Charge **S**ymmetry **B**reaking in strange nuclei

Elena Botta
Torino University and INFN- Sezione di Torino

Summary

- Introduction
- Present knowledge on CSB effects in *s*, *p*-shell Λ-hypernuclei
- Recent results and analyses
- Conclusions

Introduction

- Charge Independence: **$[H_S, T] = 0$**
  - isospin invariance - strong interaction forces do not distinguish between *n* and *p*:

    $$H_S(pp, T_3=+1) = H_S(pn, T_3=0) = H_S(nn, T_3=-1)$$

  after removing e.m. effects
  - only approximate symmetries (u&d masses difference, qq e.m. interactions → *p*&*n* masses, meson mixing ρ^0-ω)

- Charge Symmetry: **$P_{CS} = e^{i\pi T_2}$** **$[H_S, P_{CS}] = 0$**

  $$H_S(pp, T_3=+1) = H_S(nn, T_3=-1) \qquad T=1$$

  $$\mathbf{H_S(\Lambda p, T_3=+1/2) = H_S(\Lambda n, T_3=-1/2) \qquad T=1/2}$$

Introduction

Charge Symmetry Breaking (CSB) effects

mirror nuclei binding energies

(generalization of the *n*-*p* mass difference)

- $\Delta B = B(^3H) - B(^3He) = 746$ keV → ~71 keV CSB
- Nolen-Schiffer anomaly: *n*-rich nuclei more deeply bound than *p*-rich nuclei (~5%: u,d quark mass difference)

mirror hypernuclei Λ separation energies

$H_S(\Lambda p) = H_S(\Lambda n)$ → contribution to total B

Present knowledge on CSB effects in *s* and *p*-shell Λ-hypernuclei

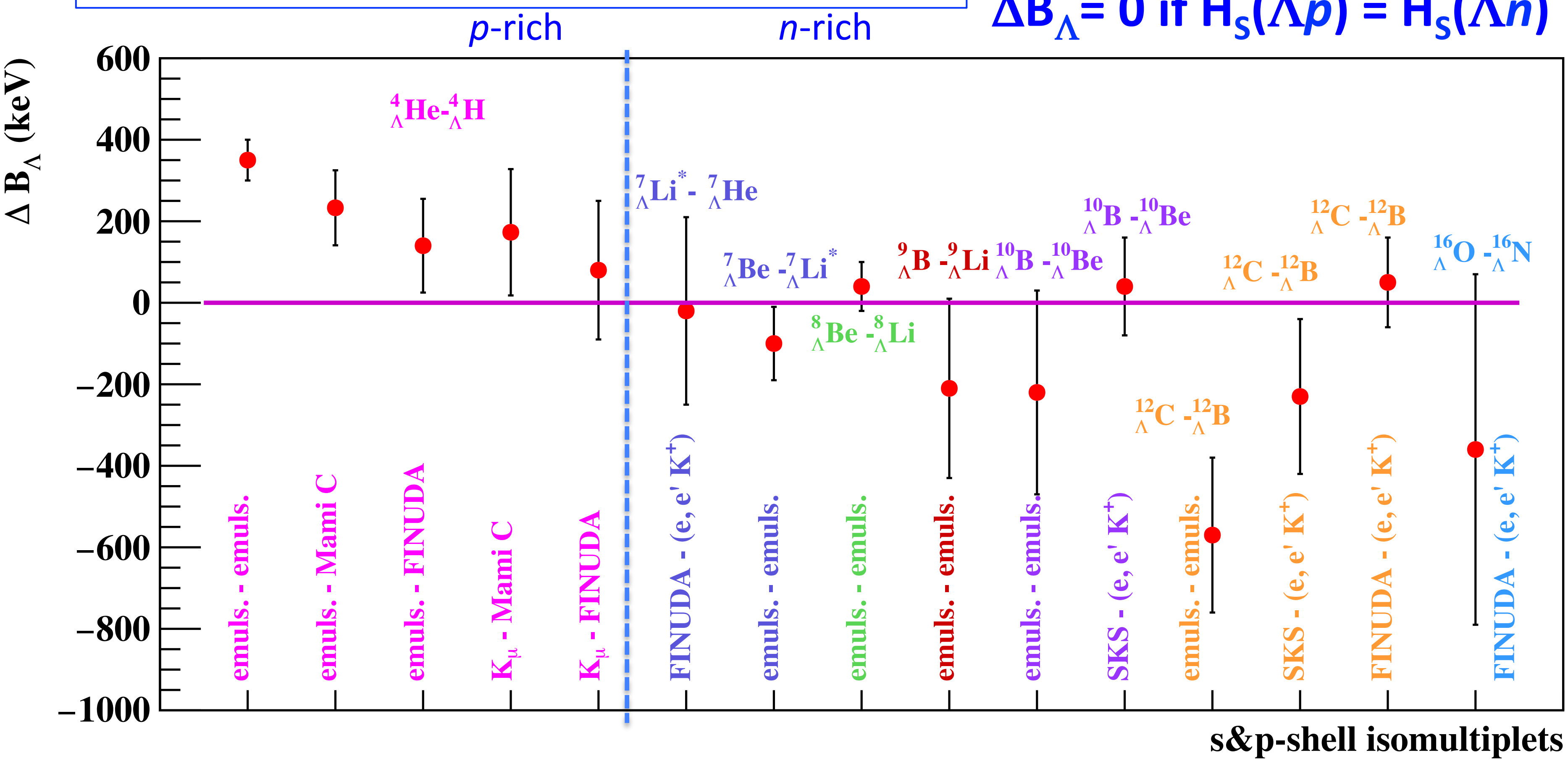
$$B_\Lambda = [M(\Lambda) + M(^{A-1}Z) - M(^{A}_{\Lambda}Z)]\, c^2$$

Λ separation energy

$$\Delta B_\Lambda(A,Z) = B_\Lambda(^{A}_{\Lambda}Z) - B_\Lambda(^{A}_{\Lambda}(Z-1))$$

mirror pair difference

$\Delta B_\Lambda = 0$ if $H_S(\Lambda p) = H_S(\Lambda n)$



Λ-hypernuclei production

- emulsion experiments: hyperfragments produced on heavy components of the emulsion (Ag, Br) by K^- (stopped and in-flight) *p*- and *n*-rich hypernuclei

- magnetic spectrometers with dedicated reactions:
  - (K^-, π^-) $K^- + n \rightarrow \Lambda + \pi^-$ on nuclei
  - (π^+, K^+) $\pi^+ + n \rightarrow \Lambda + K^+$ on nuclei
    - *p*-rich hypernuclei
  - $(e, e' K^+)$ $e + p \rightarrow e' + \Lambda + K^+$, $\gamma + p \rightarrow \Lambda + K^+$ on nuclei
    - *n*-rich hypernuclei

CSB effects: results from different experiments

absolute energy scale calibration

Absolute energy scale calibration

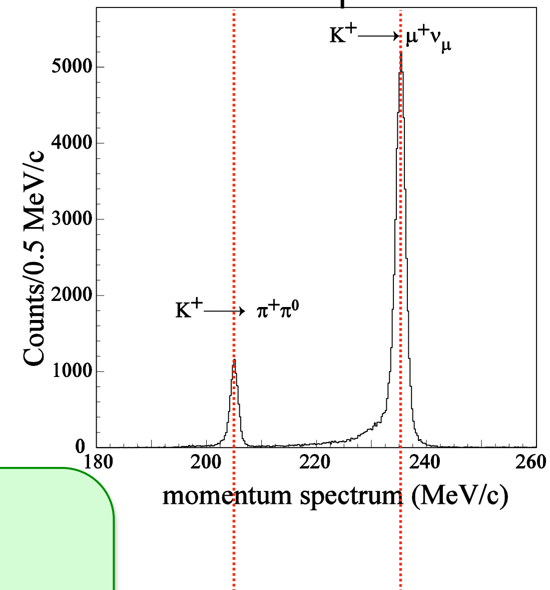
reaction	p_{exp} (MeV/c)	p_{meas} (MeV/c)	$p_{meas} - p_{exp}$ (MeV/c)	$\frac{p_{meas}-p_{exp}}{p_{exp}}$ $\times 10^{-4}$
${}^4_\Lambda H \to \pi^- + {}^4He$	132.9 ± 0.1 [16]	132.738 ± 0.038	−0.16 ± 0.11	−12 ± 8
$K^+ \to \pi^+ + \pi^0$	205.138 [23]	205.10 ± 0.01	−0.038 ± 0.010	−1.9 ± 0.5
$K^+ \to \mu^+ + \nu_\mu$	235.535 [23]	235.410 ± 0.002	−0.125 ± 0.002	−5.3 ± 0.1
$\phi \to e^+e^-$	509.730 [23]	509.5 ± 5.0	−0.23 ± 5.00	−5 ± 100

