Hypernuclear Mass Determination by the $(e,e'K^+)$ Reaction

Osamu Hashimoto
Department of Physics, Tohoku University

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Outline of the talk

1. Absolute mass determination of hypernuclei by emulsion & by the $(e,e'K^+)$ reaction
2. Charge symmetry breaking of the ΛN potential
3. Testing charge symmetry breaking of the ΛN potential in A=7 hypernuclear system
4. Summary

Emulsion data (1972)

Nuclear Physics B52 (1973) 1–30. North-Holland Publishing Company

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

M. JURIĆ
Institute of Physics, Belgrade

G. BOHM *, J. KLABUHN, U. KRECKER and F. WYSOTZKI
Institut für Hochenergiephysik, Akademie der Wissenschaften der DDR, Berlin-Zeuthen

G. COREMANS-BERTRAND, J. SACTON and G. WILQUET **
Service de Physique des Particules Elémentaires, Université Libre de Bruxelles

T. CANTWELL ***
Institute for Advanced Studies, Dublin

F. ESMAEL and A. MONTWILL
Physics Department, University College, Dublin

D.H. DAVIS
Physics Department, University College London

D. KIEŁCZEWSKA, T. PNIEWSKI, T. TYMIENIECKA and J. ZAKRZEWSKI
Instytut Fizyki Doświadczalnej, Uniwersytet Warszawski, Warszawa

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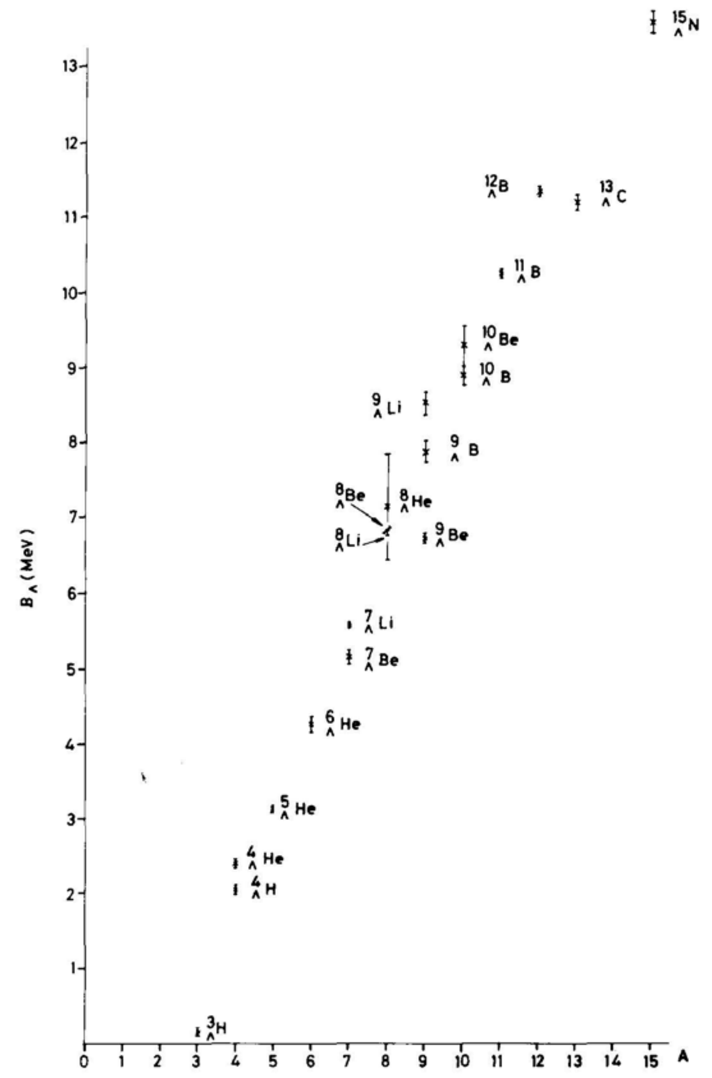


Fig. 10. Variation of the B_Λ values with the hypernuclear mass numbers.

Derivation of B_Λ in emulsion experiments

1. Hypernuclear pionic decay events all decay particles of which were fully contained in emulsion were analyzed assuming no internal excitation or emission of neutrons or γ's.
2. Barkas range-energy relation was renormalized by referencing Λ hyperon mass derived through its pionic decay events
3. Kinematical analysis requiring energy-momentum balance of all the decay particles was performed to deduce B_Λ values
4. Systematic error of 40 keV estimated

Λ Hypernuclear binding energies obtained by emulsion experiments 1

Data Summary : Davis 1992
Decay channels: Juric

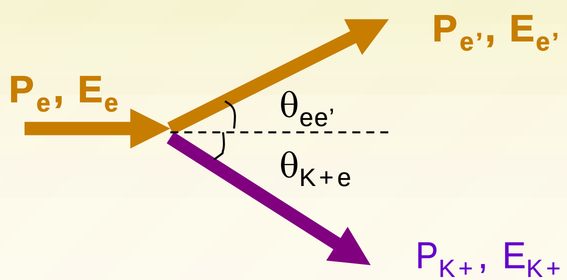
Hypernuclide	B_Λ(MeV)	# of events	Comment
$^{3}_{\Lambda}H$	0.13±0.05	204	2 decay channels*,170keV
$^{4}_{\Lambda}H$	2.04±0.04	155	2 decay channels*,220keV
$^{4}_{\Lambda}He$	2.39±0.03	279	2 decay channels,20keV
$^{5}_{\Lambda}He$	3.12±0.02	1784	4 decay channels*,150keV
$^{6}_{\Lambda}He$	4.18±0.10	31	single decay channel
$^{7}_{\Lambda}He$	Not averaged	16	Isomeric state ?
$^{7}_{\Lambda}Li$	5.58±0.03	226	2 decay channels, 100keV
$^{7}_{\Lambda}Be$	5.16±0.08	35	single decay channel
$^{8}_{\Lambda}He$	7.16±0.70	6	single decay channel
$^{8}_{\Lambda}Li$	6.80±0.03	787	3 decay channels
$^{8}_{\Lambda}Be$	6.84±0.05	68	2 decay channels*,180keV

