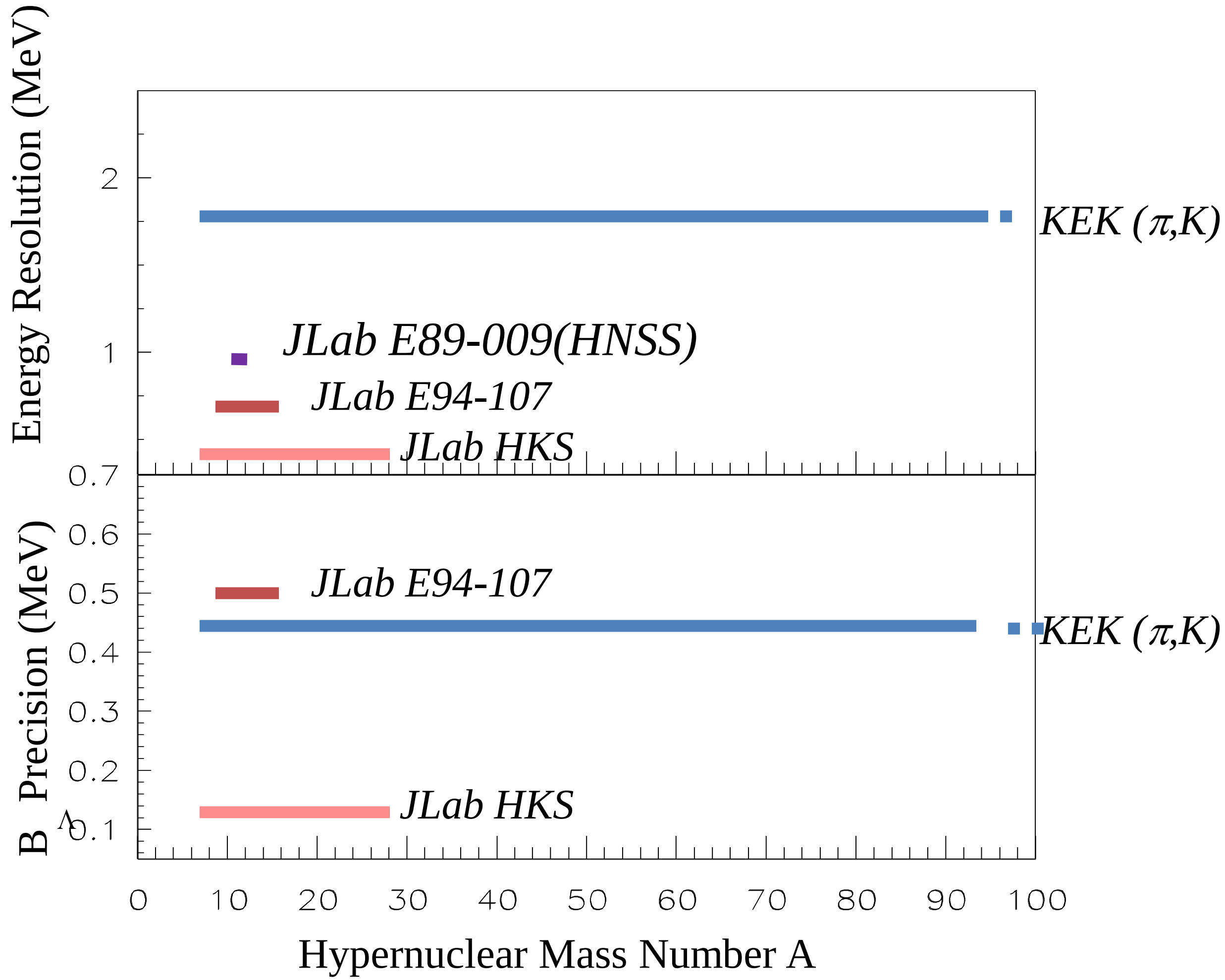
Summary Of The Spectra

Summary of the Finalized Spectroscopy						
State	B_Λ (MeV)	Ex (MeV)	Width σ (MeV)	Sys. Error (Kin.) (keV)	Sys. Error (Opt.) (keV)	Stat. Error (keV)
Λ	-0.001		0.752	±75	±31	±24
Σ^0	B_Σ = -0.054		0.780	±55	±22	±59
$^{12}_{\Lambda}$B (g.s.)	-11.559	0.000	0.198	±97	±50	±13
$^{12}_{\Lambda}$B (1st C.E.)	-8.758	2.801	0.188	±93	±50	±37
$^{12}_{\Lambda}$B (2nd C.E.)	-5.239	6.320	0.241	±91	±50	±67
$^{12}_{\Lambda}$B (p centroid)	-0.359	11.200	0.218	±90	±50	±20
$^{28}_{\Lambda}$Al (g.s.)	-17.820	0.000	0.179	±125	±50	±27
$^{28}_{\Lambda}$Al (p centroid)	-6.912	10.910	0.202	±101	±50	±33
$^{28}_{\Lambda}$Al (d centroid)	1.360	19.180	0.246	±92	±50	±42
$^{7}_{\Lambda}$He (g.s.)	-5.727	0.000	0.198	±94	±50	±41
$^{9}_{\Lambda}$Li (g.s.)	-5.634	0.000	0.193*	±94	±50	±184
$^{9}_{\Lambda}$Li (1st Ex.)	-4.348	1.296	0.192*	±93	±50	±147
$^{9}_{\Lambda}$Li (2nd Ex.)	-3.94	1.694	0.192*	±93	±50	±147
$^{9}_{\Lambda}$Li (3rd Ex.)	-2.670	2.964	0.277*	±91	±50	±123