E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

8 hyp., 6<A<16

LNF/FINUDA (K^-_{stop}, π^-)

$e^+ + e^- \to \phi \to K^+ + K^-$

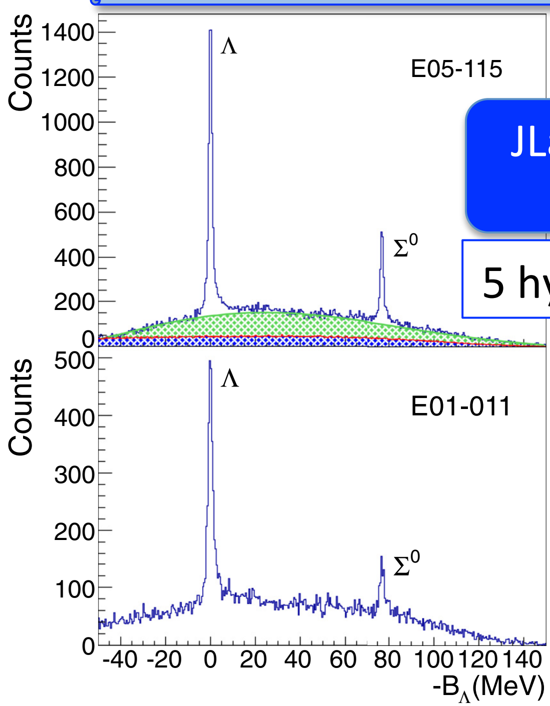


L. Tang *et al.*, PRC 90 (2014) 034320

KEK/SKS
(π^+, K^+)
$\pi^+ + n \to \Lambda + K^+$??

$B_\Lambda({}^{12}_\Lambda C)$ vs emulsions

11 hyp., 7<A<208



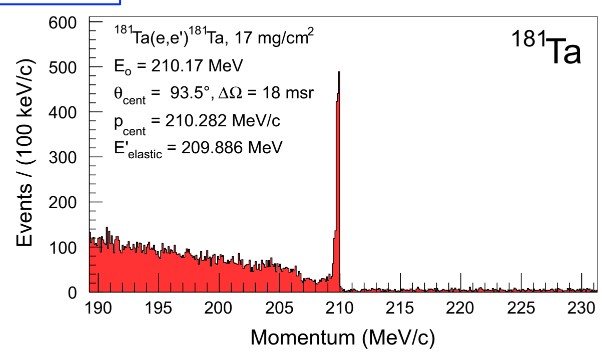
JLab/HallA,C (e, e' K^+)

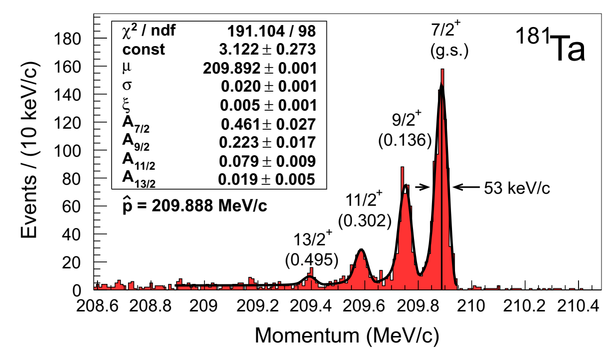
5 hyp., 7<A<16

p(e, e' K^+)Λ/Σ^0 on CH_2 target

MaMi/A1 (e, e' K^+)

${}^{181}Ta(e,e')^{181}Ta$



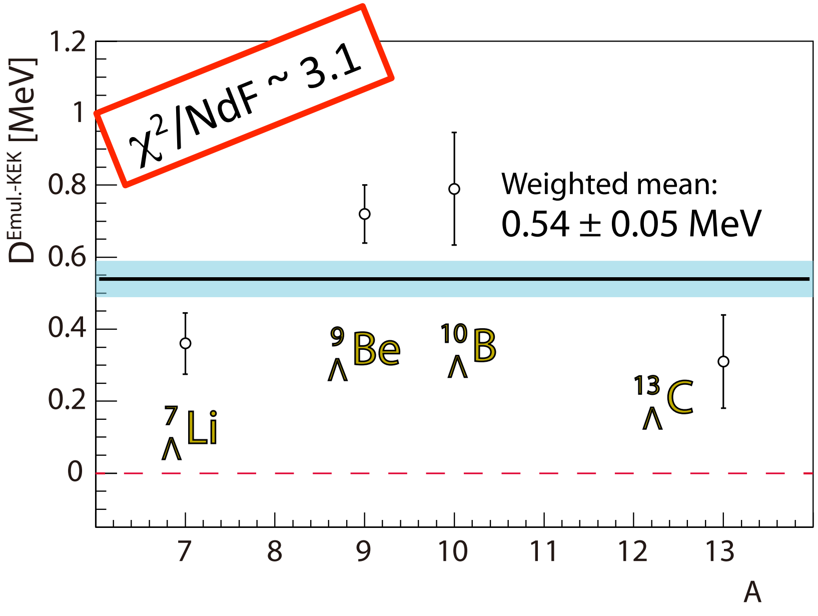


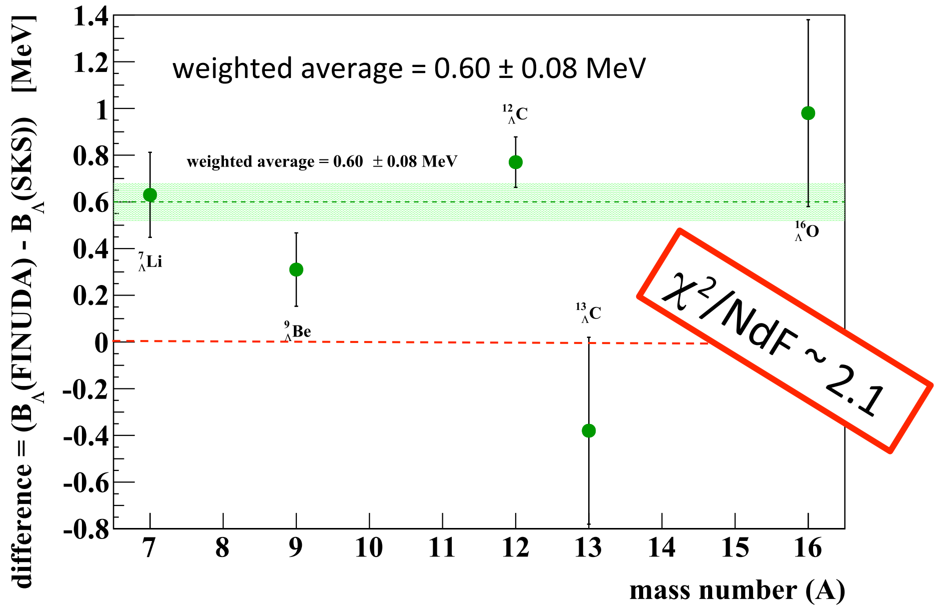
P. Achenbach *et al.*, EPJ web of Conferences 113, 07001 (2016)

Recalibration of KEK/SKS B_Λ: ${}^{10}_{\Lambda}$Be vs ${}^{10}_{\Lambda}$B and ${}^{16}_{\Lambda}$N vs ${}^{16}_{\Lambda}$O ..?

