Hypernuclear Physics with HKS

Lulin Yuan

Hampotn University

August 19, 2004

2004 Hall C Summer Workshop

Outline

- Strangeness: A new degree of freedom
- Phenomenological ΛN effective potential
- Test by hypernuclear data
- New structures in hypernuclei
- Electroproduction of hypernuclei
- E89009 spectrum: $^{12}_{\Lambda}B$ and $^{7}_{\Lambda}He$
- Expected HKS spectrum: $^{12}_{\Lambda}B$ and $^{51}_{\Lambda}Ti$
- HKS spectrometer and JLab E01-011 setup

Strangeness:A New Degree of Freedom

- ❑ Hypernuclear physics will explore
- • New nuclear many body structure induced by strangeness
- • Hyperon-nucleon(YN) interaction toward a unified understanding of baryon-baryon interaction.

- ❑ Hypernuclei created by (e,e'K) reaction:

  $^{12}{}_{\Lambda}$B and $^{7}{}_{\Lambda}$He (JLab E89009)

  $^{9}{}_{\Lambda}$Li (JLab E94107)

- ❑ JLab HKS will measure hypernuclear spectra up to medium-heavy and heavy range, including $^{12}{}_{\Lambda}$B, $^{28}{}_{\Lambda}$Al, $^{51}{}_{\Lambda}$Ti and $^{89}{}_{L}$Sr with ~350 KeV energy resolution.

Oberserved Hypernuclei by (π,K) ,(K, π) or cosmic ray:

H: 3 4	Al: 27
He: 4 5 6 8	Si: 28
Li: 6 7 8 9	S: 32
Be: 7 8 9 10	Ca: 40
B: 9 10 11 12	V: 51
C: 12 13 14	Fe: 56
N: 14 15	Y: 86
O: 16 18	La: 139
Blue numbers indicate hypernuclei also used in γ transition measurement	Pb: 208
	Bi: 209

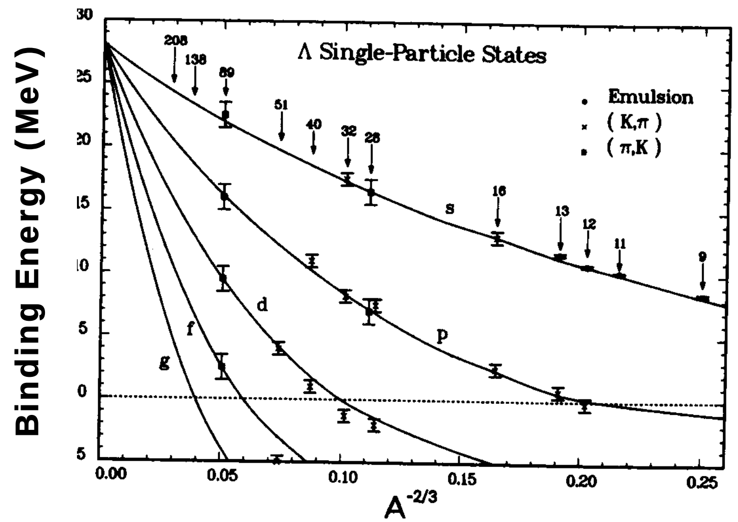
Double L hypernuclei: $^{10}{}_{\Lambda\Lambda}$Be and $^{6}{}_{\Lambda\Lambda}$He

Phenomenological ΛN Effective Potential

- Observation of a well defined series of Λ single particle states allows extraction of ΛN potential well depth, shape and effective mass, simplest form:

$$V(r) = -29.34 MeV f(r)$$
$$f(r) = (1+e^{(r-c)/a})^{-1}, a = 0.6\, fm$$
$$c = r_0(A)A^{1/3}, r_0(A) = (1.080 + 0.395 A^{-2/3})$$

f(r): nuclear charge density, c: half density radii



Λ binding energy as a function of $A^{-2/3}$

- Spin dependent part of ΛN
  For p^N-s^Λ configuration:

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

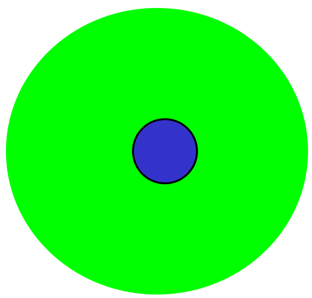
- The radial integrals of the coefficients are denoted as V, Δ, S_Λ, S_N and T, respectively, and assumed constant across shell.