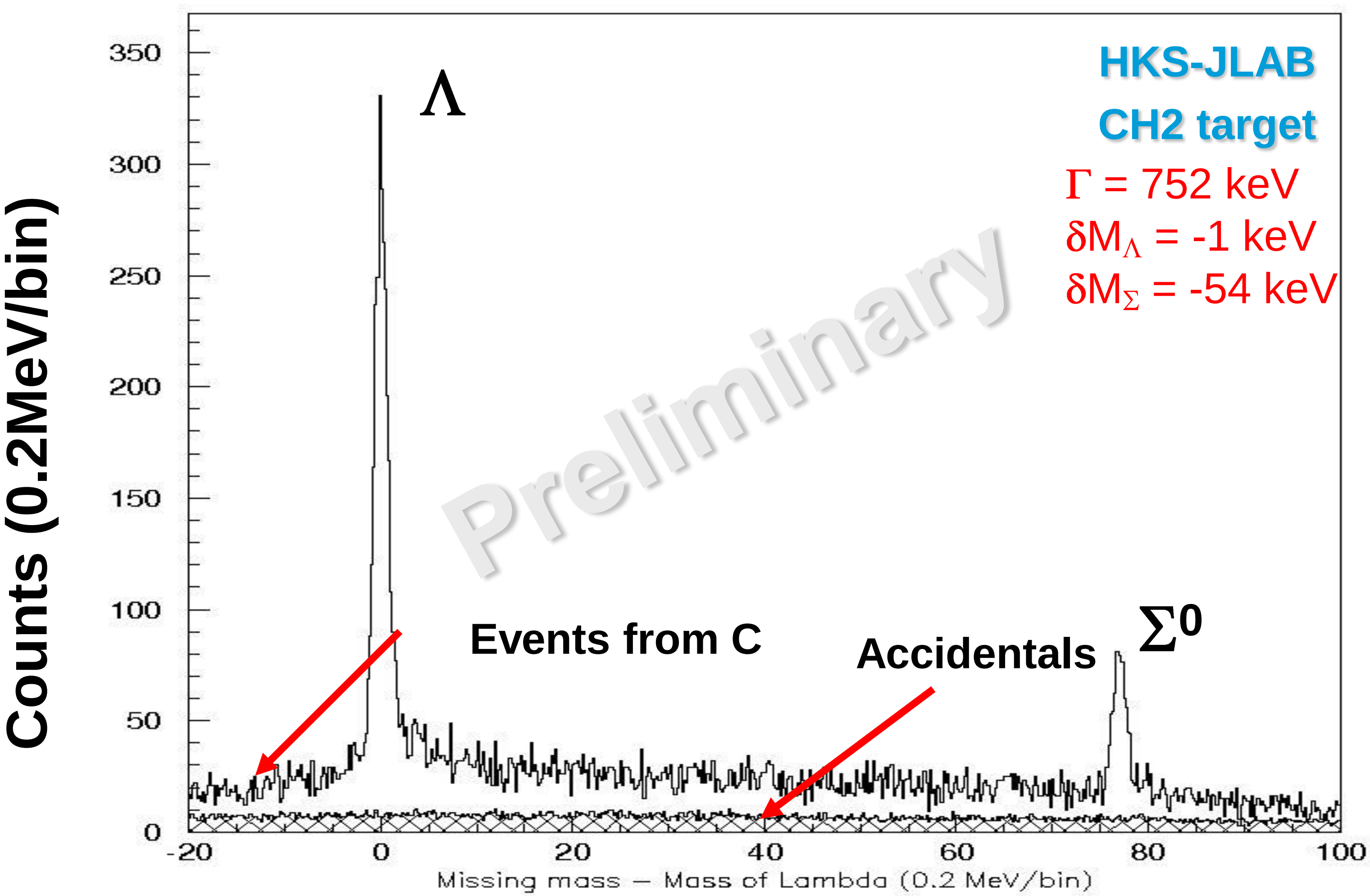
* The width of these peaks are effected by the statistics and background, but the binding energy values seemed stable within the statistical errors.