T. Gogami *et al.*, PRC 93 (2016) 034314

E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165



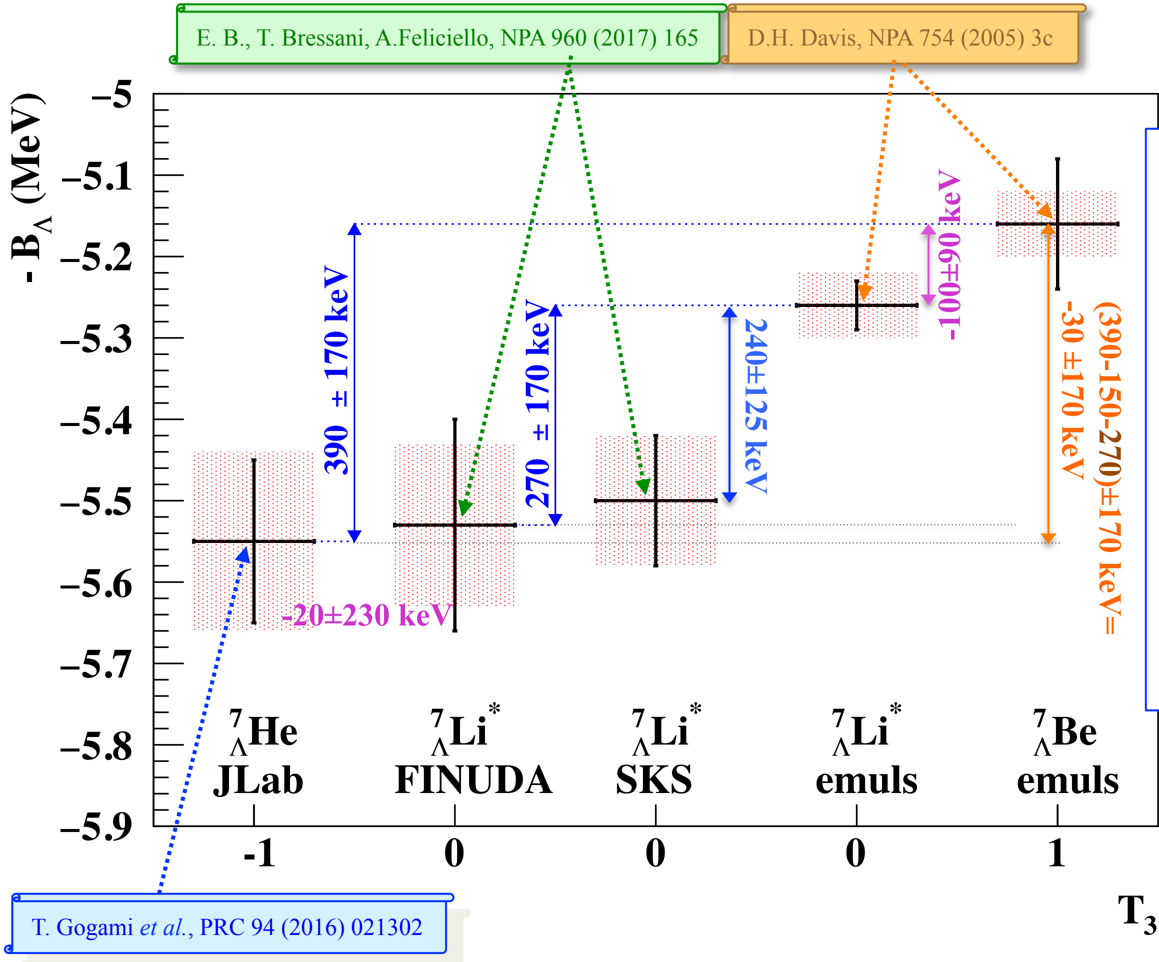


recalibrate ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B and ${}^{13}_{\Lambda}$C to corresponding emulsions data

recalibrate ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{12}_{\Lambda}$C, ${}^{13}_{\Lambda}$C and ${}^{16}_{\Lambda}$O to FINUDA results

F. Cusanno et al., Phys. Rev. Lett. 103 (2009) 202501; ${}^{16}_{\Lambda}$N/${}^{16}_{\Lambda}$O
from A. Gal et al, Rev. Mod. Phys. 88 (2016) 035004: correction of +600 keV to SKS data

CSB in A = 7, T = 1 Λ-hypernuclei?

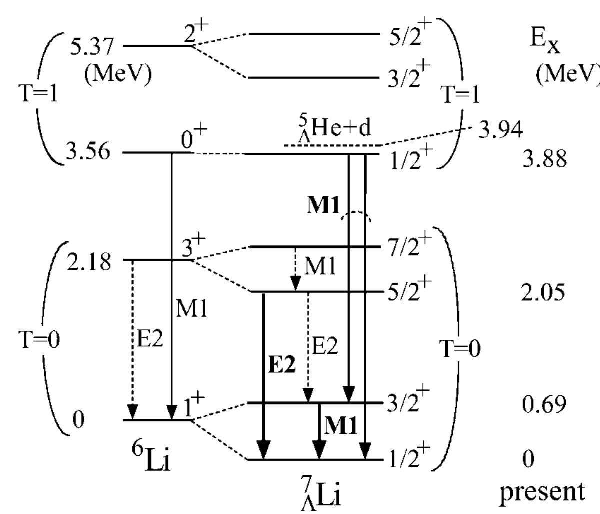


$\Delta B_\Lambda(A, Z) = B_\Lambda({}^{A}_{\Lambda}Z) - B_\Lambda({}^{A}_{\Lambda}(Z-1))$