Λ Hypernuclear binding energies obtained by emulsion experiments 2

Data Summary : Davis 1992
Decay channels: Juric

Hypernuclide	B_Λ(MeV)	# of events	Comment
$^{9}_{\Lambda}Li$	8.50±0.12	8	single decay channel
$^{9}_{\Lambda}Be$	6.71±0.04	222	2 channels*,190keV
$^{9}_{\Lambda}B$	8.29±0.18	4	2 channels*,880keV
$^{10}_{\Lambda}Be$	9.11±0.22	3	single decay channel
$^{10}_{\Lambda}B$	8.89±0.12	10	2 decay channels*
$^{11}_{\Lambda}B$	10.24±0.05	73	6 channels*, 620keV
$^{12}_{\Lambda}B$	11.37±0.06	87	single decay channel, (e,e'K+) data consistent
$^{12}_{\Lambda}C$	10.76±0.19	5	4 decay channels*,690keV
$^{13}_{\Lambda}C$	11.69±0.12	6	
$^{14}_{\Lambda}C$	12.17±0.33	3	
$^{15}_{\Lambda}N$	13.59±0.15	14	

Derivation of B_Λ by the(e,e’K+) reaction



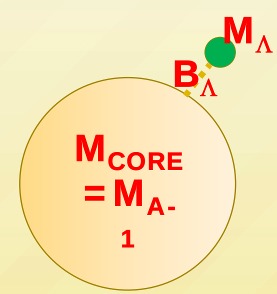
$$e + {}^{A}Z_{N} \rightarrow {}^{A}_{\Lambda}Z_{N-1} + e' + K^{+}$$

$$e + p \rightarrow \Lambda + e' + K^{+}$$

$$M_{HY}{}^{2} = E_{HY}{}^{2} - P_{HY}{}^{2}$$
$$= (E_{e} + M_{A} - E_{e'} - E_{K+})^{2}$$
$$-(P_{e}{}^{2} + P_{e'}{}^{2} + P_{K+}{}^{2} - 2\vec{P}_{e}\cdot\vec{P}_{e'} + 2\vec{P}_{e'}\cdot\vec{P}_{K} - 2\vec{P}_{K+}\cdot\vec{P}_{e})$$

$$B_{\Lambda} = M_{CORE} + M_{\Lambda} - M_{HYP}$$
$$= M_{A} - M_{HYP} + M_{\Lambda} - M_{n} + B_{n}$$

- Λ hypernuclei charge symmetric to those produced by the (π^{+},K^{+}), (K^{-},π^{-}) reactions can be studied
- Calibration of absolute hypernuclear masses is carried out with a “hydrogen” target



Nuclear Masses (M_N) etc. for the E01-011 analysis

$M_N(A,Z) = M_A(A,Z) - Z*M_e + B_{el}(Z)$

$B_{el}(Z) = 14.4381*Z^{2.39}+1.55468*10^{-6}Z^{5.35}$ [eV]