HKS Spectra: Energy Resolution And Binding Energy Precision

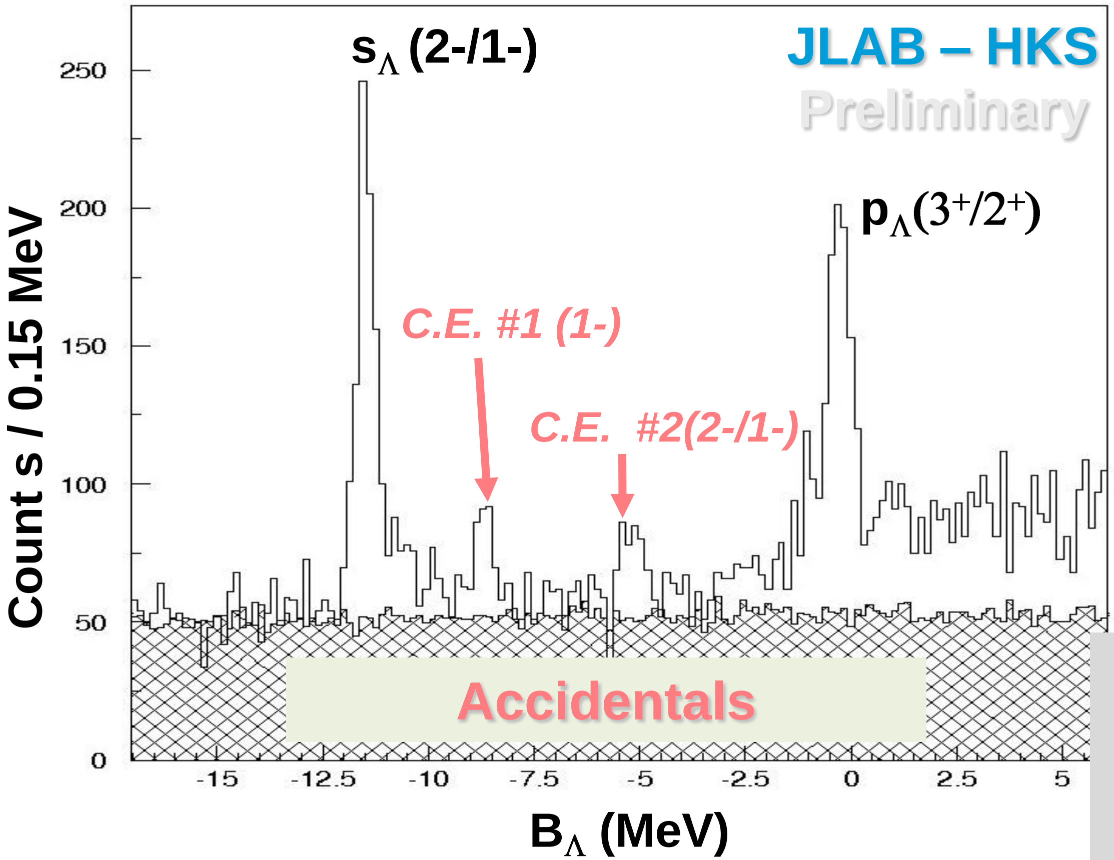
Current HKS Hypernuclear Spectra Compared With Previous Measurements In Terms of Energy Resolution And Binding Energy Precision

