Unresolved issues in Hypernuclear Physics

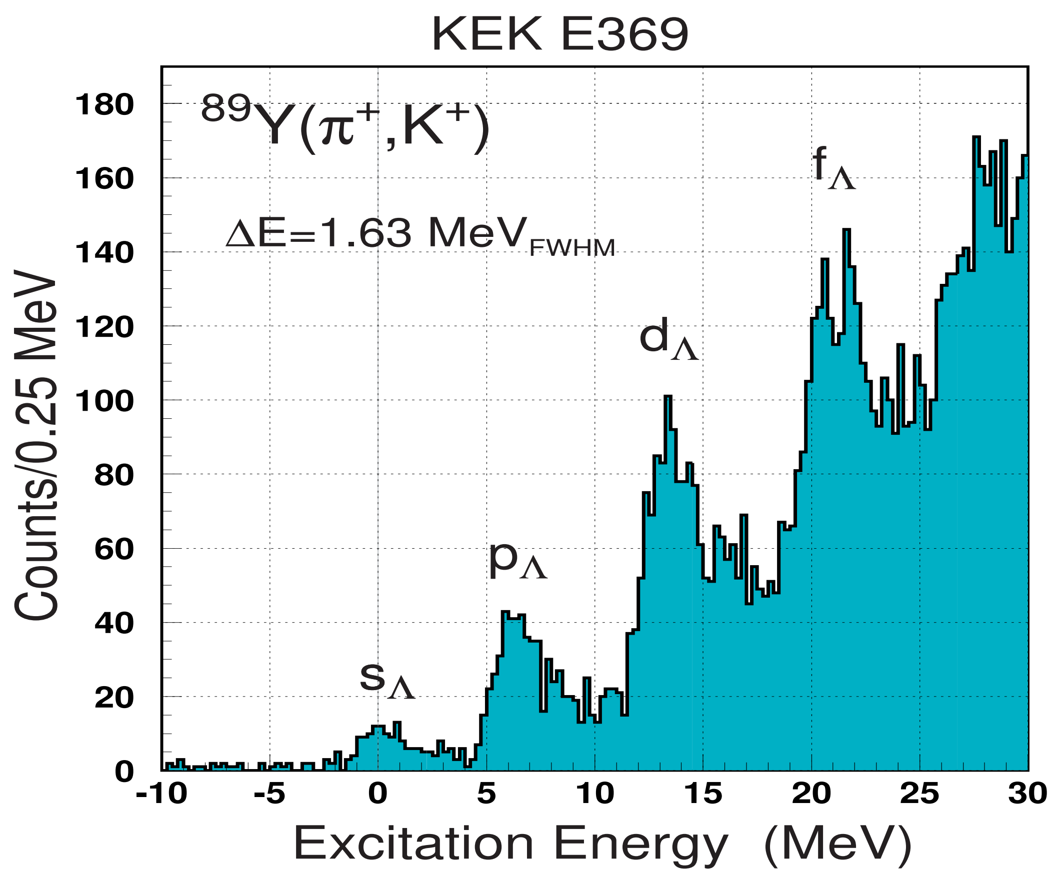
(my first 50 years in Hypernuclear Physics)

Avraham Gal, Hebrew University, Jerusalem

- **Dynamics of Λ hypernuclei ($^{A}_{\Lambda}Z$)**
  (i) s-shell few-body (ii) p-shell & beyond
- **$\Lambda\Lambda$ hypernuclei: onset of $\Lambda\Lambda$ binding?**
- **Hyperons (Λ, Σ, Ξ) in nuclear matter & beyond**
  (i) neutron stars: hyperon puzzle
  (ii) competition with $\bar{K}$ condensation?
  (iii) $\Lambda^*(1405)$, $\Sigma^*(1385)$? K^- nuclear clusters
- **NPA Topical Issues: 881 (2012) & 954 (2016)**
- **Review: A.Gal E.V.Hungerford D.J.Millener**
  Rev. Mod. Phys. 88 (2016) 035004

Λ hypernuclear dynamics

Observation of Λ single-particle states

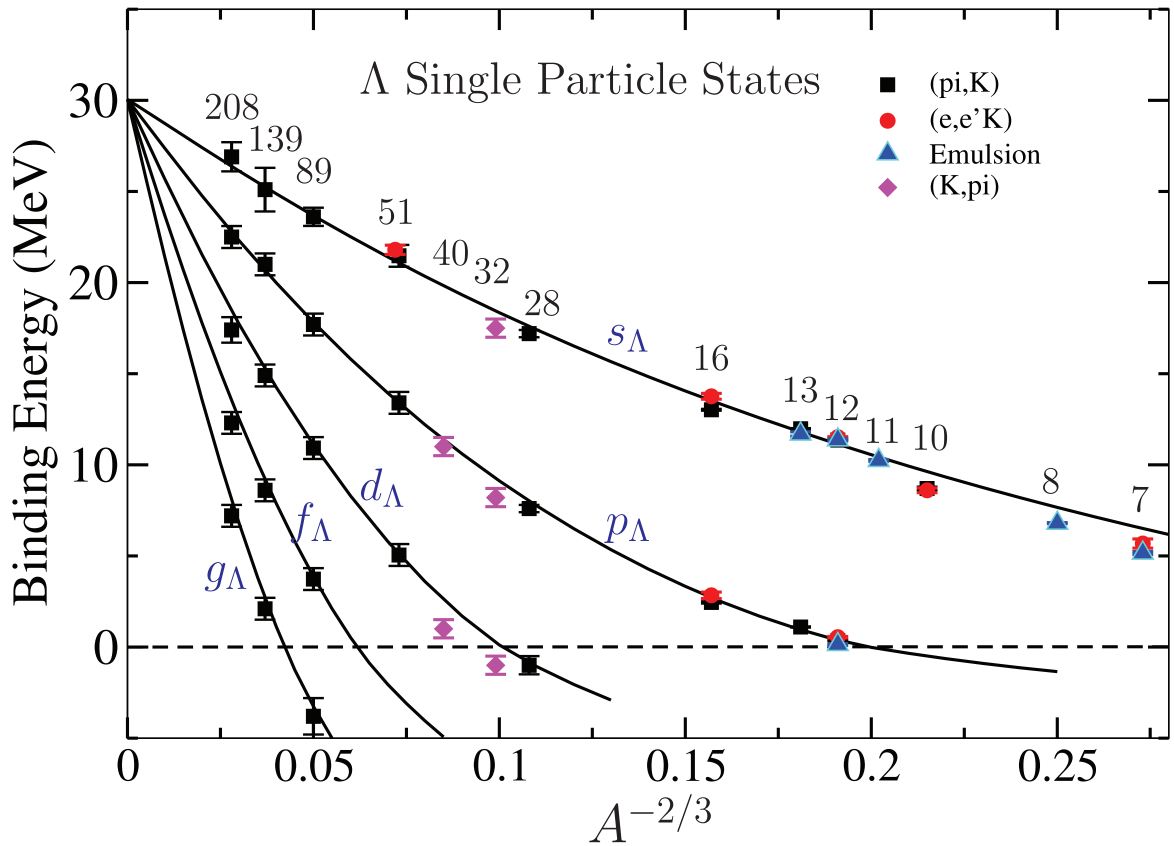


Hotchi et al., PRC 64 (2001) 044302 B_Λ=23.1(1) $\rightarrow$ 23.6(5) MeV

Motoba-Lanskoy-Millener-Yamamoto, NPA 804 (2008) 99:

negligible Λ spin-orbit splittings, 0.2 MeV for $1f_\Lambda$

Update: Millener, Dover, Gal PRC 38, 2700 (1988)



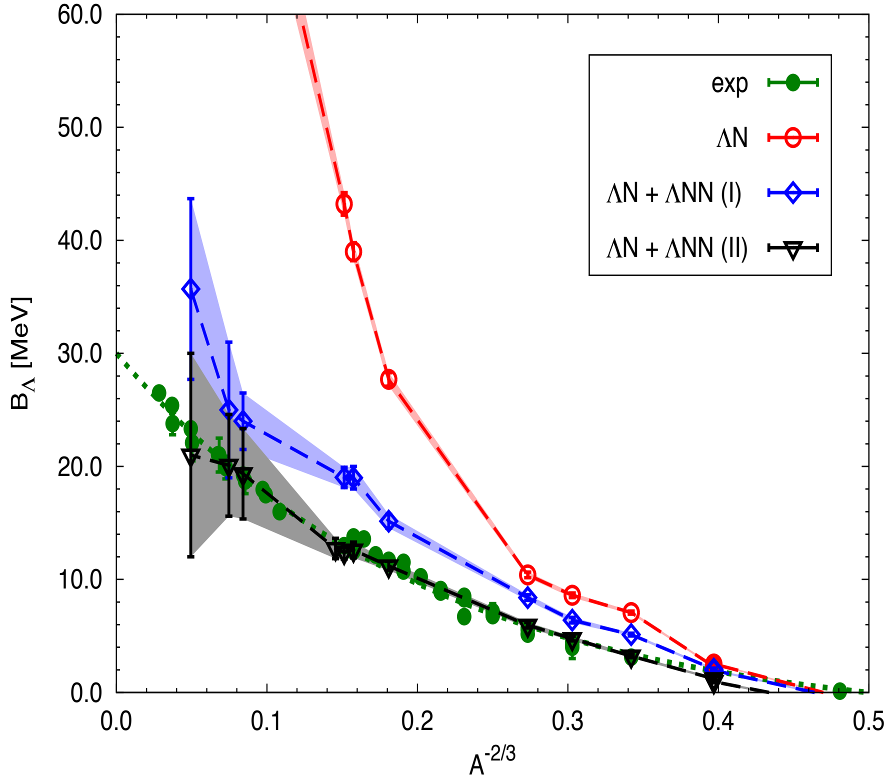
Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