G.Audi *et al.*, Nucl. Phys. A729(2003). 337

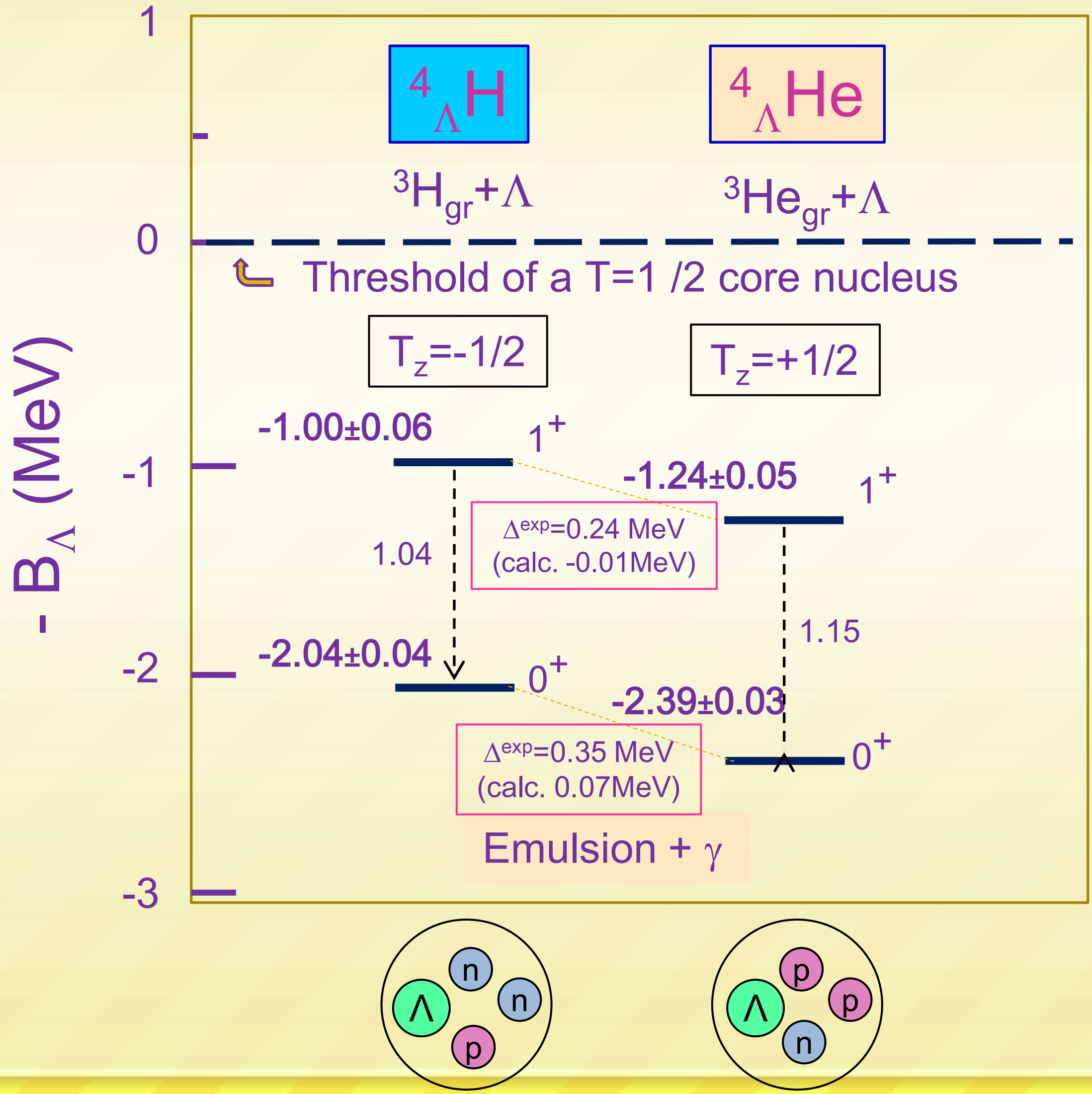
- Atomic mass unit : 931.4940539 MeV
- Electron mass : 0.510998902 MeV
- Proton mass : 938.7830247 MeV
- Neutron mass : 939.5653714 MeV
- Λ mass : 1115.683 MeV

Sources of Charge symmetry breaking (CSB) in the ΛN interaction potential

- Coulomb potential
- Λ–Σ^0 mixing, ΛN-ΣN coupling
- ???

u-d mass difference

Experimental binding energies of A=4, T=1/2 Λ Hypernuclei



$$\Delta_{CSB} = B_\Lambda({}^4_\Lambda He) - B_\Lambda({}^4_\Lambda H)$$

$$= 0.35 \pm 0.06 \text{ MeV}$$

: for the ground 0^+ states

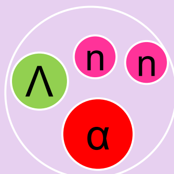
$$= 0.24 \pm 0.06 \text{ MeV}$$

: for the excited 1^+ states

A=7 T=1 iso-triplet Λ hypernuclei

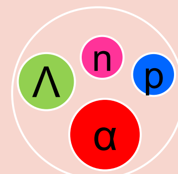
Present experimental data

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



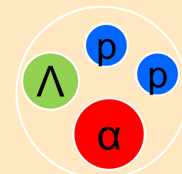
Precision reaction spectroscopy
by the (e,e'K+) reaction in JLab Hall C

$^{7}_{\Lambda}$Li*



Emulsion data
+ hypernuclear γ ray

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



Emulsion data

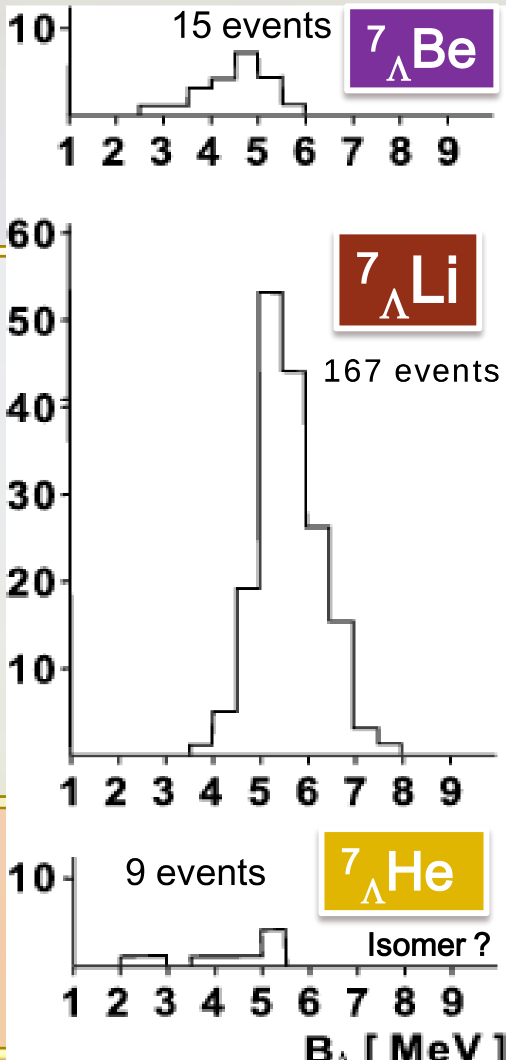
$^{7}_{\Lambda}$He Λ hypernucleus

- A member of the A=7 T=1 iso-triplet
- Precision determination of the hypernuclear mass

+ Recent cluster model calculation by Hiyama et.al.
Phys. Rev. C80, 054321 (2009)