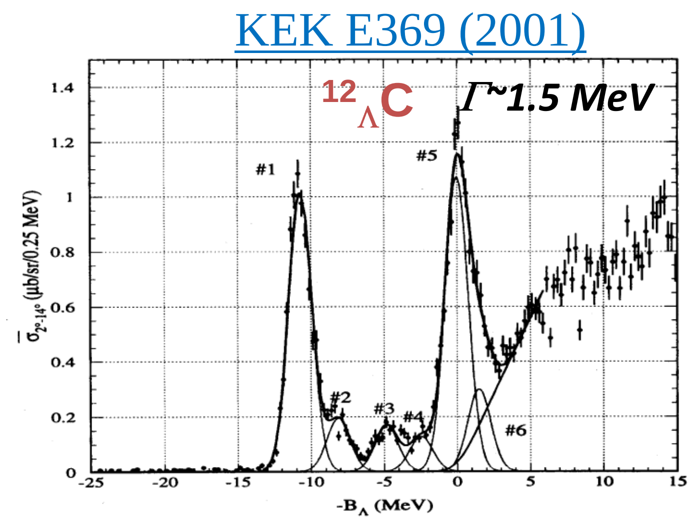


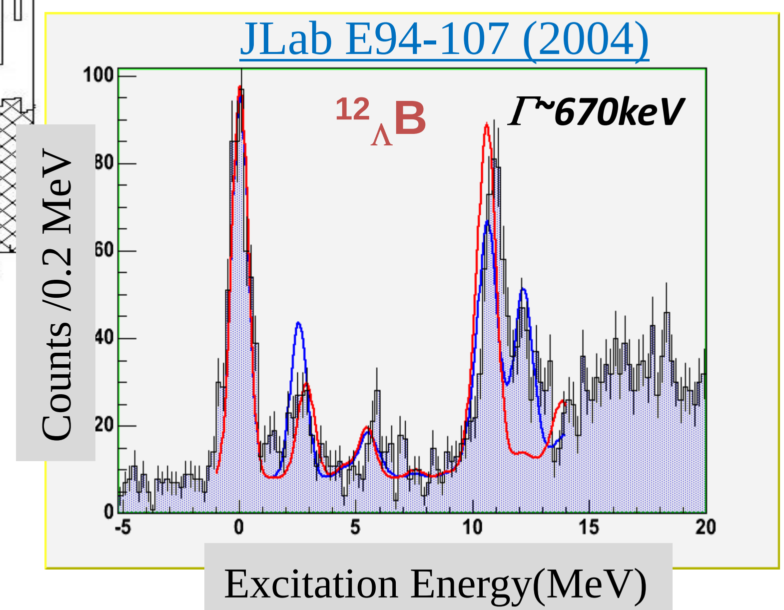
p(e,e'K$^+$)Λ&Σ^0 used for kinematics and optics calibration