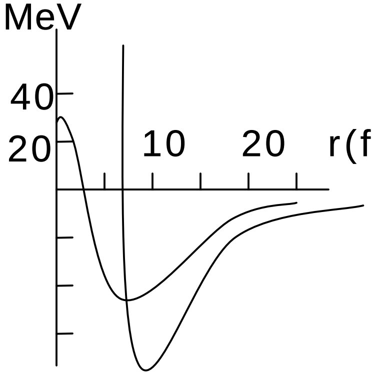
- Values fitted from recent Hyperball (K-,π-γ) experiment (in KeV):
  Δ=335~440, S_Λ=-11, S_N=-440~-450, T=24~30.

Energy separation of $^{12}_{\Lambda}B$ low lying states (KeV)

Spacing	Δ	S_Λ	S_N	T	ΔE
$1_2^- - 1_1^-$ ΔE~2.12+$\Delta E_{\Lambda N}$	168	-45	498	28	2728
$1_3^- - 1_1^-$ ΔE~5.02+$\Delta E_{\Lambda N}$	185	16	608	20	5829
$2_1^- - 1_1^-$ ΔE~$\Delta E_{\Lambda N}$	242	-15	-16	-46	165

Y-N Interaction in QHD Picture





YN NSC Potential Form
Parametrized by YNG

- Baryon baryon interaction model: Nijmegen Soft Core (NSC) and Extended Soft Core (ESC)

  - Potential generated by exchange of all nonets of mesons: pseudoscalar, vector, scalar and pomeron. Two-meson exchange included in ESC.
  - Included channels:

$$\Lambda p \to \Lambda p, \Sigma^+ n, \Sigma^0 p$$

$$\Lambda n \to \Lambda n, \Sigma^0 n, \Sigma^- p \ldots$$

  - Pomeron exchange and form factor on baryon vertices generate a soft core.
  - The Lagrangian for pseudoscaler meson nonet:

$$L_I = -g^{oct}\sqrt{2}\{[\bar{B}BP]_F + (1-\alpha)[\bar{B}BP]_D\}$$
$$- g^{\sin}\sqrt{1/3}[\bar{B}BP]_S$$

  where B is the ½+ baryon octet. The coupling constants (g's), meson mixing angle θs and F/(F+D) ratios α are constructed by (partially broken) flavor SU(3) symmetry. Free parameters to be fitted from N-N and limited Y-N scattering data.

- Result have to be compared with hypernuclear measurement.

Effective Y-N Interaction Within Nuclear Medium

- Within nuclear matter, effective YN interaction can be deduced from G-matrix method

  Hyperon s.p. potential:

$$U_Y = \sum_{K_N} \langle \mathbf{k}_Y \mathbf{k}_N | G_{YN}(\omega) | \mathbf{k}_Y \mathbf{k}_N \rangle (1-\kappa_N), \text{ while } \omega = e_Y + e_N$$

  In configuration space, the effective potential

$$V_{\Lambda N}(r) = V_c + V_\sigma(\sigma_1 \cdot \sigma_2) + V_T S_{12} + V_{LS}\frac{1}{2}(\sigma_1 + \sigma_2)\cdot L + V_{ALS}\frac{1}{2}(\sigma_1 - \sigma_2)\cdot L$$

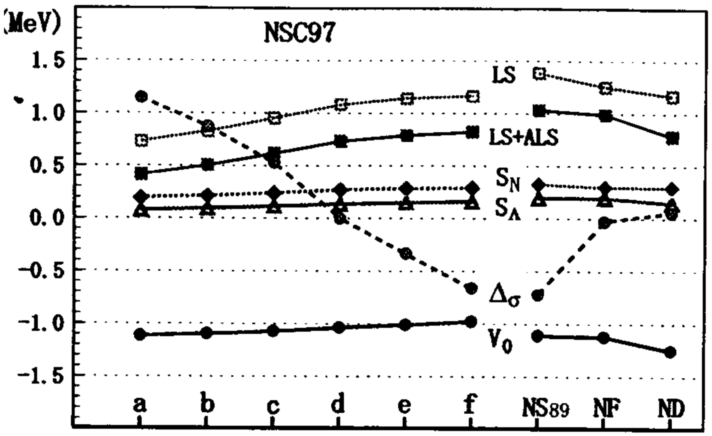
- Parametrization by three range Gaussian function.