Emulsion data for the A=7 Λ Hypernuclei

M.Jurič et al., Nucl. Phys. B52(1973) 1



Decay mode

$^{7}_{\Lambda}Be \rightarrow p^{-} + {}^{1}H + {}^{1}H + {}^{1}H + {}^{4}He$

$B_{\Lambda} = 5.16 \pm 0.08$ MeV

Decay mode

$^{7}_{\Lambda}Li \rightarrow p^{-} + {}^{3}He + {}^{4}He$

$^{7}_{\Lambda}Li \rightarrow p^{-} + {}^{1}H + {}^{2}H + {}^{4}He$

$B_{\Lambda} = 5.58 \pm 0.03$ MeV

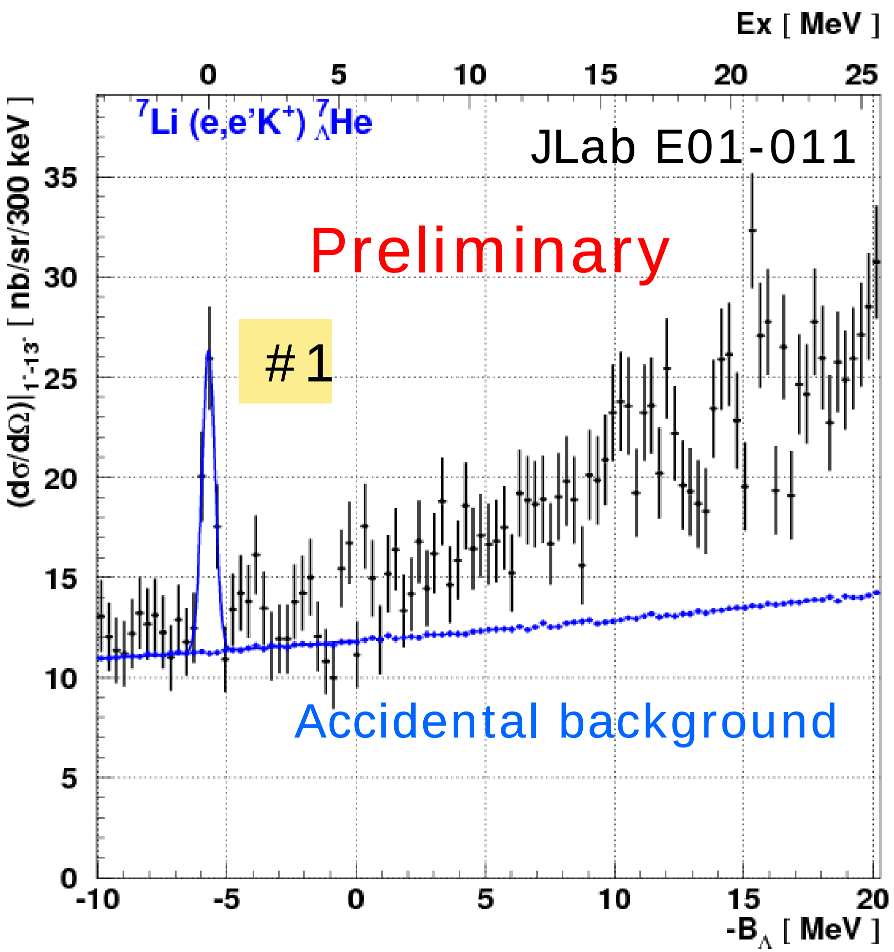
Decay mode

$^{7}_{\Lambda}He \rightarrow \pi^{-} + {}^{3}H + {}^{4}He$

$^{7}_{\Lambda}He \rightarrow \pi^{-} + p + {}^{3}H + {}^{3}He$

No binding energy obtained

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



Resolution : ~510 keV (FWHM) for g.s.

1. Present E01-011 Result (Preliminary)

ID	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]
#1	-5.68±0.03 (*stat.*) ±0.22 (*sys.*)	26±3 (*stat.*) ±10 (*sys.*)

2. Theoretical calculations

Cross section : Sotona *et. al.*

$-B_{\Lambda}$: Hiyama *et. al.*

$(1.3 < E_{\gamma} < 1.6$ GeV, $1 < \theta_{K} < 13$ deg.)

J^{π}	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$1/2^{+}$	-5.36	13.2	16.2	9.7

2010

Systematic errors

1. Absolute mass scale

A. Optical tuning

-- Blind analysis of fully simulated data

- Major peaks (S/N > 1) ΔB_Λ^{sys} < 100 keV
- Core excited states (S/N < 1) ΔB_Λ^{sys} < 400 keV