$^{12}C(e,e'K^+)^{12}_{\Lambda}B$ used for kinematics and optics calibration

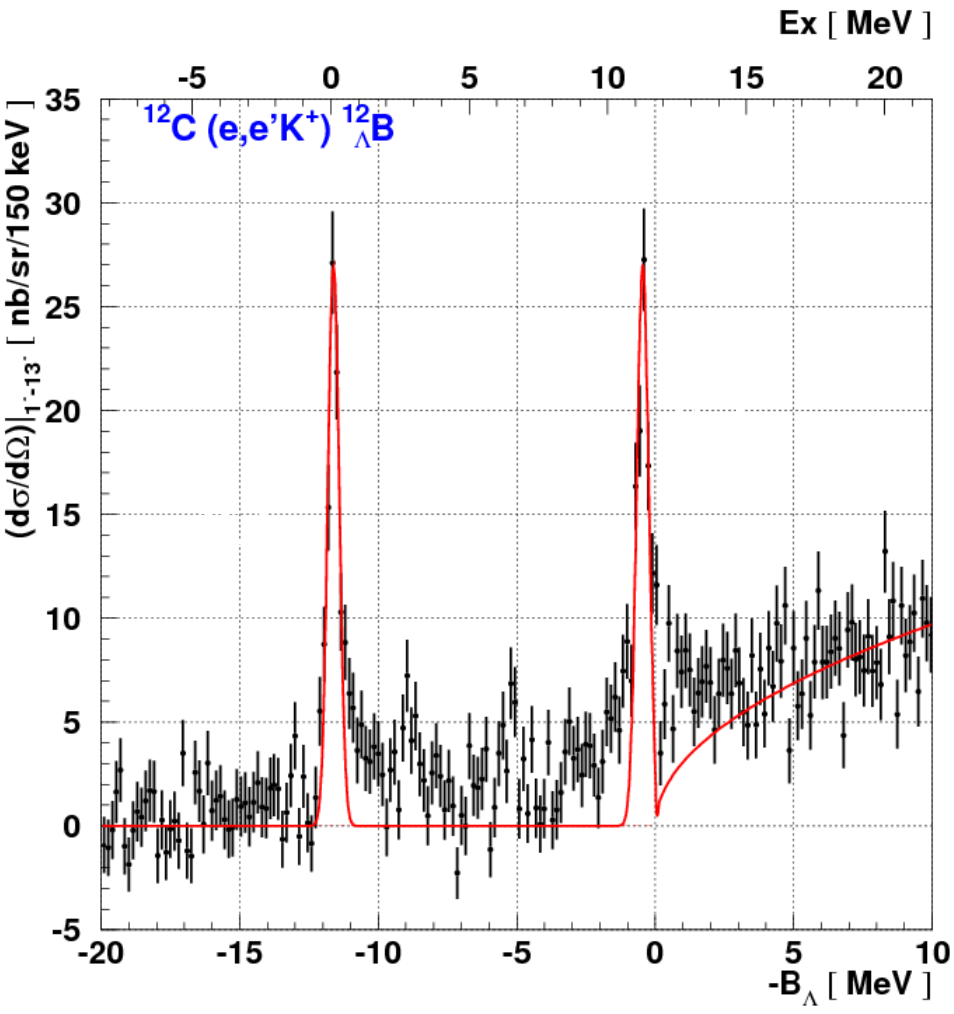






- $^{12}_{\Lambda}B$: Ground state resolution: 465 keV FWHM

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



Data taking : ~90 hours w/ 30 μA

Result

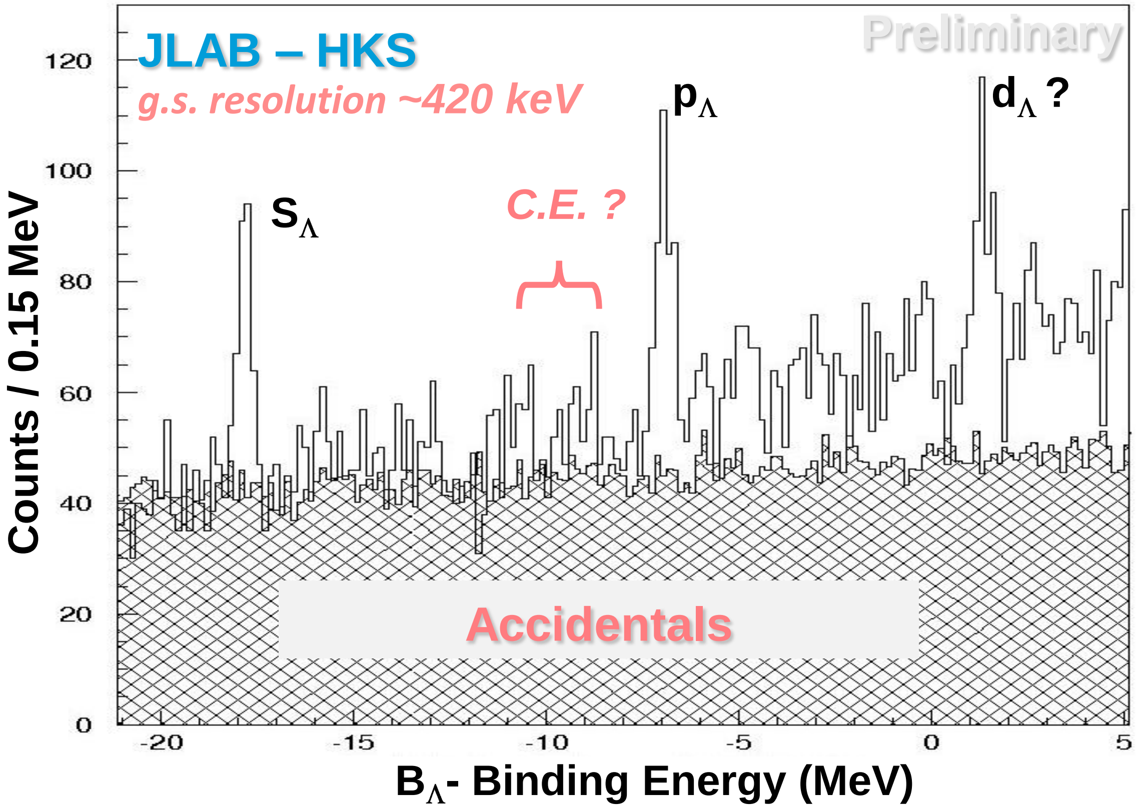
ID	Ex [MeV]	Cross section [nb/sr]
#1	0	89±7 (*stat.*) ±19 (*sys.*)
#2	11.2±0.1 (*stat.*) ±0.1 (*sys.*)	98±7 (*stat.*) ± 22 (*sys.*)

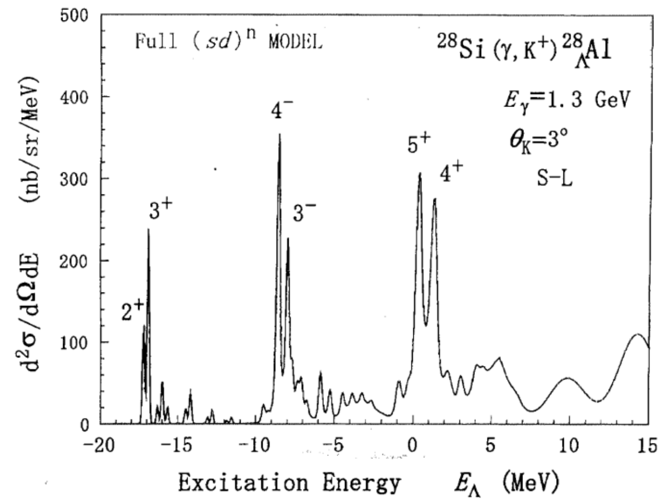
Theory by Sotona *et. al.*

(1.3 < Eγ < 1.6 GeV, 1 < θ_K < 13 deg.)