$$V_{\Lambda N}(r) = \sum_{i=1}^{3}(a_i + b_i k_F + c_i k_F^{\;2})\exp(-r^2/\beta_i^{\;2}),\ k_F : \text{Fermi momentum}$$

- Hypernuclear energy level can be calculated from Hamiltonian:

$$H = t_\Lambda + \sum_N V_{VN} + \sum e_N$$

Test by Hypernuclear Data



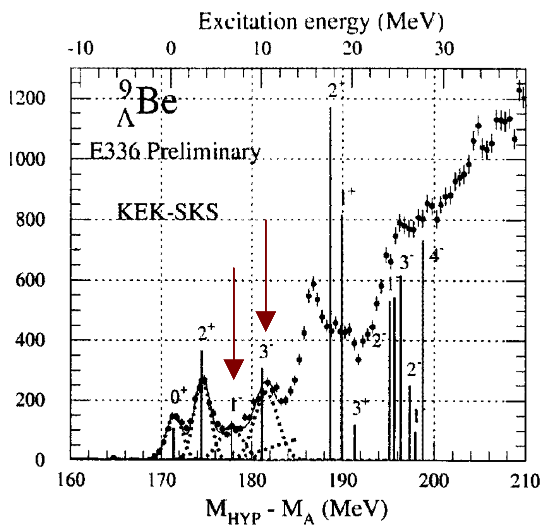
$^{13}{}_{\Lambda}$C spin-orbit splitting $E(p^{\Lambda}_{1/2})-E(p^{\Lambda}_{3/2})$

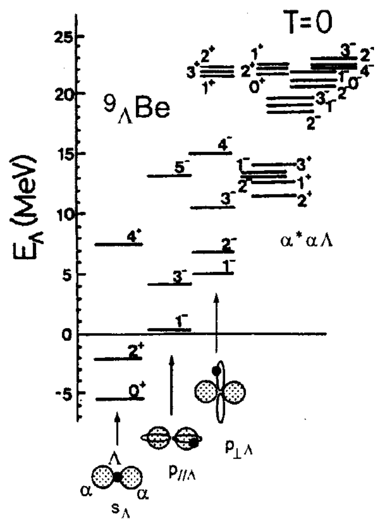
- NSC Model parameters are sensitive to YN effective potentials, e.g, α_V^m, is directly related to the L spin-spin and spin-orbit interaction .
- For spin-spin part, NSC gives right order of spin doublet splitting of s-Λ in $^4{}_{\Lambda}$H 1+ and 0+ states. For The spin orbit part, Stronger ALS suggested for model improvement.

	NSC97a	NSC97b	NSC97e	NSC97f	ESC03	Exp.
α_V^m	0.4447	0.4247	0.3747	0.3647	0.44	
Λ s.p. potential well depth (MeV)				-31.1	-30	-29
$^9{}_{\Lambda}$Be spin-orbit splittings $[^8Be(2^+)\otimes s^{\Lambda}_{1/2}](3/2^+,5/2^+)$ (MeV)				0.16	0.08	0.03
$^{13}{}_{\Lambda}$C $p^{\Lambda}_{1/2}$, $p^{\Lambda}_{3/2}$ splitting (MeV)				0.78		0.154

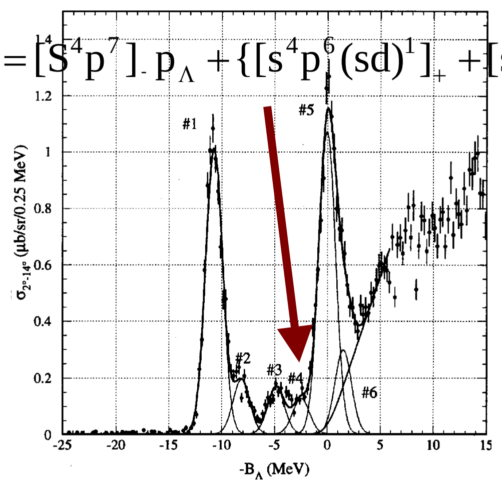
- For $^{12}{}_{\Lambda}$B ($^{12}{}_{\Lambda}$C) ground state doublet splitting $[p_{3/2}^{-1}\otimes s^{\Lambda}_{1/2}]$(1-,2-), NSC97e,f give correct order of 1- and 2- states (1- below 2-). Measurement of this splitting will further constraint the theory