B. Kinematical

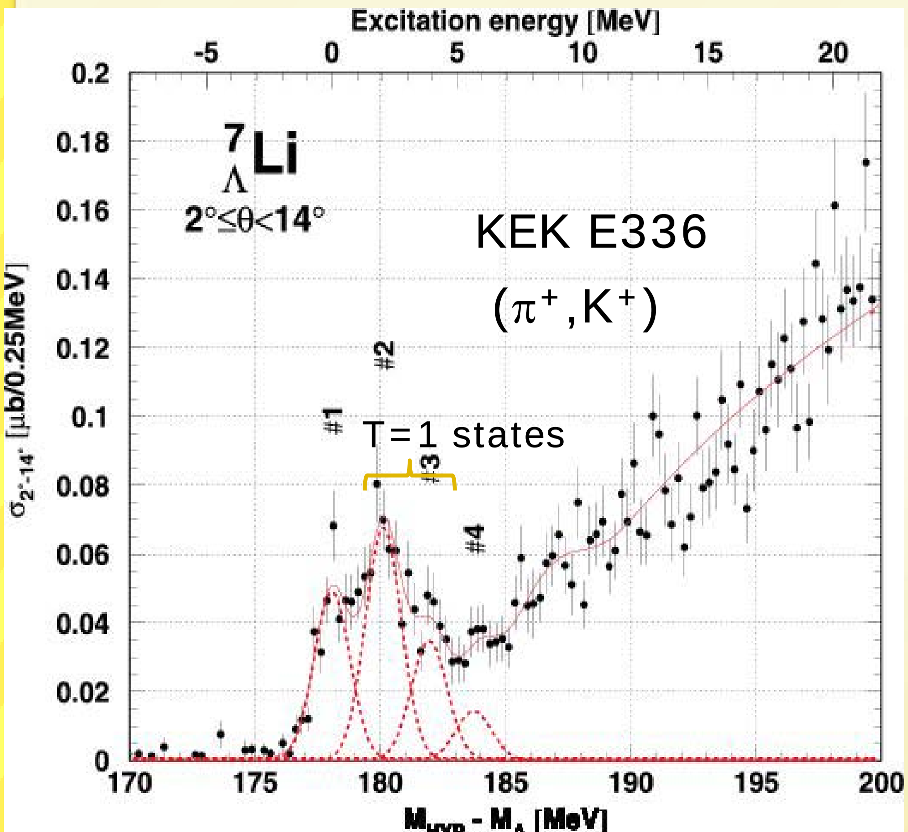
- Beam energy
- Spectrometer central momentum
- Spectrometer geometry (angle etc)