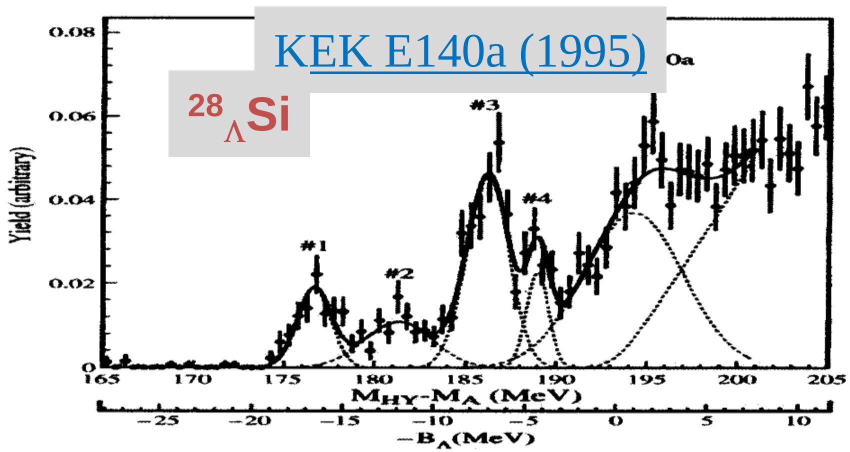
J^{π}	Ex [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
1^-	0	19.7	22.8	20.7
2^-	0.14	65.7	82.0	43.0
2^+	10.99	48.3	56.9	38.0
3^+	11.06	75.3	107.3	68.5

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

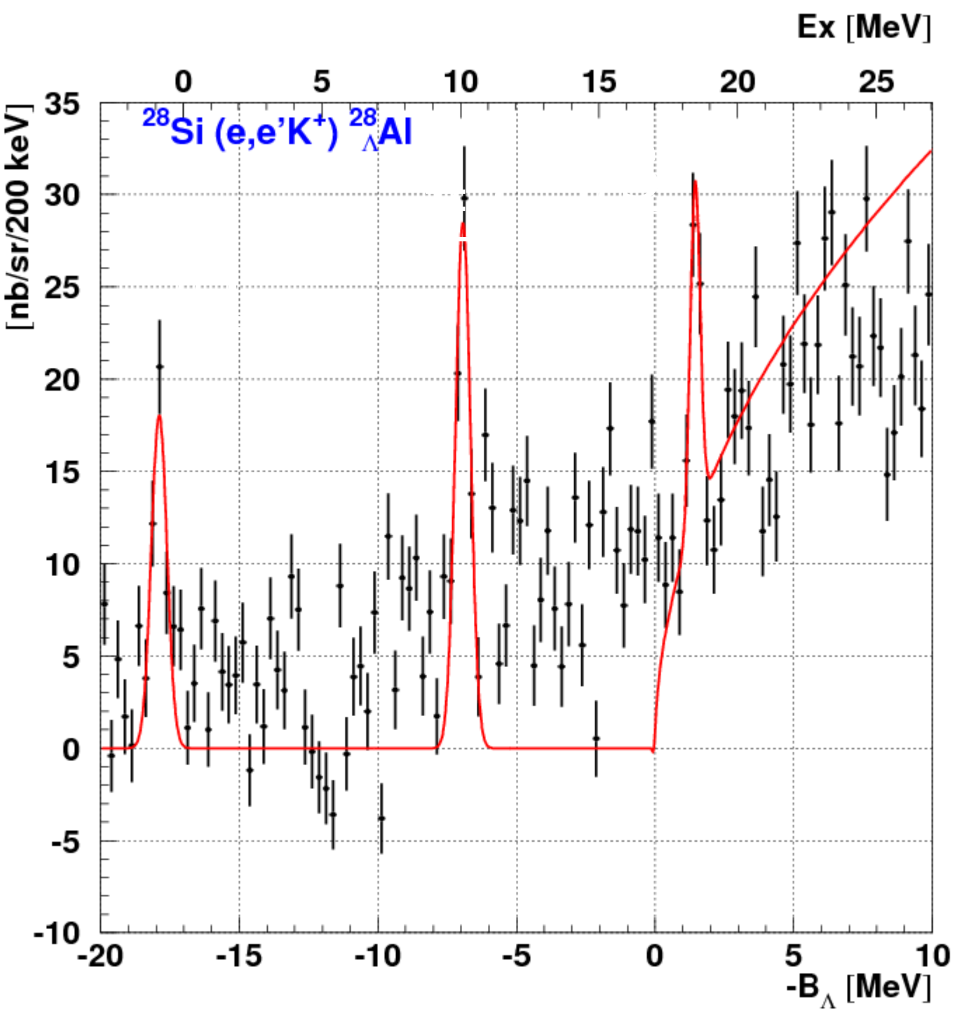




* Motoba 2003



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



Result

ID	Ex [MeV]	Cross section [nb/sr]
#1	0	51±10 (*stat.*) ±12 (*sys.*)
#2	11.0±0.1 (*stat.*) ±0.1 (*sys.*)	78±13 (*stat.*) ± 18 (*sys.*)
#3	19.3±0.1 (*stat.*) ±0.1 (*sys.*)	33±7 (*stat.*) ± 8 (*sys.*)