V(MeV) = 27±3 (1964) 27.2±1.3 (1965) 27.8±0.3 (1988)

from π^- decays of heavy spallation hypernuclei to (π^+, K^+)

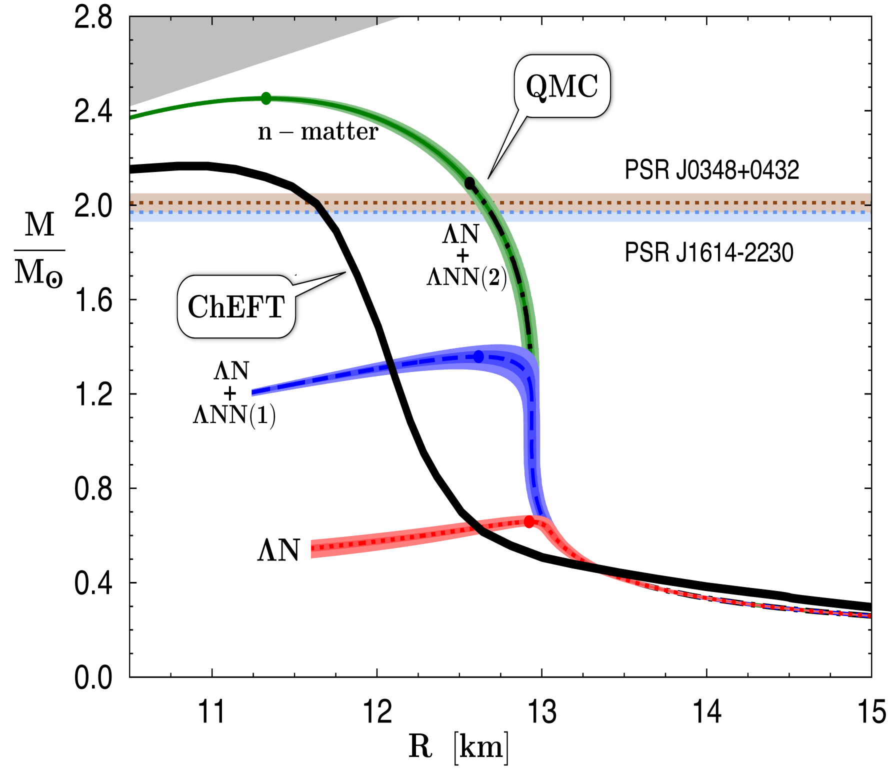
Skyrme-Hartree-Fock studies suggest ΛNN repulsion.

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314

ΛNN effect on B_Λ(g.s.)



PRL 114 (2015) 092301

ΛNN effect on neutron stars

- **ΛN overbinds, adding ΛNN stiffens EOS of neutron stars.**
- **YY add 0.3$M_\odot$ to M_{max} (Rijken-Schulze 2016).**
- **Overbinding has been a problem in s-shell hypernuclei.**

The lightest, s-shell, Λ hypernuclei

${}^{A}_{\Lambda}$Z	T	$J^{\pi}_{\text{g.s.}}$	B_{Λ} (MeV)	$J^{\pi}_{\text{exc.}}$	E_x (MeV)
${}^{3}_{\Lambda}$H	0	$1/2^{+}$	0.13(5)		
${}^{4}_{\Lambda}$H–${}^{4}_{\Lambda}$He	1/2	0^{+}	**2.16(8)–2.39(3)**	1^{+}	**1.09(2)–1.406(3)**
${}^{5}_{\Lambda}$He	0	$1/2^{+}$	3.12(2)		

- **No ΛN and no Λnn bound state are expected.**
- **$\Delta B_{\Lambda}({}^{4}_{\Lambda}\text{He}-{}^{4}_{\Lambda}\text{H})$=0.23(9) (g.s.) –0.083(94) (exc.) in MeV.**

Recent $A = 3, 4$ few-body calculations

- **A. Nogga, NPA 914 (2013) 140**
  Faddeev & Faddeev-Yakubovsky (chiral LO & NLO).
- **E. Hiyama et al., PRC 89 (2014) 061302(R)**
  Jacobi-coordinates Gaussian basis (Nijmegen soft-core).
- **R. Wirth et al., PRL 113 (2014) 192502 (chiral LO).**
  D. Gazda, A. Gal, (2016) PRL 116 122501 NPA 954 161.
- **L. Contessi, N. Barnea, A. Gal, PRL 121 (2018) 102502.**

Overbinding problem in s-shell

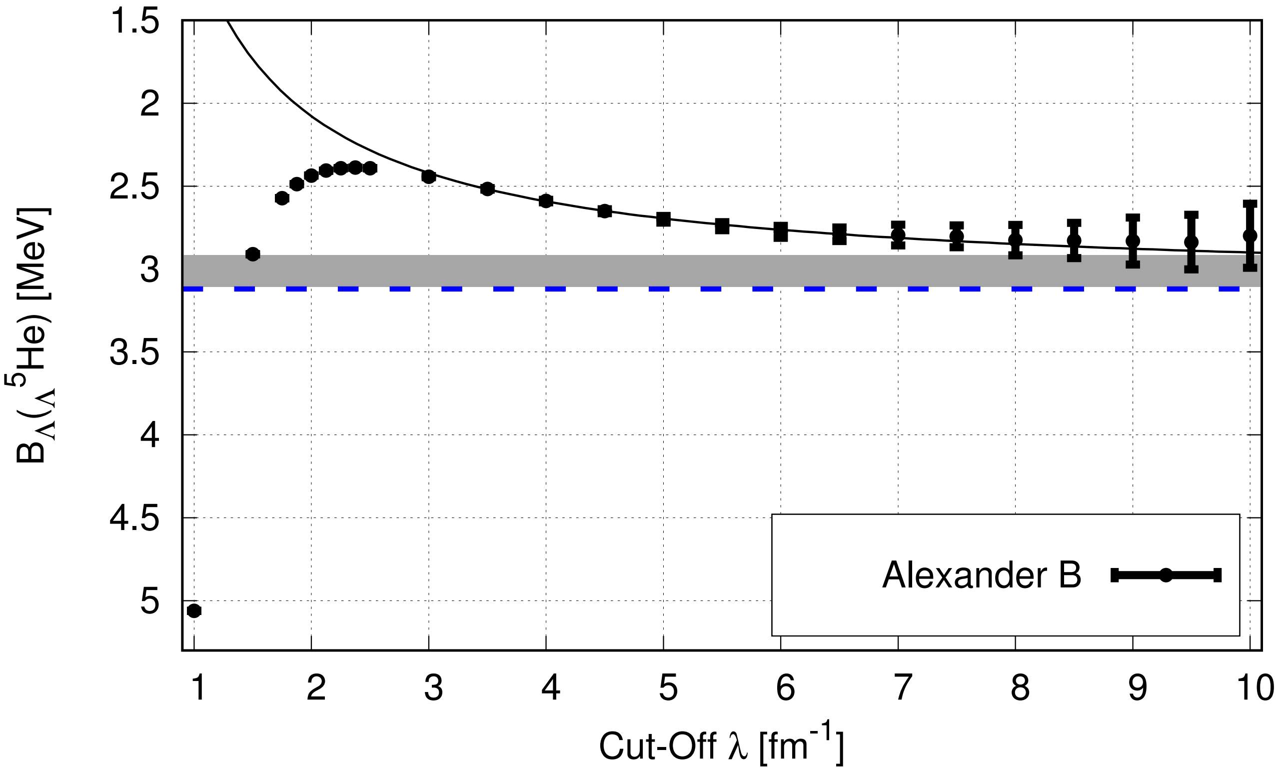
(MeV)	$B_\Lambda({}^3_\Lambda\mathrm{H})$	$B_\Lambda({}^4_\Lambda\mathrm{H}_{\mathrm{g.s.}})$	$E_x({}^4_\Lambda\mathrm{H}_{\mathrm{exc.}})$	$B_\Lambda({}^5_\Lambda\mathrm{He})$
Exp.	0.13(5)	2.16(8)	1.09(2)	3.12(2)
Dalitz	0.10	2.24	0.36	$\geq$5.16
NSC97f(S)	0.18	2.16	1.53	2.10
AFDMC(I)	–	1.97(11)	–	5.1(1)
AFDMC(II)	–1.2(2)	1.07(8)	–	3.22(14)
LOχEFT(600)	0.11(1)	2.31(3)	0.95(15)	5.82(2)
LOχEFT(700)	–	2.13(3)	1.39(15)	4.43(2)

L. Contessi, N. Barnea, A. Gal, PRL 121 (2018) 102502

Resolving the overbinding problem in $\not\pi$EFT

- Fit 2 ΛN LECs to ΛN scattering lengths.
- Fit 3 ΛNN LECs to the 3 A=3,4 levels.
- Calculate in SVM ${}^5_\Lambda$He binding.