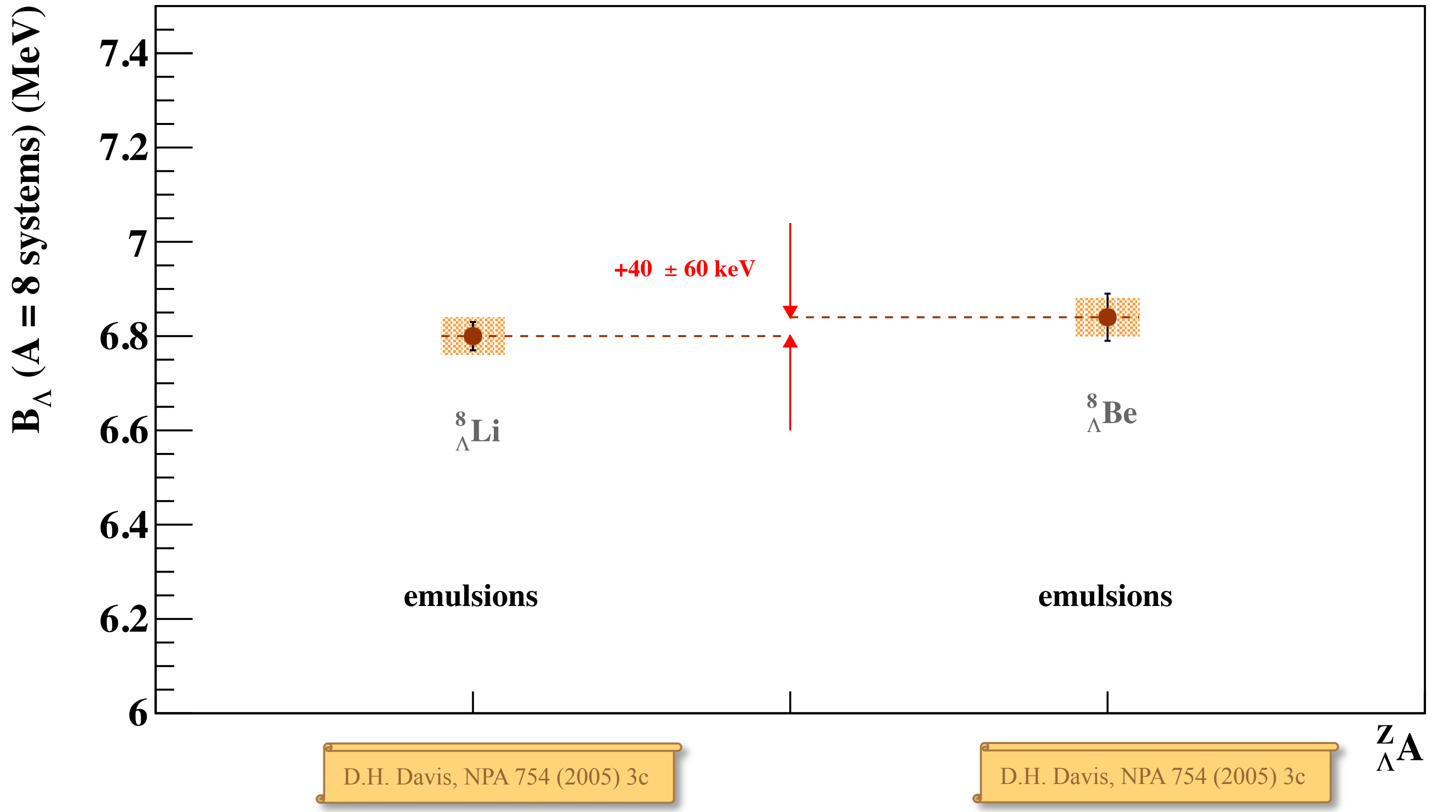
- offset between emulsions and counters experiments values
- Coulombian differential shrink of ${}^{7}He_\Lambda$ and ${}^{7}Be_\Lambda$ cores (~150 keV)
  E. Hiyama *et al.*, PRC 80 (2009) 054321
- th. prediction: $\Delta B_\Lambda({}^{7}_{\Lambda}Be - {}^{7}_{\Lambda}Li^*) = -17$ keV
  A. Gal, PLB 744 (2015) 352
- th. prediction: $\Delta B_\Lambda({}^{7}_{\Lambda}Li^* - {}^{7}_{\Lambda}He) = 220$ keV
  : $\Delta B_\Lambda({}^{7}_{\Lambda}Be - {}^{7}_{\Lambda}Li^*) = 220$ keV
  E. Hiyama *et al.*, PRC 80 (2009) 054321

$B_\Lambda({}^{7}_{\Lambda}Li^*)$ from S.N. Nakamura *et al.*, PRL 110 (2013) 012502
and H. Tamura *et al.*, PRL 84 (2000) 5963

$B_\Lambda({}^{7}_{\Lambda}Li^*) = B_\Lambda({}^{7}_{\Lambda}Li) - [M1(½^+, T=1 \rightarrow ½^+, T=0) - B({}^{6}Li^*, 0^+, T=1)]$
$= B_\Lambda({}^{7}_{\Lambda}Li) - 0.32$ MeV



CSB in A = 8, T = ½ Λ-hypernuclei?

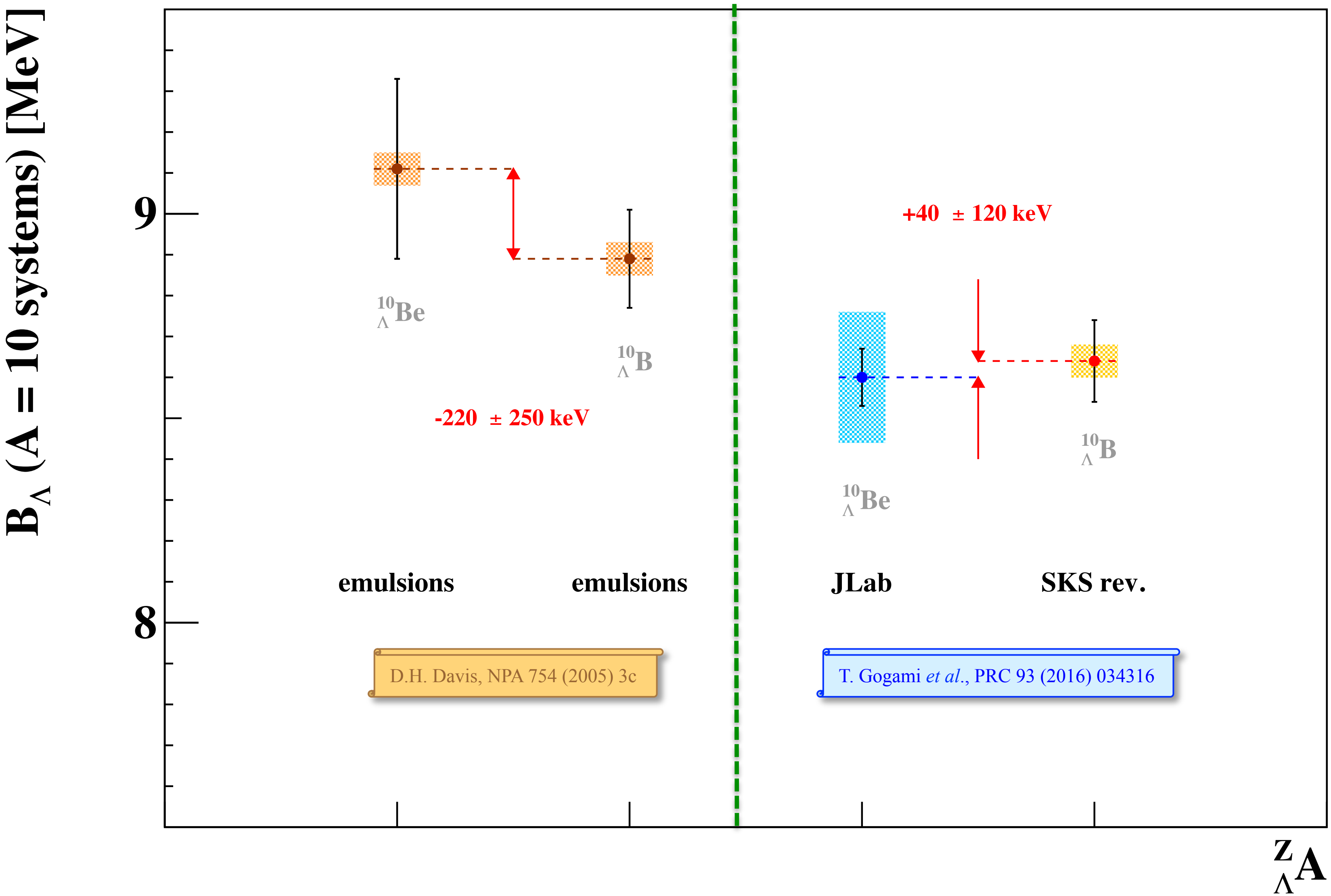


E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

th. predictions: $\Delta B_\Lambda(^{8}_{\Lambda}Be - ^{8}_{\Lambda}Li)$ = +49 keV A. Gal, PLB 744 (2015) 352

= +160 keV E. Hiyama *et al.*, PRC 80 (2009) 054321

CSB in A = 10, T = ½ Λ-hypernuclei?