by Sotona *et. al.*

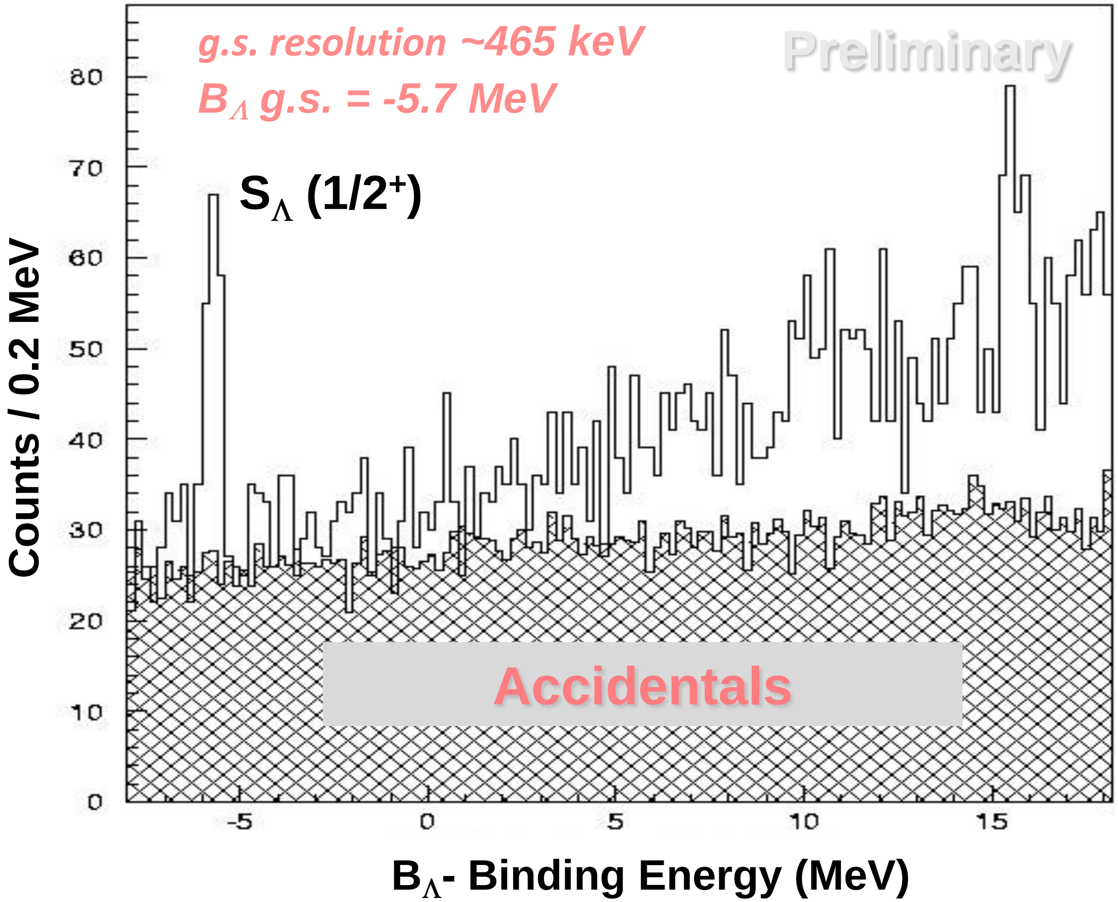
($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

J^{π}	Ex [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$2^+, 3^+$	0	92.1	112.7	71.76
4^-	9.42	134.9	167.7	117.5
3^-	9.67	91.3	109.1	58.5
4^+	17.6	148.4	184.7	135.1
5^+	17.9	139.1	167.1	89.9

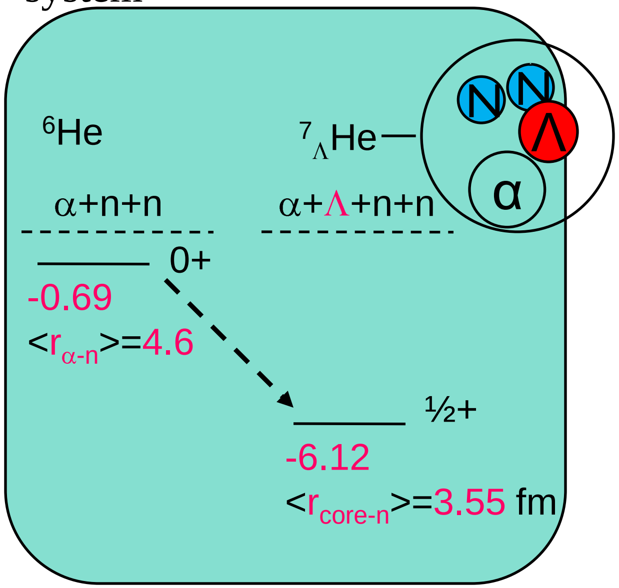
Data taking : ~140 hours w/ 30 μA

* By Matsumura

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$ – First Observation of ½⁺ G.S. of $^{7}_{\Lambda}He$