Contessi et al. Hyp. s-shell $\not\pi$EFT



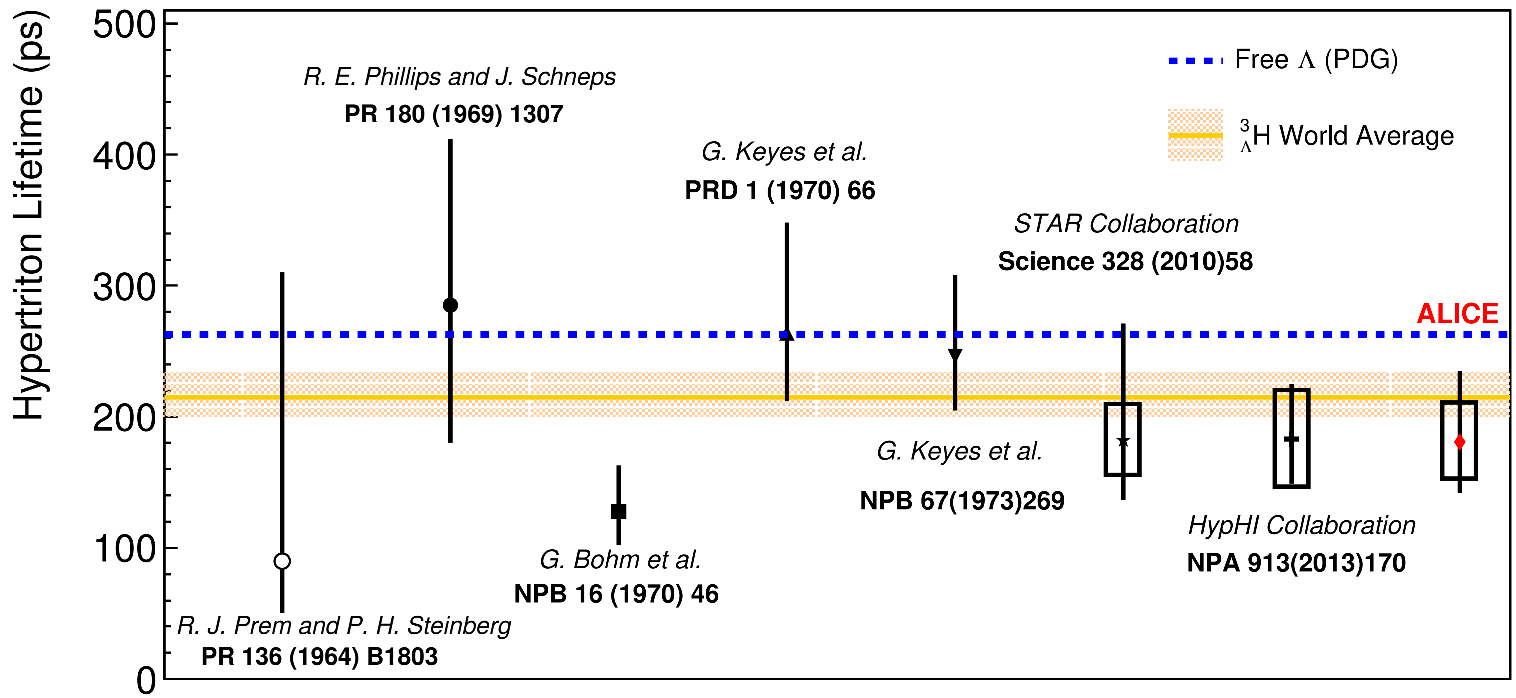
$B_\Lambda({}^5_\Lambda$He) vs. cut-off λ in LO $\not\pi$EFT SVM calculations

Solid line: a two-paraneter fit a+b/λ, $\lambda \geq 4$ fm^{-1}.

Gray horizontal band: $\lambda \to \infty$ extrapolation uncertainties.

Dashed horizontal line: $B_\Lambda^{\rm exp.}({}^5_\Lambda$He)=3.12±0.02 MeV.

${}^{3}_{\Lambda}$H lifetime puzzle



The weakly-bound ${}^{3}_{\Lambda}$H, B_{Λ}=0.13±0.05 MeV, expected to have lifetime within a few % of the free Λ lifetime.
Recent heavy-ion ${}^{3}_{\Lambda}$H production experiments yield lifetimes shorter by $\geq 30\%$. ALICE, PLB 754 (2016) 360.
STAR, PRC 97 (2018) 054909: τ=$142^{+24}_{-21}\pm29$ ps $(0.54^{+0.09}_{-0.08}\tau_{\Lambda})$.

Brief review of lifetime calculations

Reference	Method	R_3	$\Gamma({}^3_\Lambda\mathrm{H},J{=}\frac{1}{2},T{=}0)/\Gamma_\Lambda$
Experiment	wo. av.	0.35 ± 0.04	1.22 ± 0.07
Dalitz-Rayet (1966)	closure	–	1.05
Congleton (1992)	Λd	0.33 ± 0.02	1.12
Kamada et al (1998)	Λpn Fad.	0.379	1.03
Gal-Garcilazo (2018)	Λpn Fad.		$1.09+(0.06\pm0.03)$

- $R_3{=}\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+{}^3\mathrm{He})/\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+\mathrm{all})\Rightarrow J=\frac{1}{2}$.
- Closure: $\Gamma({}^3_\Lambda\mathrm{H},J{=}\frac{1}{2},T{=}0)/\Gamma_\Lambda = 1{+}0.14\sqrt{B_\Lambda}$.
- A bound, isomeric ${}^3_\Lambda\mathrm{H}(J{=}\frac{3}{2},T{=}0)$ (unlikely) would decay slower than a free Λ.
- ${}^3_\Lambda$n, if exists, lives longer by $\approx$40% than free Λ.
- Study role of pion FSI ($+0.06\pm0.03$, prelim.)

${}^{4}_{\Lambda}$H & ${}^{4}_{\Lambda}$He lifetimes

$$\Gamma({}^{4}_{\Lambda}\mathrm{H})/\Gamma_{\Lambda} \approx \frac{3}{2} \times (\frac{2}{3} \times 0.7 + 1 \times 0.3) + 0.25 = 1.40$$

$$\Gamma({}^{4}_{\Lambda}\mathrm{He})/\Gamma_{\Lambda} \approx \frac{3}{2} \times (\frac{1}{3} \times 0.7 + 1 \times 0.3) + 0.25 = 1.05$$

Input: $\frac{3}{2}$ for nuclear structure, $\mathbf{R_4}$=0.7

$\frac{2}{3}$ & $\frac{1}{3}$ for π^- or π^0 and ^{4}He, $\Gamma_{\mathrm{n.m.}}/\Gamma_{\Lambda} \approx$ 0.25

$\Rightarrow \tau({}^{4}_{\Lambda}\mathrm{H}) \approx$ **190 ps**, $\tau({}^{4}_{\Lambda}\mathrm{He}) \approx$ **250 ps**

in rough agreement with measured lifetimes.

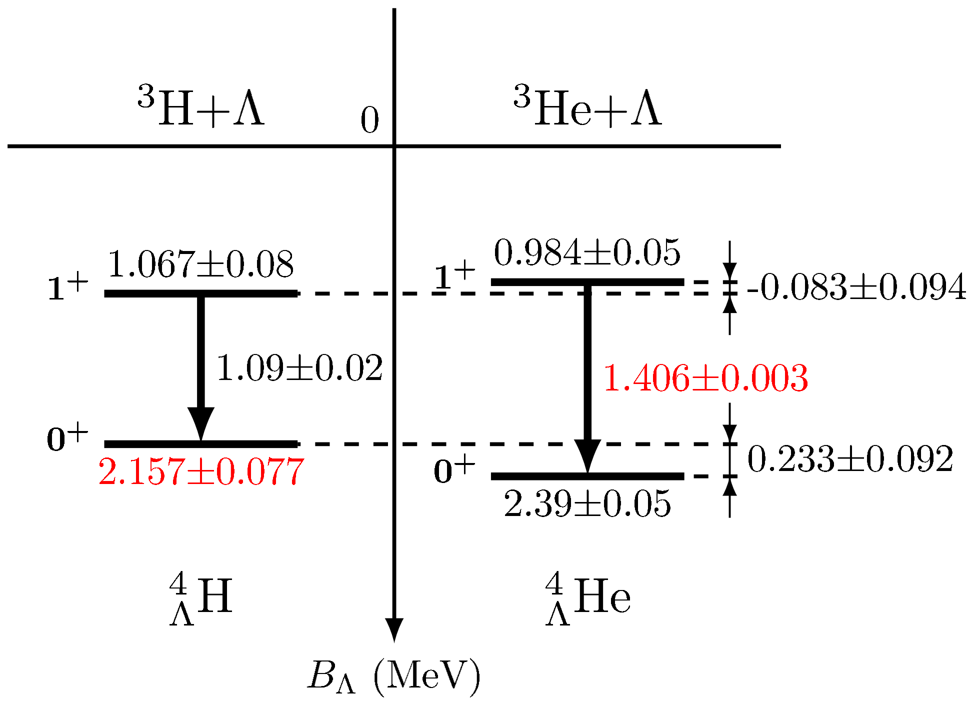
Looks like Lifetime Puzzle is limited to ${}^{3}_{\Lambda}$H.