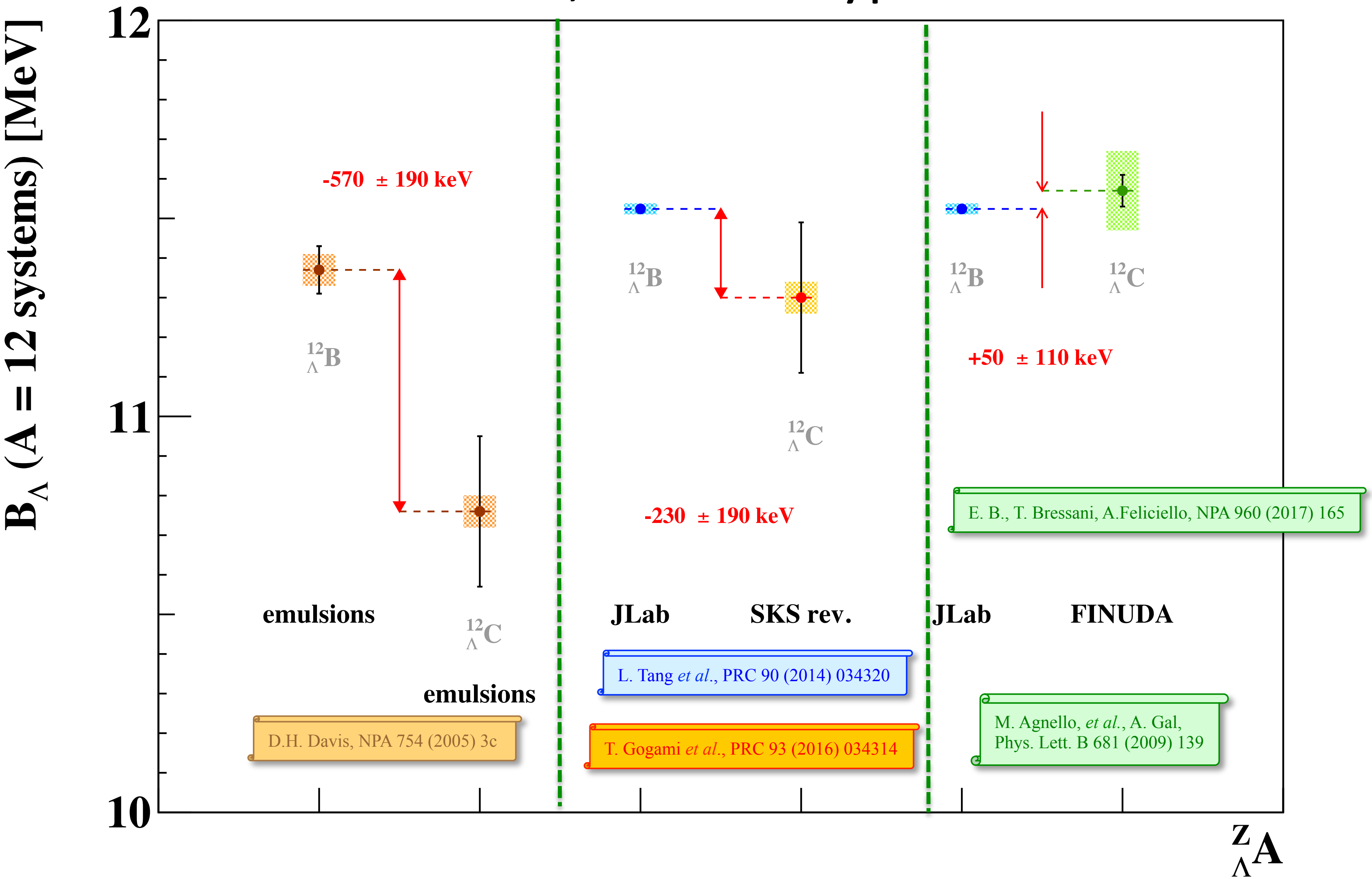


E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

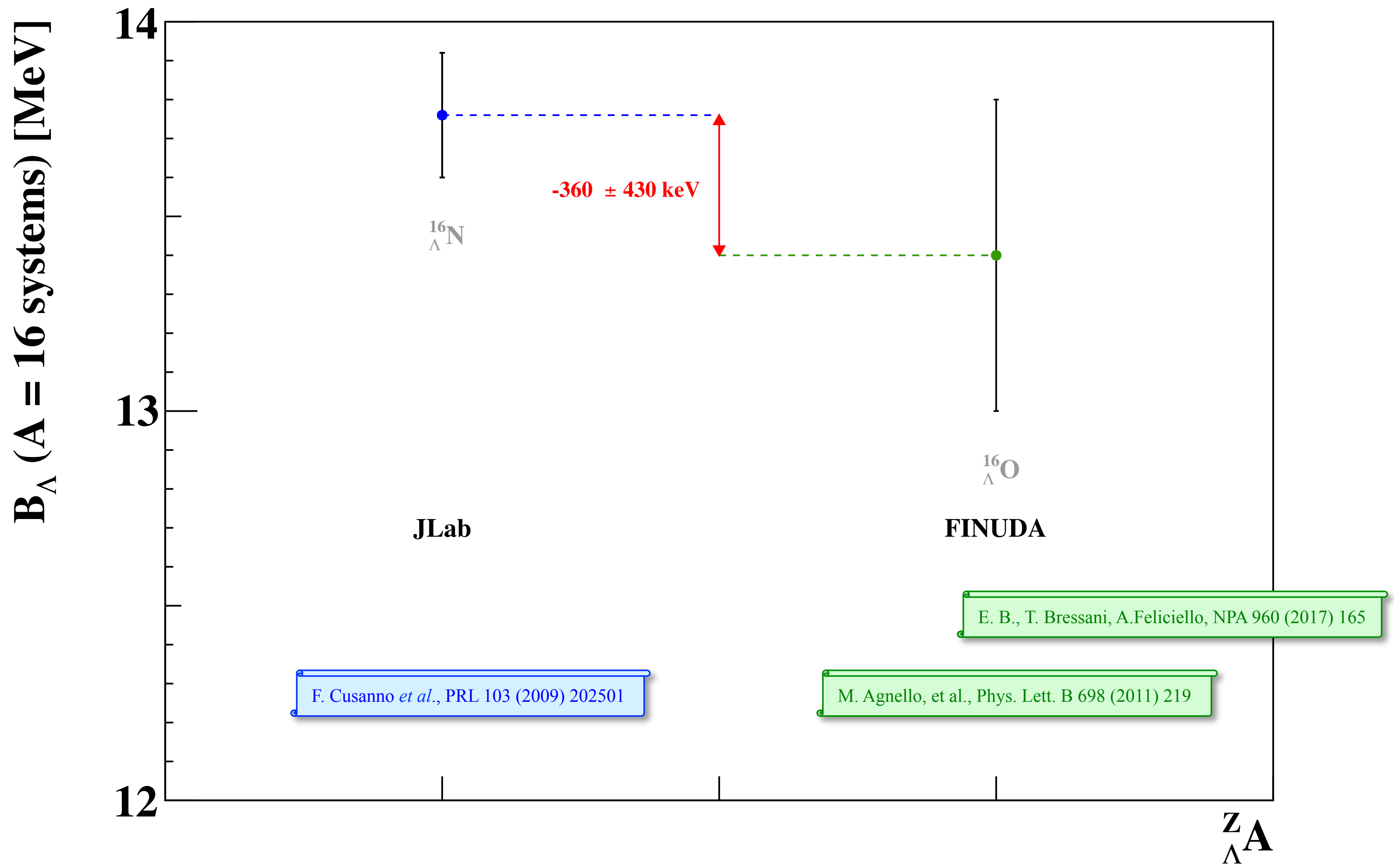
th. prediction: $\Delta B_\Lambda(^{10}{}_{\Lambda}B - {}^{10}{}_{\Lambda}Be) = -136$ keV

A. Gal, PLB 744 (2015) 352

CSB in A = 12, T = ½ Λ-hypernuclei?



CSB in A = 16, T = ½ Λ-hypernuclei?