New Structures in Hypernuclei





KEK E369: $\pi^+ + {}^{12}C \rightarrow K^+ + {}^{12}{}_\Lambda C$

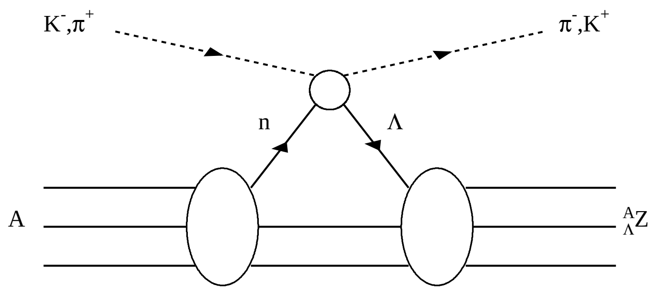


$$2^+ = [S^4p^7]_- p_\Lambda + \{[s^4p^6(sd)^1]_+ + [s^3p^8]_+\}1s_\Lambda$$

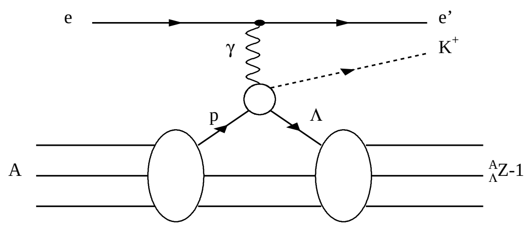
- The "genuine hypernuclear states" in $^9{}_\Lambda$Be
- Parity mixing intershell coupling induced by Λ

  Through the coupling with Λ, configuration mixing can be formed from core nuclear states with different parities.

Electroproduction of Hypernuclei



Hadronic Reaction:
$K^- + n \rightarrow \pi^- + \Lambda$ or $\pi^+ + n \rightarrow K^+ + \Lambda$

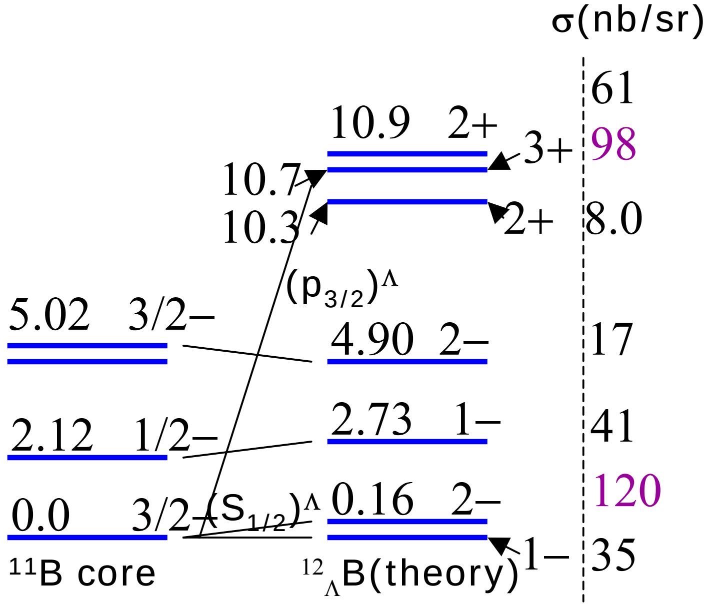


Electromagnetic Reaction:
$\gamma * + p \rightarrow K^+ + \Lambda$

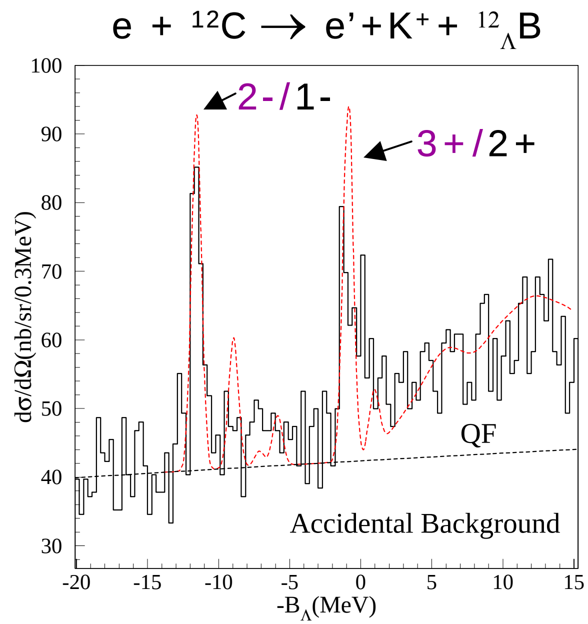
Electroproduction

- Convert proton to Λ—neutron rich hypernuclei
- High spin, spin-flip unnatural-parity states
- High resolution spectrum by primary e beam
- First experiment was carried out at Jlab in year 2000. Resolution <1 MeV