- **For A$\geq$12, $\tau({}^{A}_{\Lambda}\mathrm{Z})\sim$200 ps, from KEK and very recently from HKS JLab E02-E017 NPA 973 (2018) 116. Lifetime is due to ΛN$\rightarrow$NN.**

The ${}^4_\Lambda$H–${}^4_\Lambda$He complex & CSB since 2015

MAMI's A1, ${}^4_\Lambda\mathrm{H}\to{}^4\mathrm{He}+\pi^-$, PRL 114 (2015) 232501

J-PARC's E13, ${}^4\mathrm{He}(K^-,\pi^-\gamma)$, PRL 115 (2015) 222501

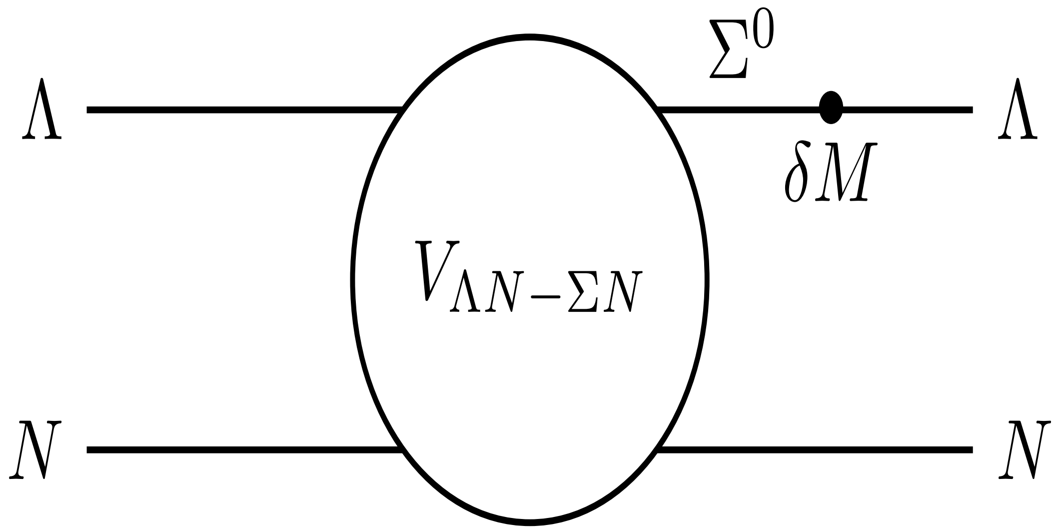


CSB due to Λ-Σ^0 mixing, strongly spin dependent,

dominantly in $0^+_{\mathrm{g.s.}}$, large w.r.t. ≈−70 keV in ^{3}H-^{3}He.

Re-measure ${}^4_\Lambda\mathrm{He}_{\mathrm{g.s.}}$ (E13 → E63).

Relating Λ-Σ^0 CSB mixing to $\Lambda\Sigma$ SI coupling



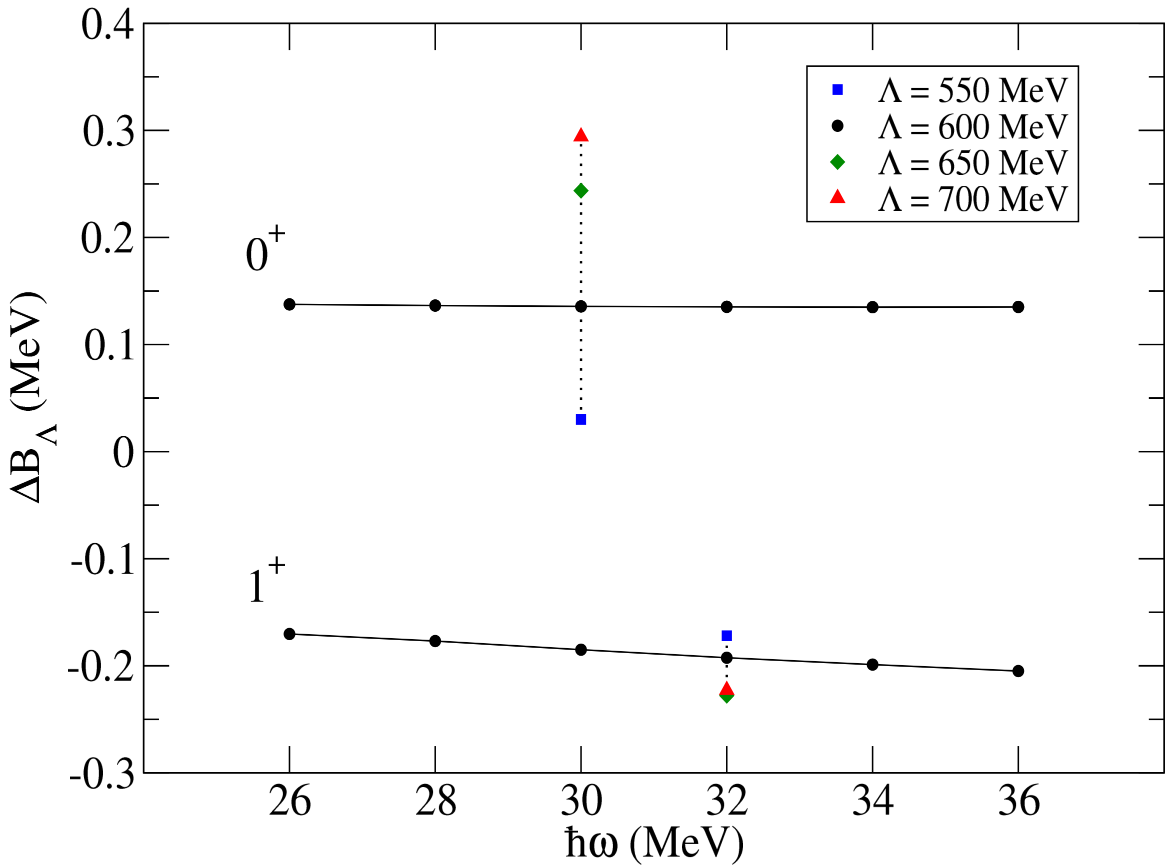
Dalitz-von Hippel (1964): "applies to any isovector meson exchange, π, ρ..." & also to χEFT contact interactions.

$$\langle N\Lambda|V^{\rm CSB}_{\Lambda N}|N\Lambda\rangle = -0.0297\,\tau_{Nz}\,\frac{1}{\sqrt{3}}\,\langle N\Sigma|V^{\rm SI}|N\Lambda\rangle.$$

Applied systematically by A. Gal, PLB 744 (2015) 352

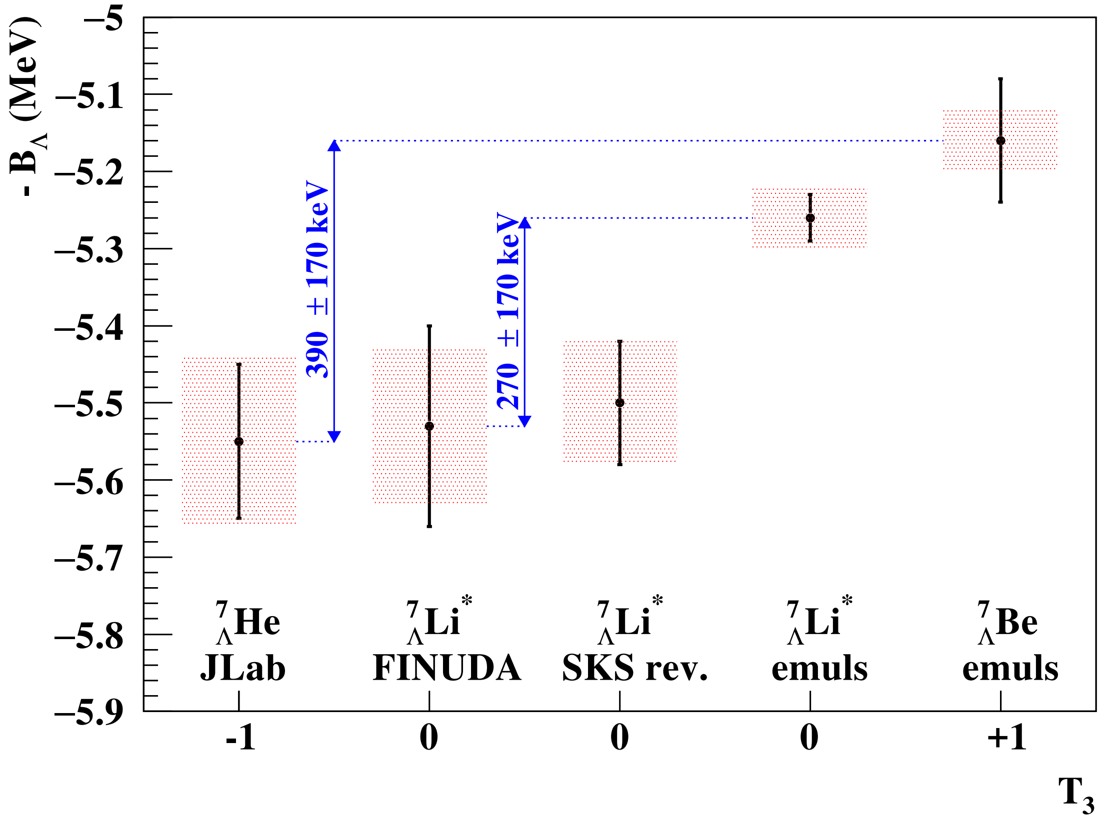
A=4: D.Gazda A.Gal (2016), PRL 116 122501; NPA 954 161.

Latest summary: J. Phys. Conf. Series 966 (2018) 012006.