2. Cross section

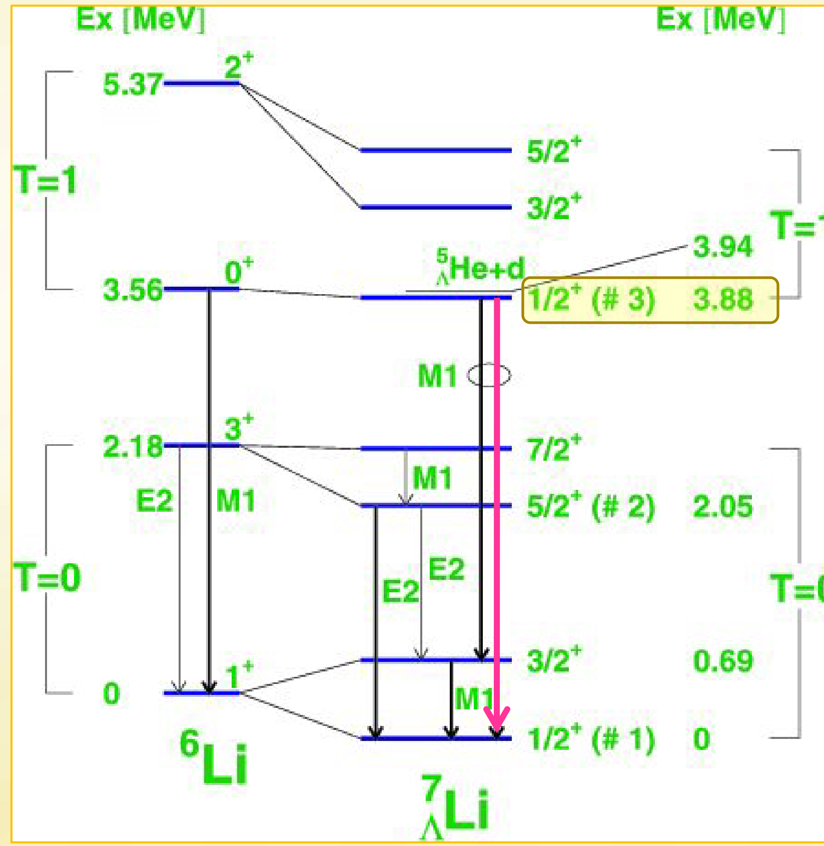
Virtual photon flux

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

T=1 states of $^{7}_{\Lambda}$Li

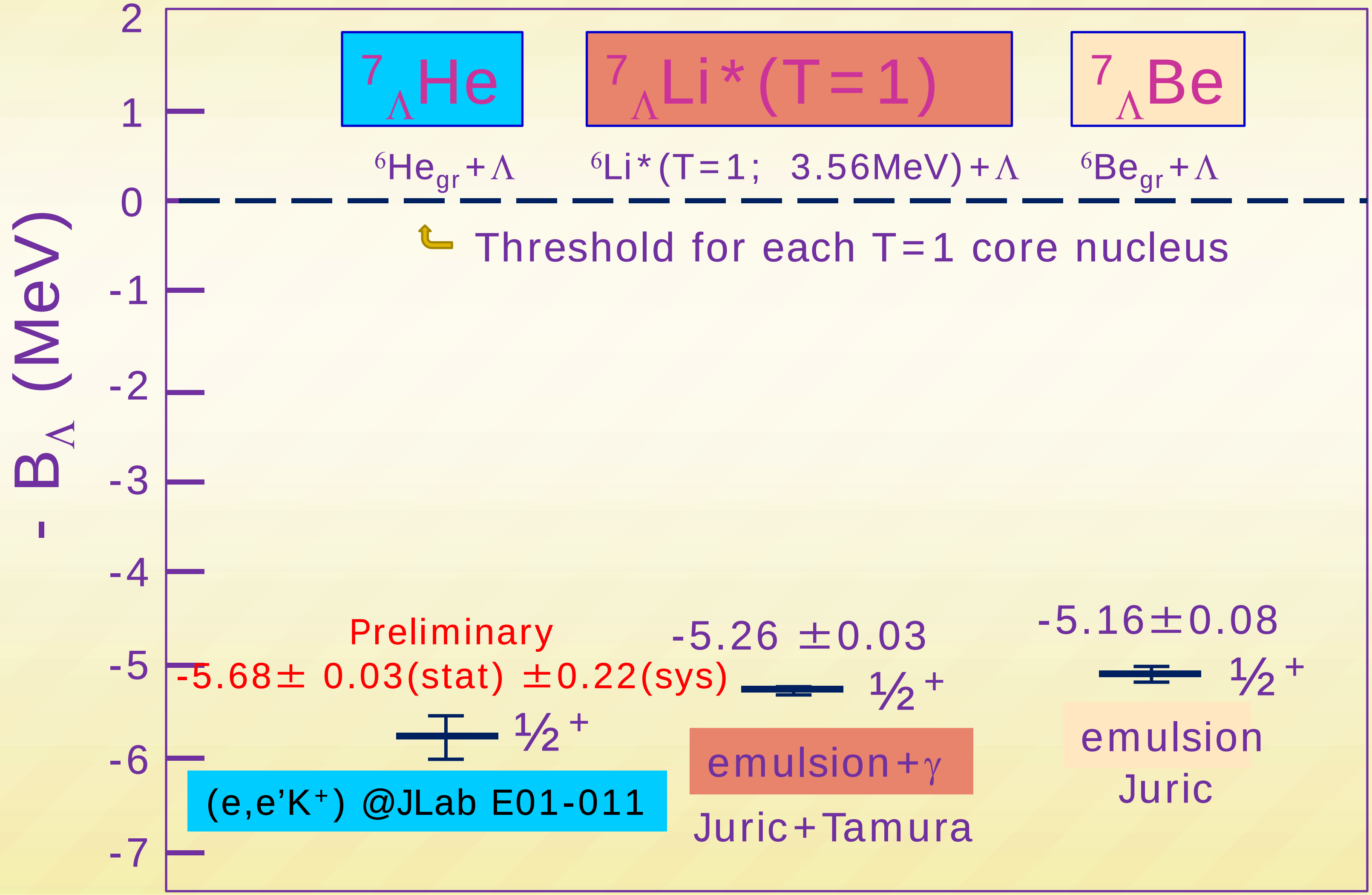


O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. **57**, 564 (2006)