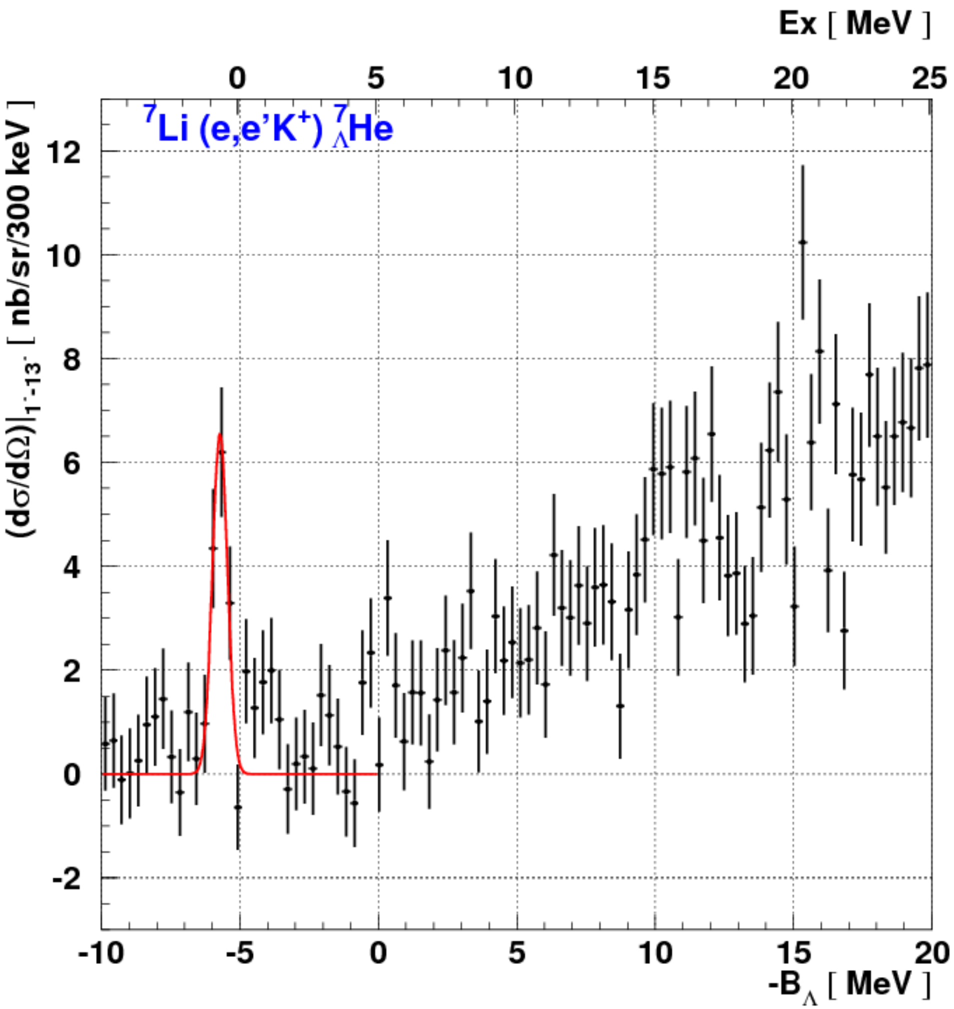


- *"Gluelike role" of hyperon*-- $^{7}_{\Lambda}$He formed by adding Λ to a typical neutron halo state ^{6}He and results in a more stable system



* Hiyama 1997

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



Result

ID	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]
#1	-5.7±0.2 (*stat.*) ±0.1 (*sys.*)	15±3 (*stat.*) ±3 (*sys.*)

Sotona *et. al.* (Cross section)

by Hiyama *et. al.* ($-B_{\Lambda}$)

($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

J^{π}	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$1/2^{+}$	-5.56	13.2	16.2	9.7

HKS (E01-011) Physics Outputs

- $^{12}{}_{\Lambda}B$ Best resolution HY-reaction spectrocopy (<470keV FWHM)
  - Generally consistent with E89-009 and Hall A
  - Answer to gs width problem suggested by Hall A data
- $^{7}{}_{\Lambda}He$ First reliable g.s. energy and cross section measurement
  - Neutron rich hypernucleus
- $^{28}{}_{\Lambda}Al$ First beyond p-shell hypernuclei by (e,e'K^{+})
  - LN interaction, Shell models, Door to medium heavy HY

Work To Do:

- Consistence check on $^{28}{}_{\Lambda}Al$ Spectrum
- Refine cross section estimation