NCSM HO $\hbar\omega$ dependence of $\Delta B_\Lambda({}^{4}_{\Lambda}\mathrm{He}\text{–}{}^{4}_{\Lambda}\mathrm{H})$ for 0^+ & 1^+. Note $\pm$ sign pattern resulting from $^1S_0$ Λ-Σ contact term dominance at LO [see OPE discussion NPA 954 (2016) 161]. Λ=600 MeV: $\Delta E_\gamma=\Delta(\Delta B_\Lambda)=0.33\pm0.03$ MeV compared to a measured $\Delta E_\gamma=0.32\pm0.02$ MeV.

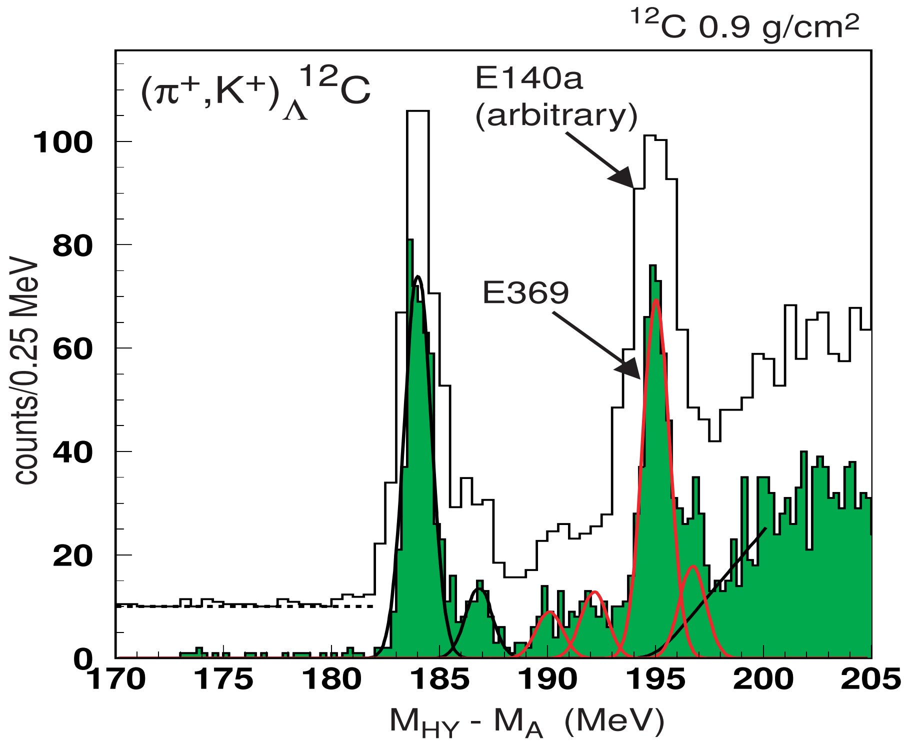
CSB in p-shell hypernuclei

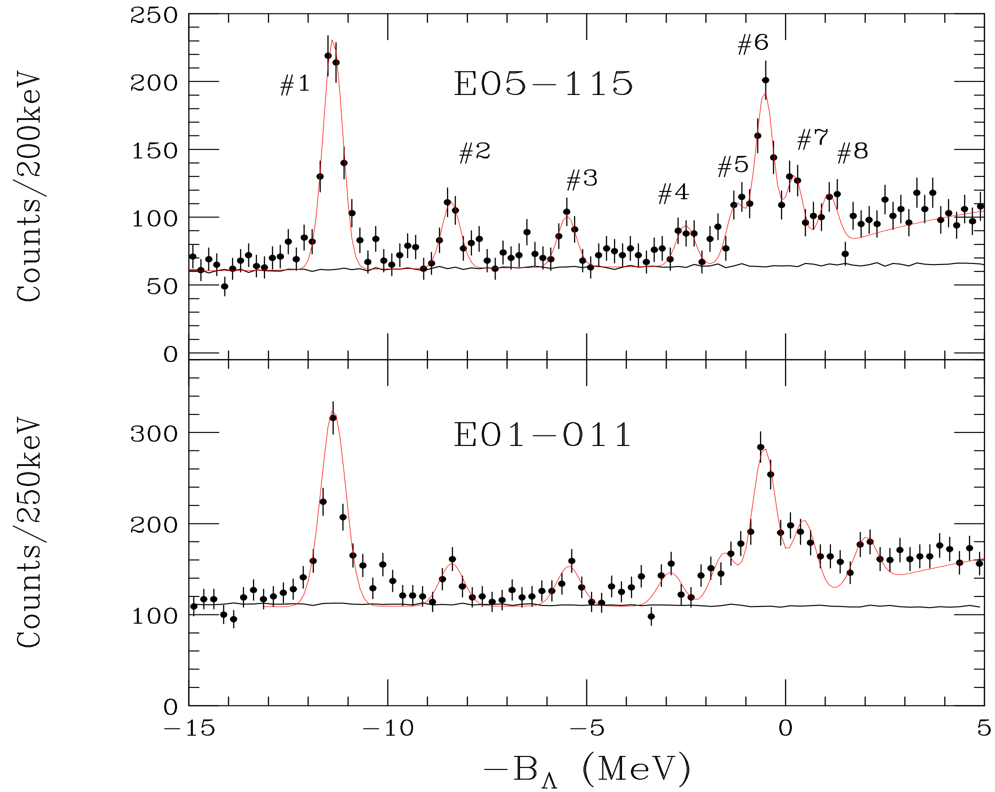


E. Botta, T. Bressani, A. Feliciello, NPA 960 (2017) 165-179

CSB appears to be much weaker in the A=7 isotriplet than in the A=4 isodoublet provided counter experiments are not compared directly with old emulsion results.

Room for hypernuclear spectroscopy





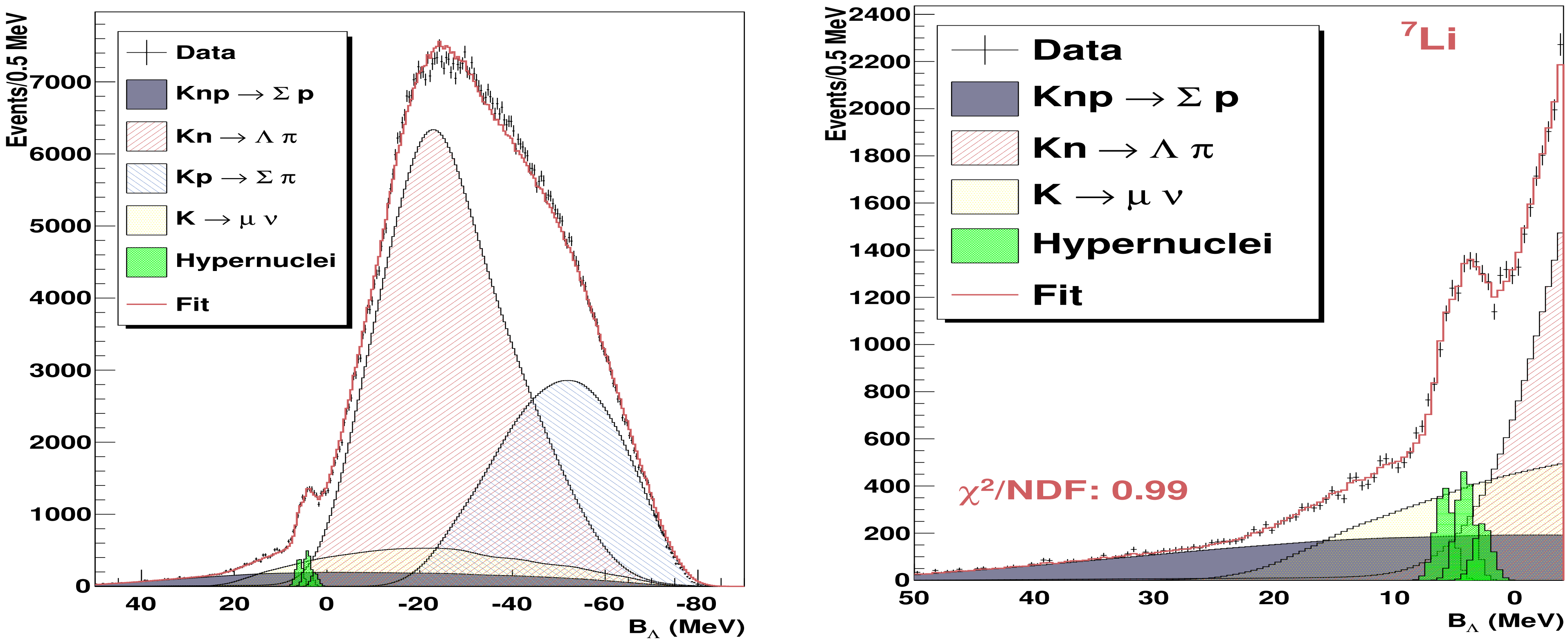
H. Hotchi et al., PRC 64 (2001) 044302 L. Tang et al., PRC 90 (2014) 034320

$1s_\Lambda$-$1p_\Lambda$ intermediate structure **Jlab: $^{12}\mathrm{C}(e, e'K^+)^{12}_{\Lambda}$B (HKS)**

Spin-nonflip exc., ΔS=0 **Spin-flip excitations, ΔS=1**

energy resolution 1.6 MeV $\rightarrow$ **0.6 MeV in Hall-C E05-115**

Hypernuclear production in $(K^-_{\mathrm{stop}}, \pi^-)$, PLB 698 (2011) 219 & 226