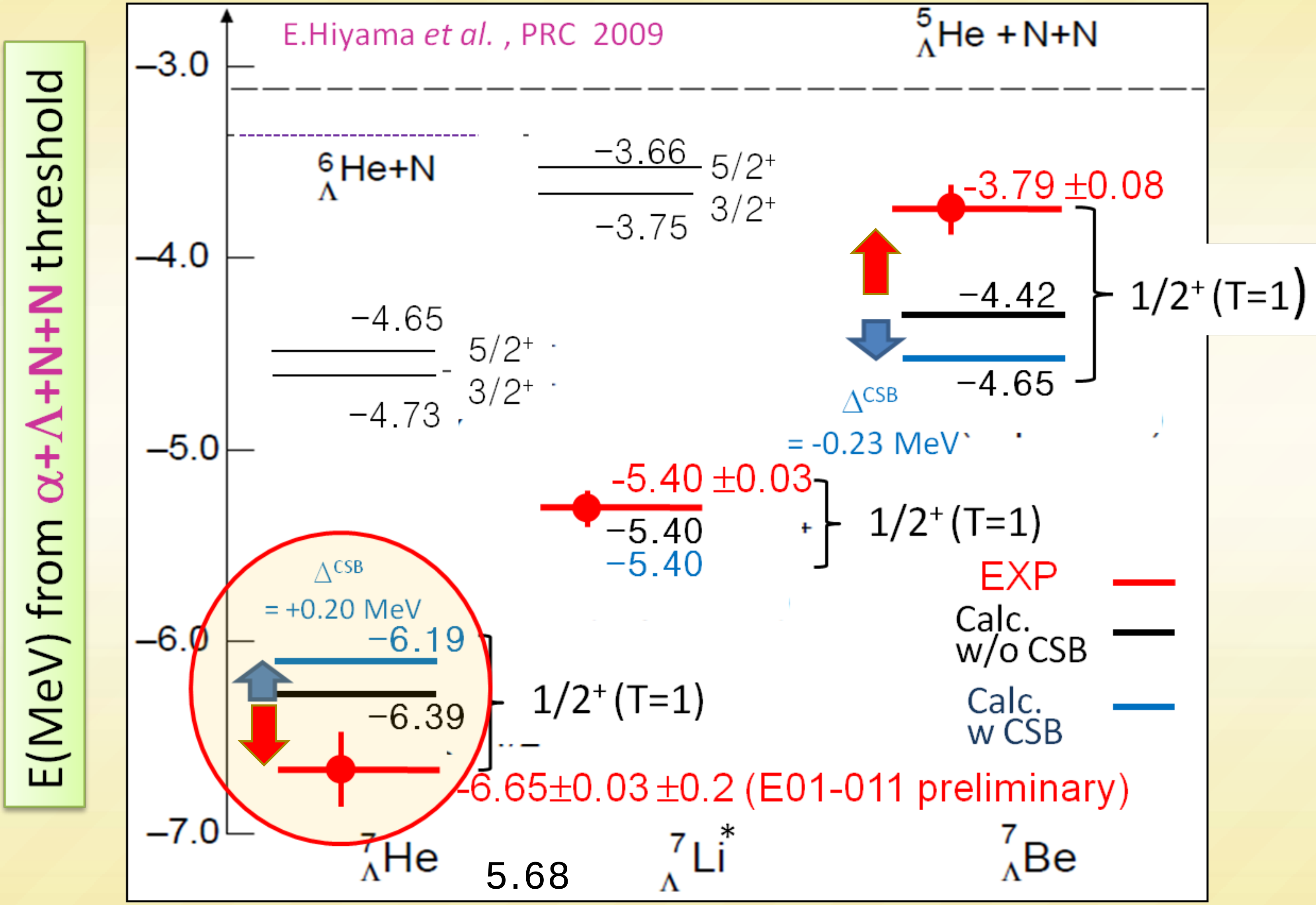


H. Tamura et. al. Phys. Rev. Lett. **84**, 5963 (2000)

Experimental binding energies of A=7, T=1 Λ Hypernuclei



Comparison with the 4-body cluster m



Shifts due to the phenomenological CSB have opposite sign to the calculation

Binding energy of the $^{12}{}_{\Lambda}C$ ground state

by Dluzewski et. al. 1988

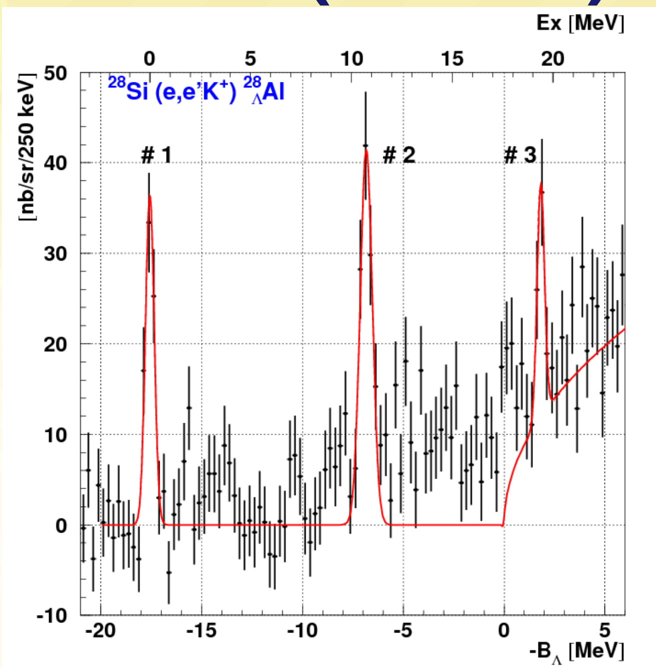
1. $^{12}{}_{\Lambda}C \rightarrow \pi^- + {}^{12}N$ **1 event** $B_{\Lambda} = 11.14 \pm 0.57$ MeV
2. $^{12}{}_{\Lambda}C \rightarrow \pi^- + p + {}^{4}He + {}^{7}Be$ **1 event** $B_{\Lambda} = 10.45 \pm 0.33$ MeV
3. $^{12}{}_{\Lambda}C \rightarrow \pi^- + p + {}^{11}C$ **4 events** $B_{\Lambda} = 10.50 \pm 0.47$ MeV