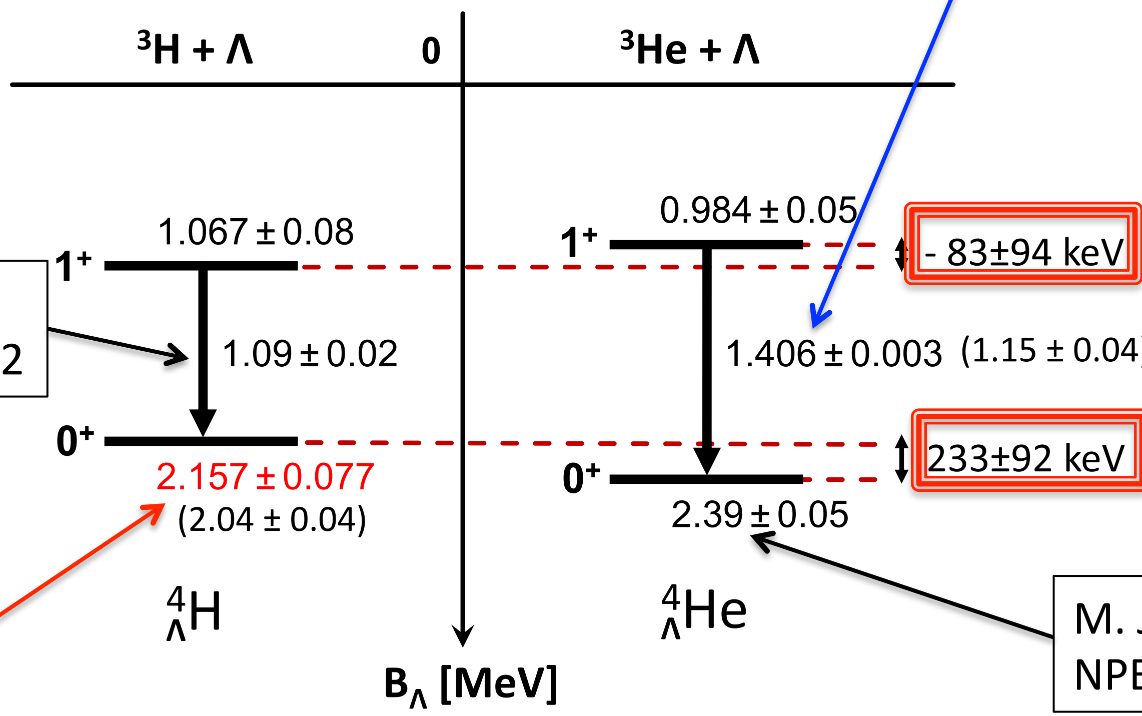


CSB in A = 4, T = ½ Λ-hypernuclei

emulsions and old
γ measurements:
$\Delta B_\Lambda(0+)$ = 350 ± 60 keV
$\Delta B_\Lambda(1+)$ = 290 ± 60 keV

T.O. Yamamoto et al.,Phys. Rev. Lett. 115 (2015) 222501
1406 ± 2 ± 2 keV
strong CSB dependence on spin

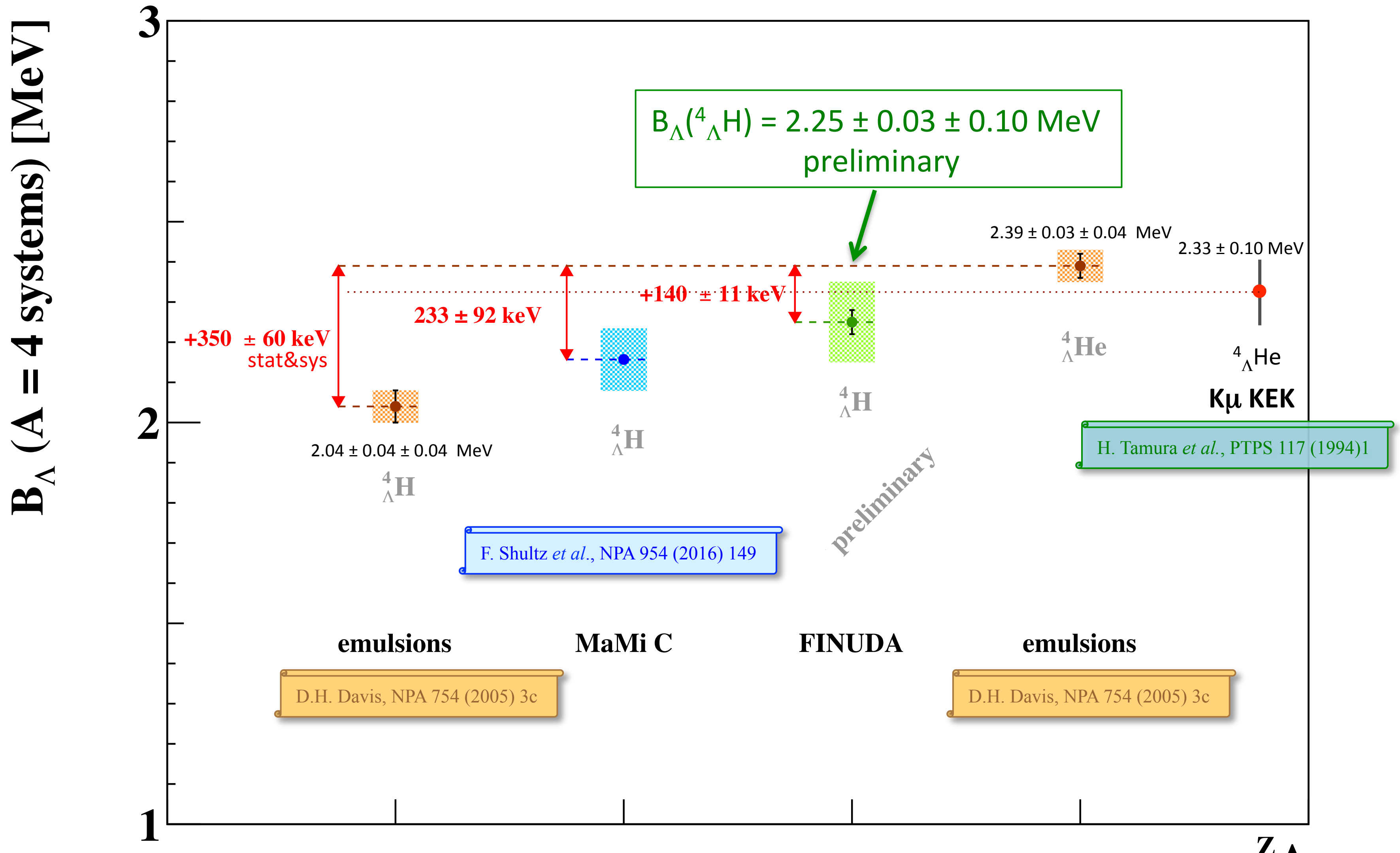
Bedjidian et al.,
PLB 83 (1979) 252



M. Juric et al.,
NPB 52 (1973) 1

A1 Collaboration, F. Schulz et al., Nucl. Phys. A 954 (2016) 149.
2.157 ± 0.005 ± 0.077 MeV

CSB in A = 4, T = ½ Λ-hypernuclei?