E89009 Spectrum: $^{12}{}_{\Lambda}B$



Shell model prediction of $^{12}{}_{\Lambda}B$ bound states

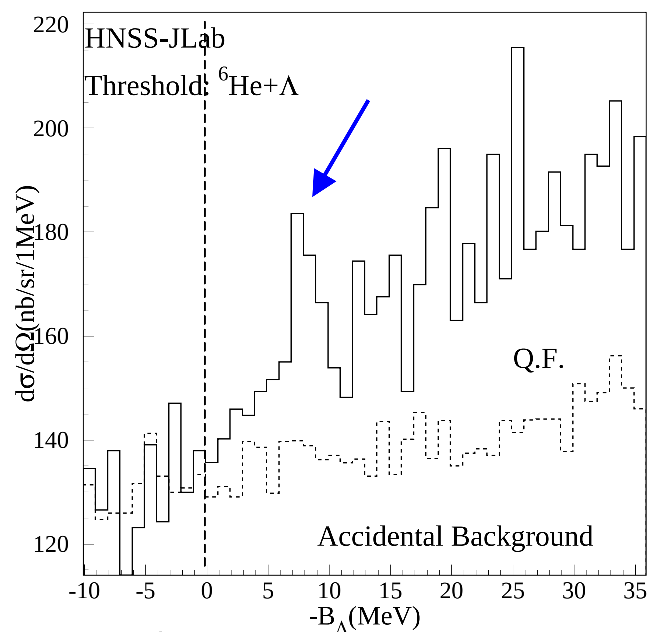


- Resolution ~750 keV (FWHM)
- s and p shell peaks dominated by unnatural parity states
- Peak positions and strengths consistent with theoretical predictions†

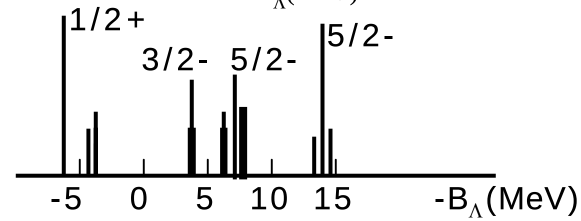
E89009 Spectrum: $^{7}_{\Lambda}$He

- $^{7}_{\Lambda}$He: light neutron rich halo hypernucleus a+n+n+L
- No evidence of bound state: GS cross section <30nb/sr (2σ)
- Need better understanding of few- body system with strangeness

e + ^{7}Li → e'+K^{+}+ $^{7}_{\Lambda}$He

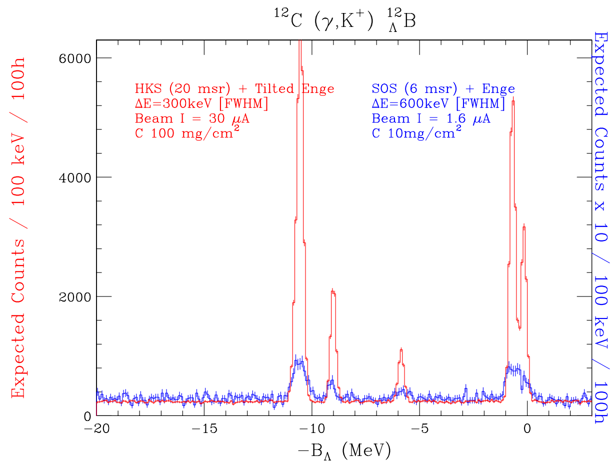


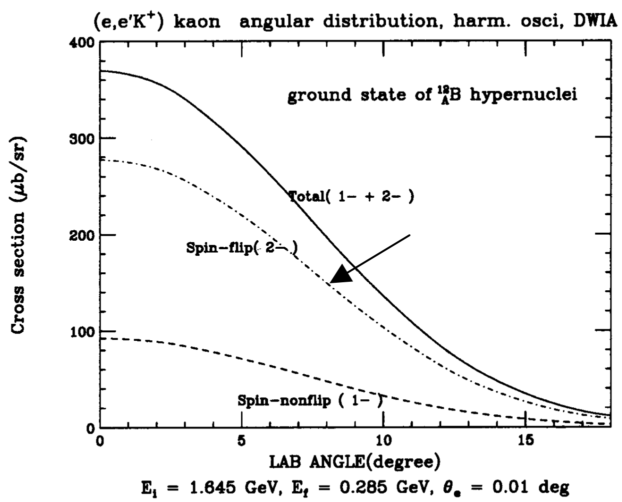
Energy Levels and Excitation Strength from Theory†