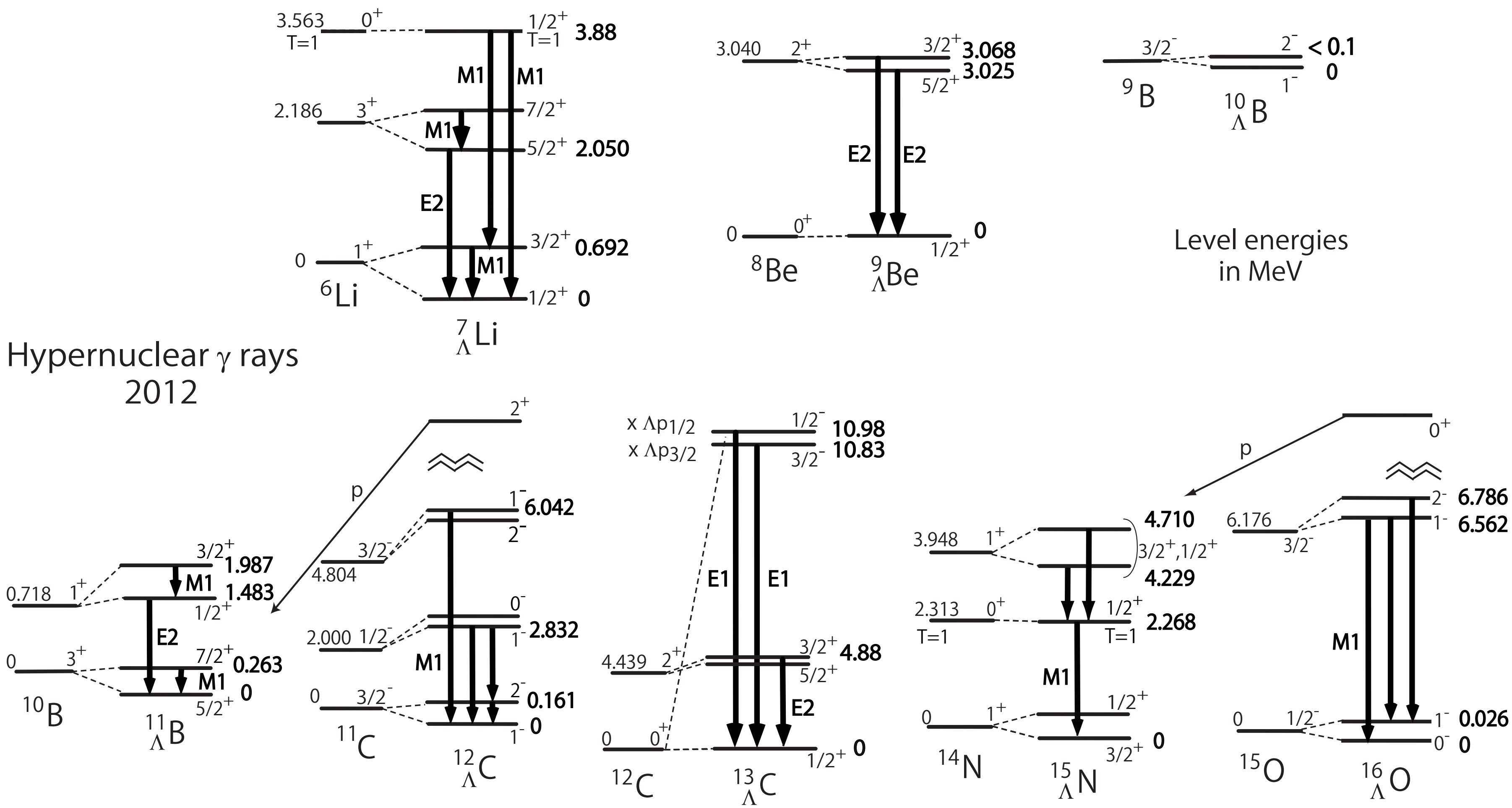
Production spectrum on ^{7}Li

FINUDA, DAΦNE, Frascati

Three $^7_\Lambda$Li levels, δB_Λ=0.4 MeV

Formation rate $1 \cdot 10^{-3}/K^-_{\mathrm{stop}}$

A=7–16 data also indicate DEEP K$^-$ nuclear potential.



p-shell spectra from $(K^-,\pi^-\gamma)$ $(+{}^{19}_{\Lambda}\mathrm{F}$ @HYP2018)

H. Tamura et al., Nucl. Phys. A 835 (2010) 3, updated at HYP12

Λ spin-orbit splitting (keV): 150 in ${}^{13}_{\Lambda}\mathrm{C}$ & related 43 in ${}^{9}_{\Lambda}\mathrm{Be}$

p-shell Λ Hypernuclei

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\, s_N \cdot s_\Lambda + V_{LS}(r)\, l_{N\Lambda} \cdot (s_\Lambda + s_N) + V_{ALS}(r)\, l_{N\Lambda} \cdot (s_\Lambda - s_N) + V_T(r)\, S_{12}$$

For $p_N s_Y$: $\quad V_{\Lambda N} = \bar{V} + \Delta\, s_N \cdot s_\Lambda + S_\Lambda\, l_N \cdot s_\Lambda + S_N\, l_N \cdot s_N + T\, S_{12}$

R.H Dalitz, A. Gal, Ann. Phys. 116 (1978) 167

D.J. Millener, A. Gal, C.B. Dover, R.H. Dalitz, PRC 31 (1985) 499

$N\Lambda$-$N\Lambda$	$\bar{V}$	Δ	S_Λ	S_N	T	(MeV)
$A = 7 - 9$	(-1.32)	0.430	-0.015	-0.390	0.030	fit
$A = 11 - 16$	(-1.32)	0.330	-0.015	-0.350	0.024	fit
$N\Lambda$-$N\Sigma$	1.45	3.04	-0.085	-0.085	0.157	input

D.J. Millener, Nucl. Phys. A 804 (2008) 84

Doublet spacings in p-shell hypernuclei (in keV)

D.J. Millener, NPA 881 (2012) 298

	J_u^π	J_l^π	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
${}^{7}_{\Lambda}\mathrm{Li}$	$3/2^+$	$1/2^+$	72	628	-1	-4	-9	693	692
${}^{7}_{\Lambda}\mathrm{Li}$	$7/2^+$	$5/2^+$	74	557	-32	-8	-71	494	471
${}^{8}_{\Lambda}\mathrm{Li}$	2^-	1^-	151	396	-14	-16	-24	450	(442)
${}^{9}_{\Lambda}\mathrm{Be}$	$3/2^+$	$5/2^+$	-8	-14	37	0	28	44	43
${}^{11}_{\Lambda}\mathrm{B}$	$7/2^+$	$5/2^+$	56	339	-37	-10	-80	267	264
${}^{11}_{\Lambda}\mathrm{B}$	$3/2^+$	$1/2^+$	61	424	-3	-44	-10	475	505
${}^{12}_{\Lambda}\mathrm{C}$	2^-	1^-	61	175	-22	-13	-42	153	161
${}^{15}_{\Lambda}\mathrm{N}$	$3/2^+_2$	$1/2^+_2$	65	451	-2	-16	-10	507	481
${}^{16}_{\Lambda}\mathrm{O}$	1^-	0^-	-33	-123	-20	1	188	23	26
${}^{16}_{\Lambda}\mathrm{O}$	2^-	1^-_2	92	207	-21	1	-41	248	224

$\Lambda\Sigma$ coupling contributions normally are below 100 keV

ΛN interaction matrix elements in Nijmegen models

- G-Matrix elements from $N\Lambda$-$N\Sigma$ calculation fitted with sums of Gaussians, Yukawas, OBEP forms, ...
- $p_N s_\Lambda$ matrix elements (MeV) calculated with WS wave functions.

		p-shell					s-shell	
		$\overline{V}$	Δ	S_Λ	S_N	T	$\overline{V}_s$	Δ_s
fit-DJM	${}^{7}_{\Lambda}$Li	-1.142	0.438	-0.008	-0.414	0.031		
	${}^{16}_{\Lambda}$O	-1.161	0.441	-0.007	-0.401	0.030		
NSC97f	${}^{7}_{\Lambda}$Li	-1.086	0.421	-0.149	-0.238	0.055	-1.725	0.775
ESC04a	${}^{7}_{\Lambda}$Li	-1.287	0.381	-0.108	-0.236	0.013	-1.577	0.850
ESC08a	${}^{7}_{\Lambda}$Li	-1.221	0.146	-0.074	-0.241	0.055	-1.796	0.650

- Fitted matrix elements are roughly constant with A - same YNG interaction, WS wells have $R = r_0 A^{1/3}$, but rms radii of p-shell nuclei are roughly constant.