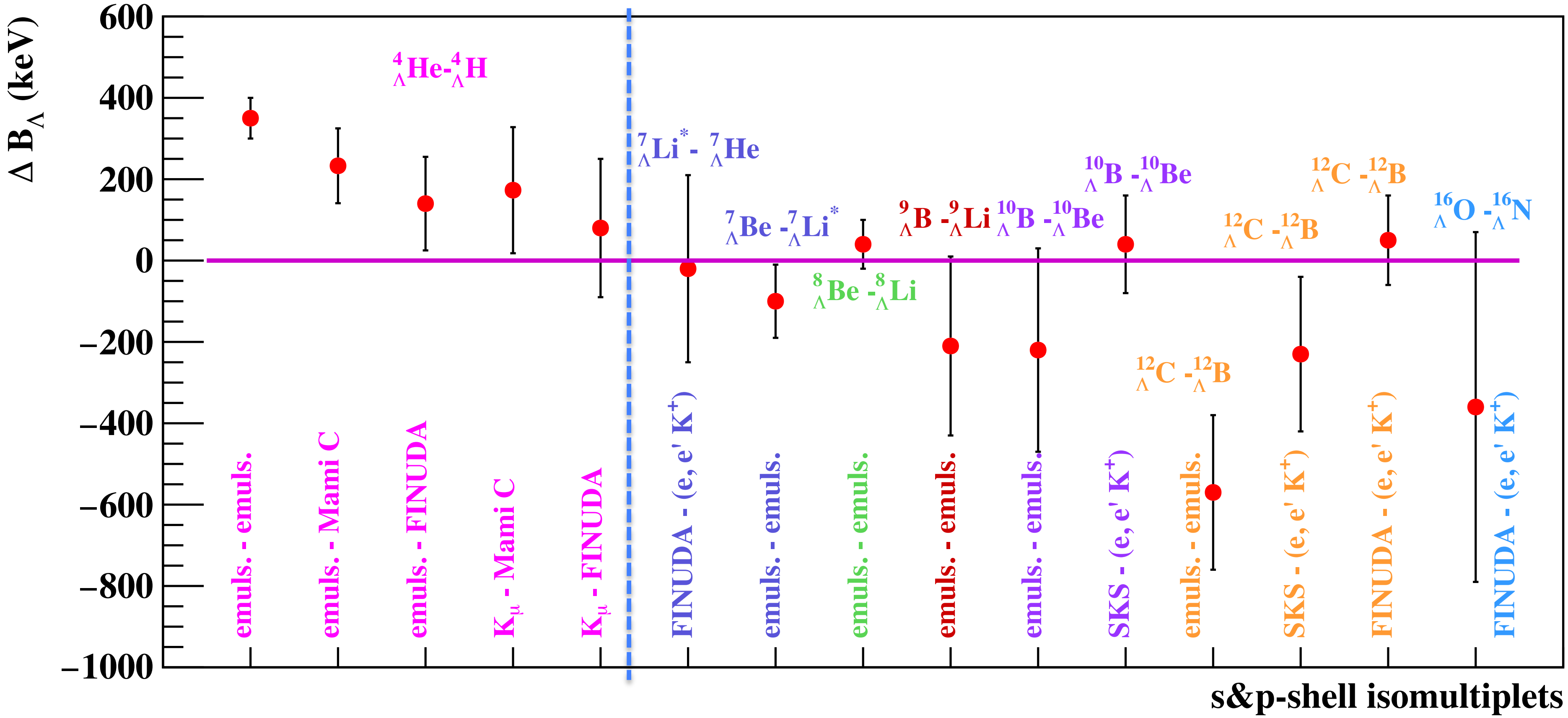
th. prediction: $\Delta B_\Lambda(^4_\Lambda He - ^4_\Lambda H)$ = +226 keV

$\Delta B_\Lambda(^4_\Lambda He - ^4_\Lambda H)$ = ~200 keV

A. Gal, PLB 744 (2015) 352

D. Gazda, A. Gal, NPA 954 (2016) 161

Conclusions



- A=4 system:
  measure with precision $^{4}_{\Lambda}$He g.s. and $^{4}_{\Lambda}$H $\gamma(1^{+} \rightarrow 0^{+})$ transition
- A=7, $^{7}_{\Lambda}$Be (emulsions-counters)
- A=16 system, increase statistics

backup

Theoretical calculations

E. Hiyama *et al.*, PRC 80 (2009) 054321

4 body cluster model (Λ+α+N+N) for A=7, 8
4-body potential given by the sum of two-body interactions that reproduce the observed properties of any subsystems composed of αN, αΛ, αNN and αΛN. The ΛN interaction is adjusted so as to reproduce the 0^+ - 1^+ splitting of in $^4_\Lambda$H. Phenomenological ΛN CSB interaction: central force only with a one-range Gaussian form which includes spin-independent and spin-spin parts.

A. Gal, PLB 744 (2015) 352

Dalitz and von Hippel Λ-Σ mixing mechanism in SU(3) to produce CSB contributions from OPE interactions in hypernuclei. G-matrix YN effective inter. derived from NSC97
~1% Σ admixture percentages in 0+; 1+ admixture considerably weaker .
A=4 then 7, 8, 9, 10

D. Gazda, A. Gal, NPA 954 (2016) 161

Gazda-Gal: ab-initio No Core Shell Model calculation based on Bonn-Julich LO chiral EFT for YN and NN (N3LO), NNN (N2LO) interactions.
CSB mechanism: Λ-Σ mixing (ΛN-ΣN coupling), OPE exchange interactions: CSB is driven by relatively long-range OPE. A=4

Revised CSB effect in *p*-shell Λ-hypernuclei

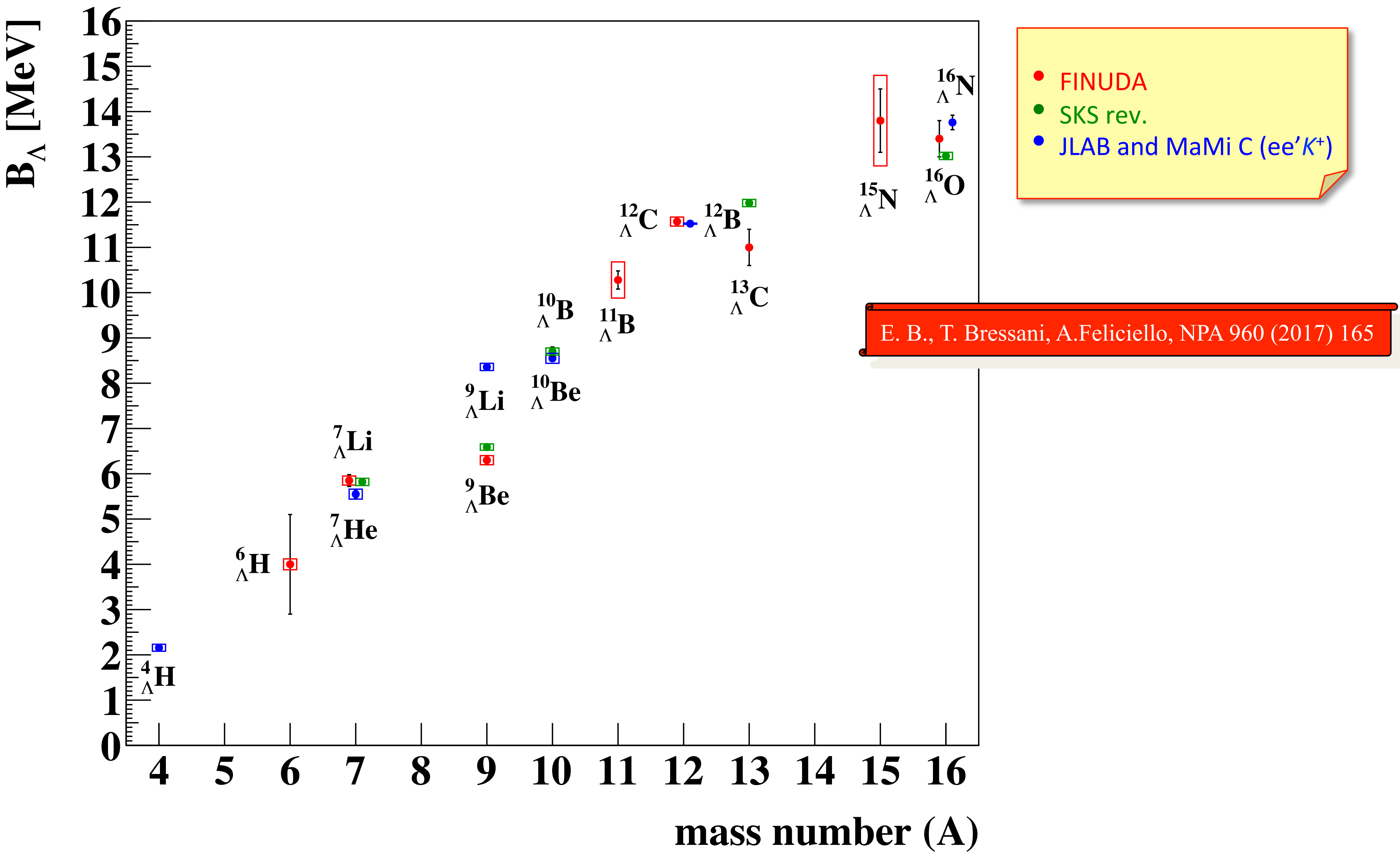
$$\Delta B_\Lambda(A,Z) = B_\Lambda({}^A_\Lambda Z) - B_\Lambda({}^A_\Lambda(Z-1))$$