Expected HKS Spectrum: $^{12}{}_{\Lambda}B$

- Expected Missing mass resolution:
  C: 390 KeV, Si: 360KeV, V: 350 KeV, Y: 345 KeV
- $^{12}{}_{\Lambda}B$ GS spin doublet splitting may be extracted by angle correlation.





Expected $^{51}{}_{\Lambda}$Ti Spectrum

- Level splittings due to spin-orbit interaction expected to increase with higher orbit

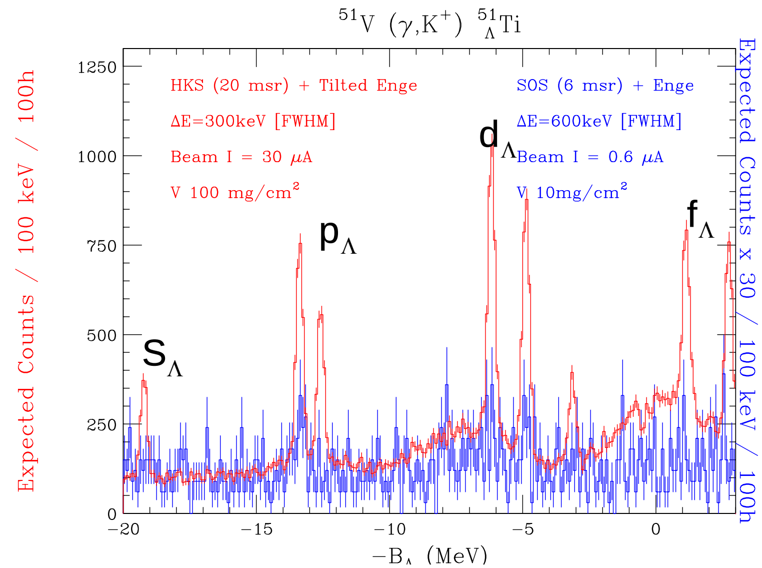
$$E_{l-1/2} - E_{l+1/2} \propto (l+1/2)\cdot A^{-2/3}$$

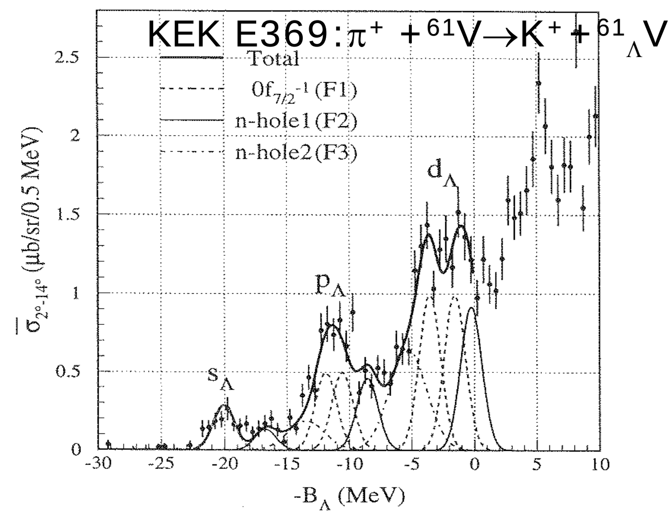
- Charge Symmetry Broken(CSB) effect:

$$\Delta B_{\Lambda} \approx V_{0}{}^{CSB} B_{\Lambda}'\left(\frac{N-Z}{A-1}\right), B_{\Lambda}' = \frac{dB_{\Lambda}}{dV_{0}}$$

Estimated from binding energy difference (~-0.35 MeV) of $^{4}{}_{\Lambda}$H and $^{4}{}_{\Lambda}$He V_0^{CSB}~-0.05.

- For heavy targat such as ^{51}V and ^{89}Y, CSB effect is small but significant due to neutron excess, $^{51}{}_{\Lambda}$Ti 6 and $^{89}{}_{\Lambda}$Sr 12.





HKS Spectrometer and JLab E01-011 Setup

Tilt 7.75^0 (6cm offset)
Scat. Angle: 4.7^0