YN interaction contributions to g.s. binding energies

	$^{7}_{\Lambda}$Li	$^{8}_{\Lambda}$Li	$^{9}_{\Lambda}$Be	$^{9}_{\Lambda}$Li	$^{10}_{\Lambda}$B	$^{11}_{\Lambda}$B	$^{12}_{\Lambda}$B	$^{13}_{\Lambda}$C	$^{15}_{\Lambda}$N	$^{16}_{\Lambda}$N
keV	$1/2^+$	1^-	$1/2^+$	$3/2^+$	1^-	$5/2^+$	1^-	$1/2^+$	$3/2^+$	1^-
$\Lambda\Sigma$	78	160	4	183	35	66	103	28	59	62
Δ	419	288	0	350	125	203	108	-4	40	94
S_Λ	0	-6	0	-10	-13	-20	-14	0	12	6
S_N	94	192	207	434	386	652	704	841	630	349
T	-2	-9	0	-6	-15	-43	-29	-1	-69	-45
sum	589	625	211	952	518	858	869	864	726	412
Exp	5.58	6.80	6.71	8.50	8.89	10.24	11.37	11.69		13.76
$\bar{V}$	-0.94	-1.02	**-0.84**	-1.06	-1.05	-1.04	-1.05	-0.96		-0.93

$$B_\Lambda^{\rm exp}({\rm g.s.}) = [B_\Lambda^{\rm exp}({}^{5}_{\Lambda}{\rm He}) = 3.12 \pm 0.02 \text{ MeV}] - (A-5)\bar{V} + \text{‘sum’}$$

Note $^{9}_{\Lambda}$Be anomaly. Improve fit by adding a ΛNN term

see Millener-Gal-Dover-Dalitz, PRC 31 (1985) 499

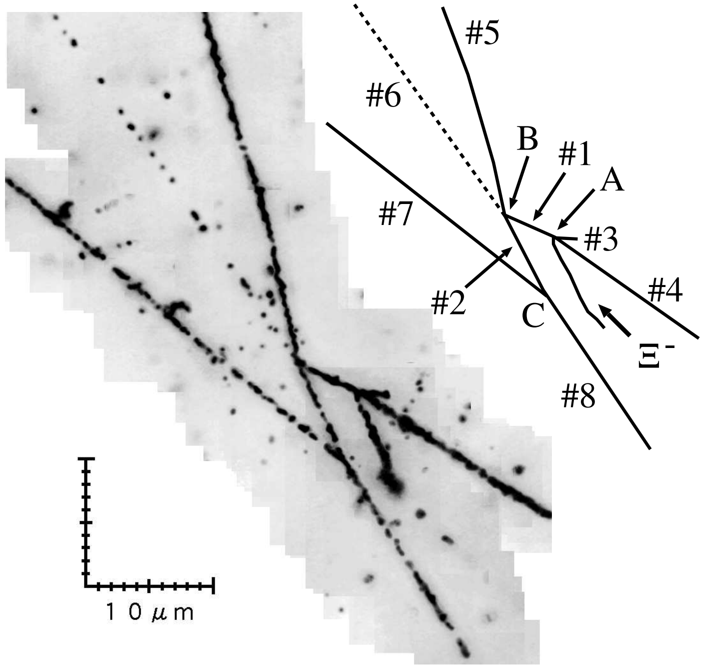
$\Lambda\Sigma$ matrix elements & contributions to $B_\Lambda^{\rm g.s.}$ (in MeV) across the periodic table

A. Gal & D.J. Millener PLB 725 (2013) 445

$N-Z$	${}^A_\Lambda Z$	$V_{\Lambda\Sigma}$	$\Lambda\Sigma(V)$	$\Delta_{\Lambda\Sigma}$	$\Lambda\Sigma(\Delta)$	$\Delta B_\Lambda^{\rm g.s.}(\Lambda\Sigma)$
4	${}^{9}_{\Lambda}$He	1.194	0.143	4.070	0.104	0.246
8	${}^{49}_{\Lambda}$Ca	0.175	0.010	0.946	0.014	0.024
22	${}^{209}_{\Lambda}$Pb	0.0788	0.052	0.132	0.001	0.053

- **$\Lambda\Sigma$ from Halderson, following NSC97f.**
- **$V_{\Lambda\Sigma}$ & $\Delta_{\Lambda\Sigma}$ decrease drastically as overlap between 0s hyperon and high-ℓ excess neutrons becomes poorer with A ($0f_{7/2}$ in ${}^{49}_{\Lambda}$Ca, $0h_{9/2}$ & $0i_{13/2}$ in ${}^{209}_{\Lambda}$Pb).**
- **Conclusion: $\Lambda\Sigma$ contributes less than 100 keV to binding of medium & heavy n-rich hypernuclei.**

$\Lambda\Lambda$ hypernuclei



Nagara event, ${}_{\Lambda\Lambda}{}^{6}\mathrm{He}$, (KEK-E373) PRL 87 (2001) 212502

$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He}_{\mathrm{g.s.}})$**=6.91±0.16 MeV, unambiguously determined.**

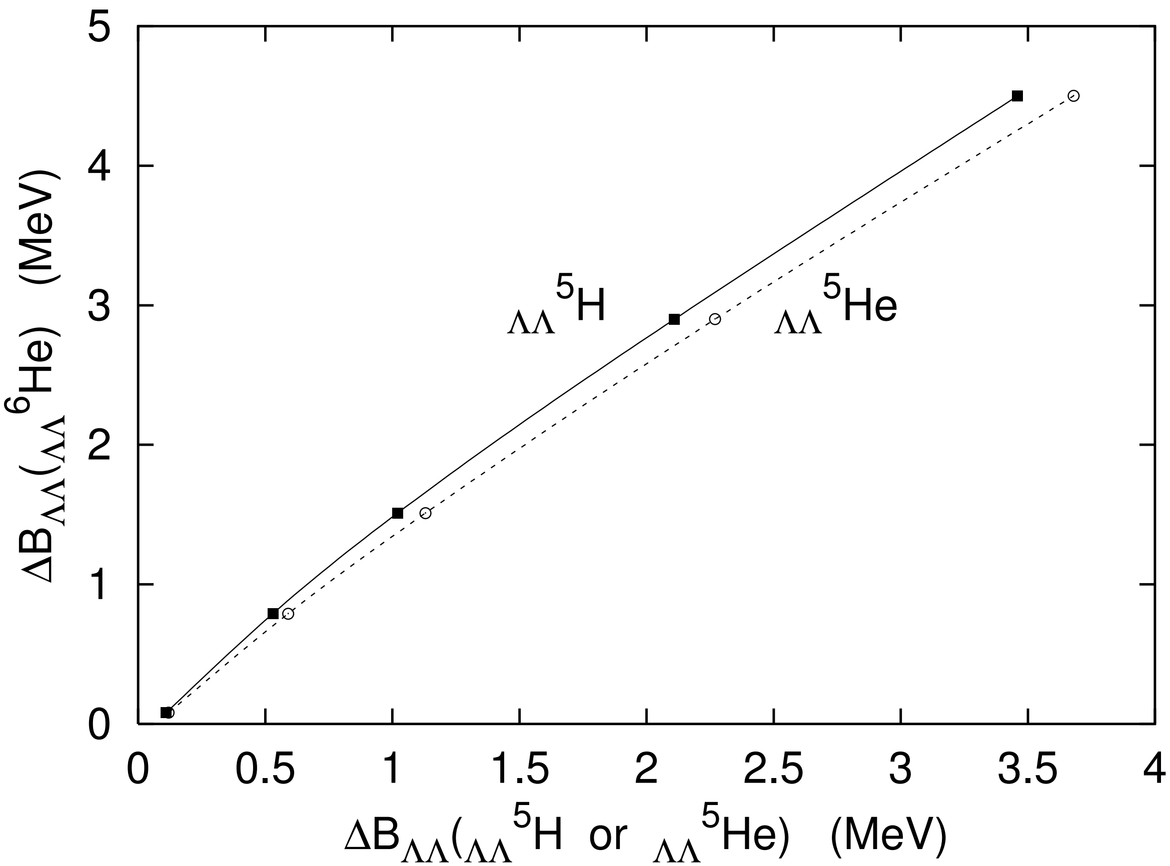
- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}{}^{6}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}_{\Lambda\Lambda}{}^{6}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$ **(no** ${}_{\Lambda\Lambda}{}^{6}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + H$**)**
- **C:** ${}^{5}_{\Lambda}\mathrm{He}$ **nonmesic weak decay to 2** Z**=1 recoils + n.**

The elusive H dibaryon

Jaffe's **H**($uuddss$) [PRL 38 (1977) 195] **predicted stable**

$$\mathbf{H} \sim \mathcal{A}[\sqrt{1/8}\,\Lambda\Lambda + \sqrt{1/2}\,N\Xi - \sqrt{3/8}\,\Sigma\Sigma,]_{I=S=0}$$

- **To forbid $^{6}_{\Lambda\Lambda}$He$\to$H+^{4}He, impose B(H)$\leq$7 MeV. A bound H most likely overbinds $^{6}_{\Lambda\Lambda}$He** **[Gal, PRL 110 (2013) 179201].**
- **Weakly bound H in Lattice QCD calculations. SU(3)$_{\rm f}$ breaking pushes it to $\approx N\Xi$ threshold, $\approx$26 MeV in $\Lambda\Lambda$ continuum** **[HALQCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].**
- **$\Lambda\Lambda$ correlation femtoscopy in pp at $\sqrt{s}$=7 TeV** **(ALICE exp. at the LHC, arXiv:1805.12455)** **rules out a bound H (Laura Fabbietti @HYP18).**



Faddeev calc. by I.N. Filikhin, A. Gal, NPA 707 (2002) 491

$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He}) \equiv B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He}) - 2B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) \approx 0.7$ **MeV**

implying that $_{\Lambda\Lambda}{}^{5}$H & $_{\Lambda\Lambda}{}^{5}$He are also bound.

With $_{\Lambda\Lambda}{}^{4}$H likely unbound, $\Lambda\Lambda$ binding onset is $_{\Lambda\Lambda}{}^{5}$H & $_{\Lambda\Lambda}{}^{5}$He.