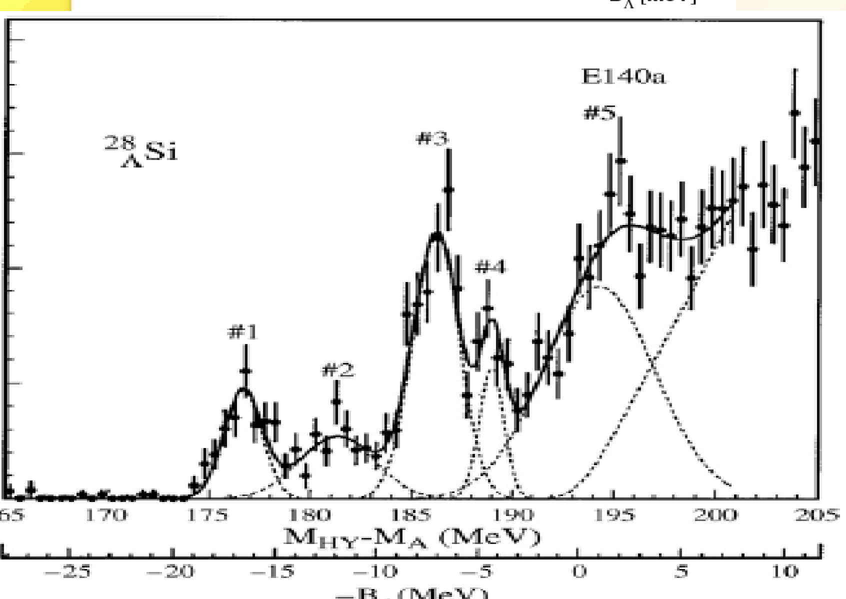
$B_{\Lambda} = 10.80 \pm 0.19$ MeV

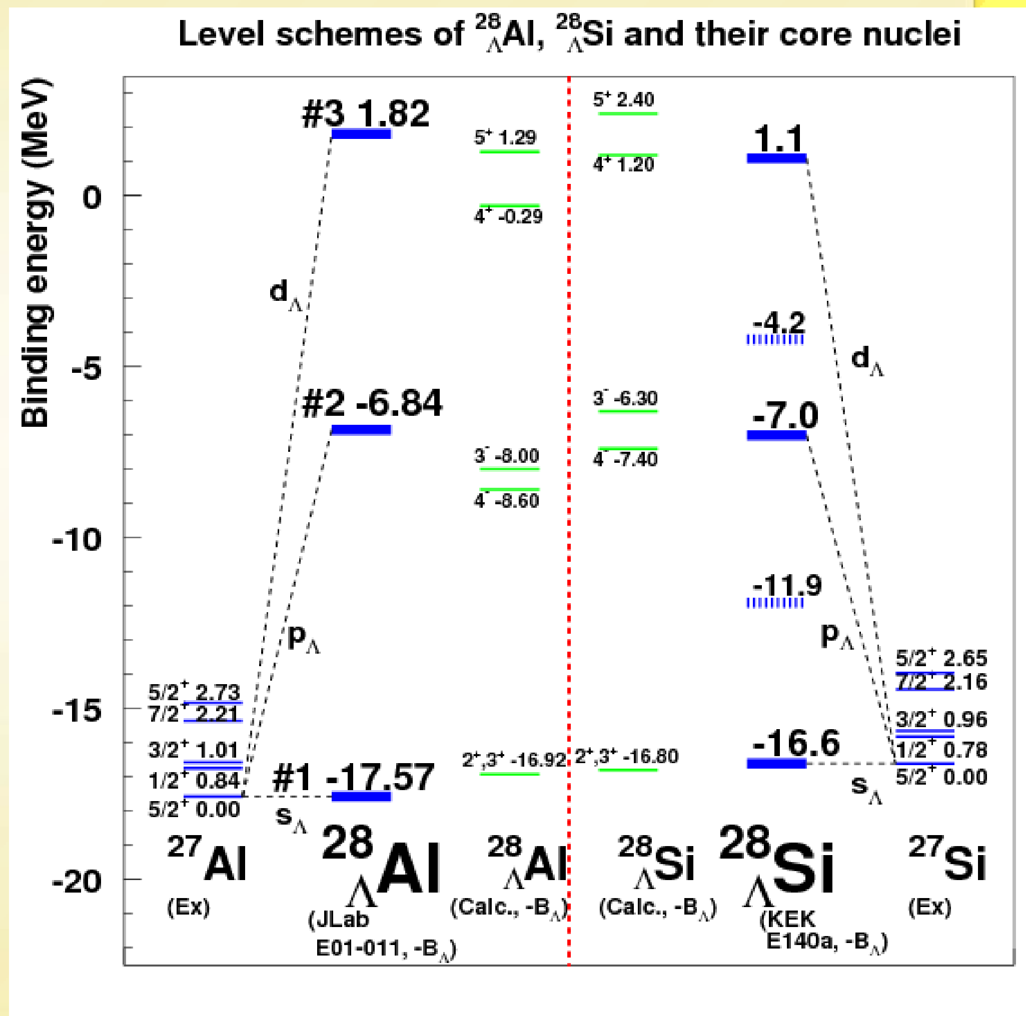
Davis re-examined the data and analyzed 5 events

$B_{\Lambda} = 10.76 \pm 0.19$ MeV

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







Binding energy differences of hypernuclear iso-multiplets

Davis

Iso-multiplet	ΔB_Λ (MeV)	Comment
${}^{4}_{\Lambda}He - {}^{4}_{\Lambda}H$	$+0.35\pm0.05$	
${}^{8}_{\Lambda}Be - {}^{8}_{\Lambda}Li$	$+0.04\pm0.06$	
${}^{9}_{\Lambda}B - {}^{9}_{\Lambda}Li$	-0.21 ± 0.22	
${}^{10}_{\Lambda}B - {}^{10}_{\Lambda}Be$	-0.22 ± 0.25	
${}^{12}_{\Lambda}C - {}^{12}_{\Lambda}B$	-0.57 ± 0.19	

E01-011

Iso-multiplet	ΔB_Λ (MeV)	Comment
${}^{28}_{\Lambda}Si - {}^{28}_{\Lambda}Al$	-0.97 ± 0.46	

$B_\Lambda({}^{28}_{\Lambda}Si) = +16.6\pm0.2\pm0.5$ MeV : KEK E140a
$B_\Lambda({}^{28}_{\Lambda}Al) = +17.57\pm0.02\pm0.24$ MeV : Jlab E01-011(Preliminary)

Coulomb repulsion → negative binding energy difference in heavier Λ hypernuclei

Summary

- Precision determination of absolute masses of Λ hypernuclei is offered by the (e,e'K+) reaction complimentary to emulsion experiments
- A ${}^{7}_{\Lambda}$He spectrum(preliminary) and absolute hypernuclear mass measured
  - * $-B_{\Lambda}=-5.68\pm0.03$ (stat.)±0.22 (sys.) for g.s.
- "Charge symmetry breaking" effect has been tested in the A=7 T=1 iso-triplet hypernuclei (${}^{7}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li*, ${}^{7}_{\Lambda}$Be)

  Opposite contribution of the CSB effect compared with the recent cluster-model calculation,
- Further examination of binding energies in light iso-multiplet Λ hypernuclei and also possible CSB effects are required both experimentally and theoretically
  - * Revisiting the A=4 emulsion data
  - * Any contribution from the odd term CSB potential
  - * Further theoretical study of light Λ hypernuclear systems .. ${}^{10}_{\Lambda}$Be,…
  - * Validity of ${}^{12}_{\Lambda}$C binding energy measured by emulsion as a reference at a few 100 keV level
- 3rd generation spectroscopy at JLab Hall C will also offer new data
- Decay pion spectroscopy possibly provides us with unique opportunity to reliably measure binding energies of isospin multiplet Λ hypernuclei