multiplet pair	$\Delta B_\Lambda(A,Z)$ (keV)	experimental sources	Reference
${}^7_\Lambda\mathrm{Be} - {}^7_\Lambda\mathrm{Li}^*$	-100 ± 90	emuls. − emuls.	[2, 4]
${}^7_\Lambda\mathrm{Li}^* - {}^7_\Lambda\mathrm{He}$	-20 ± 230	FINUDA − $(e,e'K^+)$	[t.w.]
${}^8_\Lambda\mathrm{Be} - {}^8_\Lambda\mathrm{Li}$	$+40 \pm 60$	emuls. − emuls.	[2]
${}^{10}_\Lambda\mathrm{B} - {}^{10}_\Lambda\mathrm{Be}$	-220 ± 250	emuls. − emuls.	[2]
	$+40 \pm 120$	SKS − (e,e',K^+)	[13]
${}^{12}_\Lambda\mathrm{C} - {}^{12}_\Lambda\mathrm{B}$	-570 ± 190	emuls. − emuls.	[2]
	-230 ± 190	SKS − (e,e',K^+)	[13]
	$+50 \pm 110$	FINUDA − $(e,e'K^+)$	[t.w.]
${}^{16}_\Lambda\mathrm{O} - {}^{16}_\Lambda\mathrm{N}$	-360 ± 430	FINUDA − $(e,e'K^+)$	[t.w.]

[2] D.H. Davis, Nucl. Phys. A 754 (2005) 3c.
[4] H. Tamura et al., Phys. Rev. Lett. 84 (2000) 5963.
[13] T. Gogami et al., Phys. Rev. C 93 (2016) 034314
[t.w.] E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

$\Delta B_\Lambda({}^9_\Lambda\mathrm{B} - {}^9_\Lambda\mathrm{Li}) = -210 \pm 220$ keV from emulsions ($\Delta Z=2$)

s, *p*-shell hypernuclei B_Λ from counter experiments with absolute energy scale calibration



E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

	emulsions (MeV)	(π^+, K^+) (MeV) KEK-SKS [5]	(π^+, K^+) (MeV) KEK-SKS revised [t.w.]	(K^-_{stop}, π^-) (MeV) DAΦNE-FINUDA	$(e, e'K^+)$ (MeV) JLab, MaMi
$^{3}_{\Lambda}$H	0.13±0.05±0.04 [1, 2]				
$^{4}_{\Lambda}$H	2.04±0.04±0.04 [1, 2]				2.157±0.005±0.077 [16]
$^{4}_{\Lambda}$He	2.39±0.03±0.04 [1, 2]				
$^{5}_{\Lambda}$He	3.12±0.02±0.04 [1, 2]				
$^{6}_{\Lambda}$H				4.0±1.1 [20, 28]	
$^{6}_{\Lambda}$He	4.25±0.10 [1] 4.18±0.10±0.04 [2]				
$^{7}_{\Lambda}$He					5.55±0.10±0.11 [11]
$^{7}_{\Lambda}$Li	5.58±0.03±0.04 [1, 2]	5.22±0.08±0.36	5.82±0.08±0.08	5.85±0.13±0.10 [19],[t.w.] 5.8±0.4 [21]	
$^{7}_{\Lambda}$Li* [4]	5.26±0.03±0.04	4.90±0.08±0.36	5.50±0.08±0.08	5.53±0.13±0.10 5.48±0.40	
$^{7}_{\Lambda}$Be	5.16±0.08±0.04 [1, 2]				
$^{8}_{\Lambda}$He	7.16±0.70±0.04 [1, 2]				
$^{8}_{\Lambda}$Li	6.80±0.03±0.04 [1, 2]				
$^{8}_{\Lambda}$Be	6.84±0.05±0.04 [1, 2]				
$^{9}_{\Lambda}$Li	8.53±0.15 [1] 8.51±0.12±0.04 [2]				8.36±0.08±0.08 [12]
$^{9}_{\Lambda}$Be	6.71±0.04±0.04 [1, 2]	5.99±0.07±0.36	6.59±0.07±0.08	6.30±0.10±0.10 [19],[t.w.] 6.2±0.4 [21]	
$^{9}_{\Lambda}$B	7.88±0.15 [1] 8.29±0.18±0.04 [2]				
$^{10}_{\Lambda}$Be	9.30±0.26 [1] 9.11±0.22±0.04 [2]				8.60±0.07±0.16 [13]
$^{10}_{\Lambda}$B	8.89±0.12±0.04 [1, 2]	8.1±0.1±0.5	8.7±0.1±0.08		
$^{11}_{\Lambda}$B	10.24±0.05±0.04 [1, 2]			10.28±0.2±0.4 [t.w.]	
$^{12}_{\Lambda}$B	11.37±0.06±0.04 [1, 2]				11.524±0.019±0.013 [14]
$^{12}_{\Lambda}$C	10.76±0.19±0.04 [2]	10.80 fixed		11.57±0.04±0.10 [19],[t.w.] 10.94±0.06±0.50 [18]	
$^{13}_{\Lambda}$C	11.22±0.08 [1] 11.69±0.12±0.04 [2]	11.38±0.05±0.36	11.98±0.05±0.08	11.0±0.4 [21]	
$^{14}_{\Lambda}$C	12.17±0.33±0.04 [2]				
$^{15}_{\Lambda}$N	13.59±0.15±0.04 [1, 2]			13.8±0.7±1.0 [t.w.]	
$^{16}_{\Lambda}$N					13.76±0.16 [15]
$^{16}_{\Lambda}$O		12.42±0.05±0.36	13.02±0.05±0.08	13.4±0.4 [21]	

E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165

[1] M. Jurič, et al., Nucl. Phys. B 52 (1973) 1.
[2] D.H. Davis, Nucl. Phys. A 754 (2005) 3c.
[3] S.N. Nakamura, et al., Phys. Rev. Lett. 110 (2013) 012502.
[4] H. Tamura, et al., Phys. Rev. Lett. 84 (2000) 5693.
[5] O. Hashimoto, T. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.
[6] E. Botta, T. Bressani, G. Garbarino, Eur. Phys. J. A 48 (2012) 41.
[7] A. Feliciello, T. Nagae, Rep. Prog. Phys. 78 (2015) 006301.
[8] A. Gal, E.V. Hungerford, D.J. Millener, Rev. Mod. Phys. 88 (2016) 035004.
[9] T. Hasegawa, et al., Phys. Rev. C 53 (1996) 1210.
[10] H. Hotchi, et al., Phys. Rev. C 64 (2001) 044302.
[11] T. Gogami, et al., Phys. Rev. C 94 (2016) 021302.
[12] G.M. Urciuoli, et al., Phys. Rev. C 91 (2015) 034308.
[13] T. Gogami, et al., Phys. Rev. C 93 (2016) 034314.
[14] L. Tang, et al., Phys. Rev. C 90 (2014) 034320.
[15] F. Cusanno, et al., Phys. Rev. Lett. 103 (2009) 202501.
[16] A1 Collaboration, F. Schulz, et al., Nucl. Phys. A 954 (2016) 149.
[17] A. Gal, Phys. Lett. B 744 (2015) 352.
[18] FINUDA Collaboration, M. Agnello, et al., Phys. Lett. B 622 (2005) 35.
[19] FINUDA Collaboration, M. Agnello, et al., A. Gal, Phys. Lett. B 681 (2009) 139.
[20] M. Agnello, et al., Nucl. Phys. A 881 (2012) 269.
[21] M. Agnello, et al., Phys. Lett. B 698 (2011) 219.

E. B., T. Bressani, A.Feliciello, NPA 960 (2017) 165