Binding energy consistency of ΛΛ hypernuclei

event	${}^{A}_{\Lambda\Lambda}Z$	$B^{\rm exp}_{\Lambda\Lambda}$	$B^{\rm CM}_{\Lambda\Lambda}$ †	$B^{\rm SM}_{\Lambda\Lambda}$ † †
E373-Nagara	${}^{6}_{\Lambda\Lambda}$He	6.91 ± 0.16	6.91 ± 0.16	6.91 ± 0.16
E373-DemYan	${}^{10}_{\Lambda\Lambda}$Be	14.94 ± 0.13 ‡	14.74 ± 0.16	14.97 ± 0.22
E373-Hida	${}^{11}_{\Lambda\Lambda}$Be	20.83 ± 1.27	18.23 ± 0.16	18.40 ± 0.28
E373-Hida	${}^{12}_{\Lambda\Lambda}$Be	22.48 ± 1.21	–	20.72 ± 0.20
E176	${}^{13}_{\Lambda\Lambda}$B	23.4 ± 0.7 *	–	23.21 ± 0.21

† **E. Hiyama et al., PRL 104 (2010) 212502, & refs. therein**

†† **A. Gal, D.J. Millener, PLB 701 (2011) 342, assuming that**

$< V_{\Lambda\Lambda} > \approx \Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He})$**=0.67±0.16 MeV**

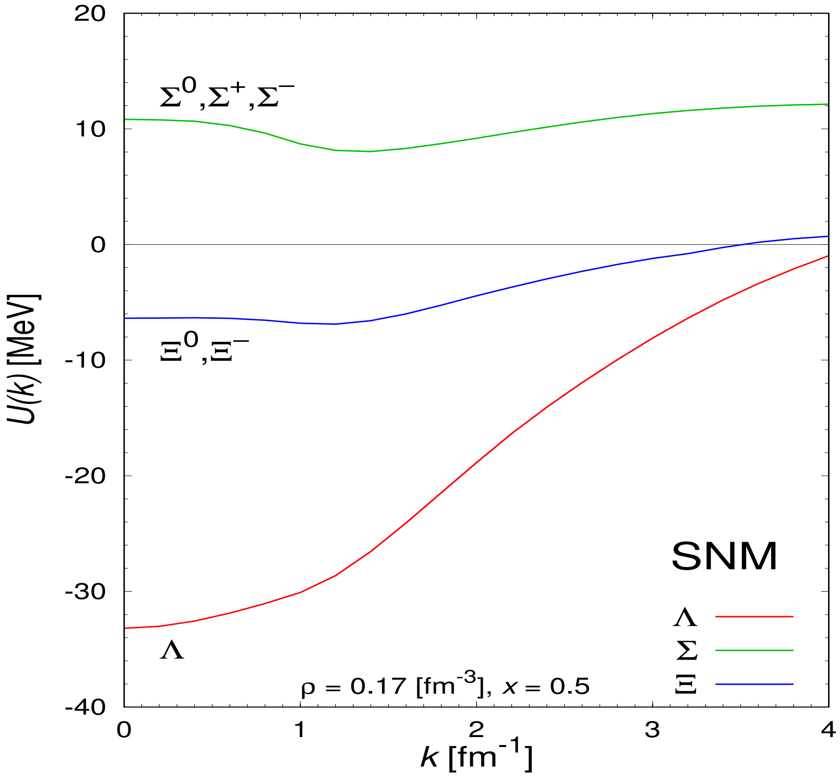
‡ **Assuming production in** ${}^{10}_{\Lambda\Lambda}$Be **non g.s.** $2^+(3.04\ \mathrm{MeV})$

* **Assuming** ${}^{13}_{\Lambda\Lambda}\mathrm{B}_{\rm g.s.}$ **decay to** ${}^{13}_{\Lambda}\mathrm{C}^*(5/2^+, 3/2^+;\ 4.8\ \mathrm{MeV}) + \pi^-$

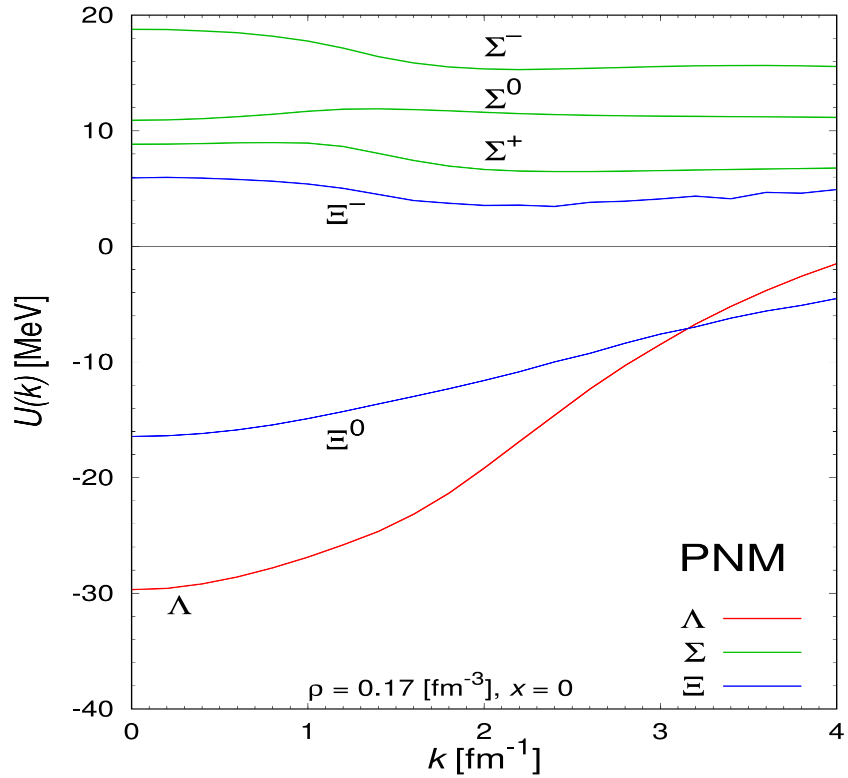
- **Unassigned Hida event [PTPS 185 (2010) 335]**
- $B^{\rm SM}_{\Lambda\Lambda} \approx B^{\rm CM}_{\Lambda\Lambda}$**, but SM spans a wider** A **range**

Other Strange Hadrons in Matter

Hyperon-Nucleus potentials from LQCD



Symmetric nuclear matter



Pure neutron matter

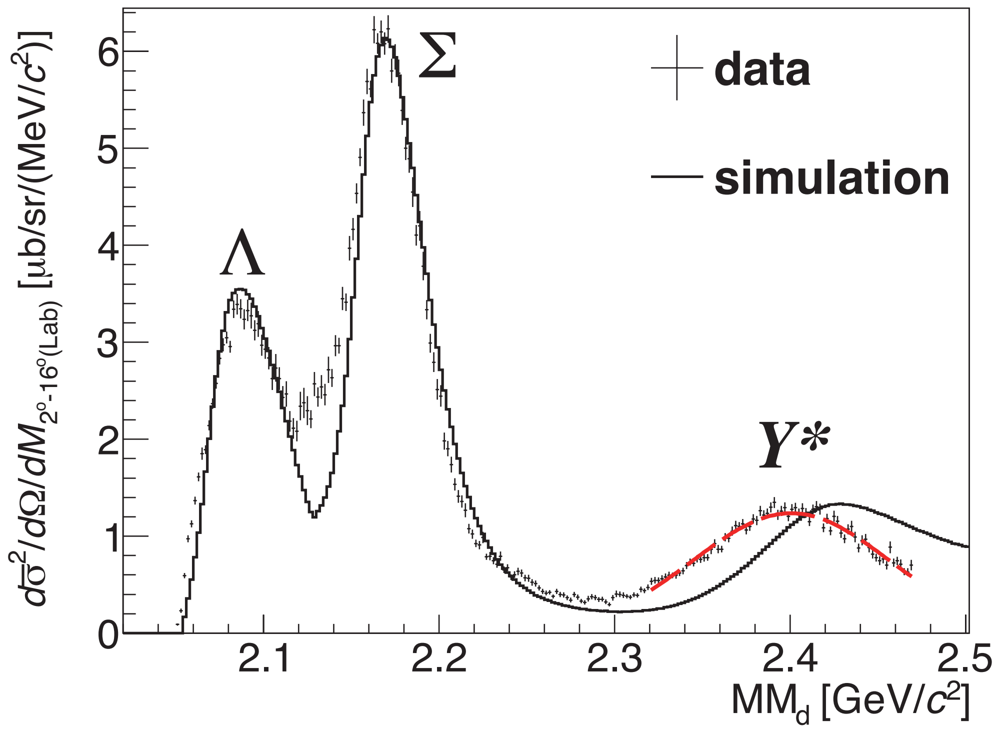
T. Inoue, for HAL QCD Collab., arXiv:1612.08399

BHF applied to Lattice YN potentials

Σ – repulsion, Ξ – weak attraction

How about YN* potentials, e.g. $\Lambda^*(1405)$N, related to K^-pp?

J-PARC E27 $d(\pi^+, K^+)$ missing-mass spectrum



PTEP 2014, 101D03

Y* quasi-free peak shifted by ≈−22 MeV,
indicating Y*N attraction [Y* = Σ*(1385) & Λ*(1405)].
Two dibaryons likely below K$^-$pp threshold:
(i) Λ*N observed in E15 (ii) Σ*N formed in E27 ?

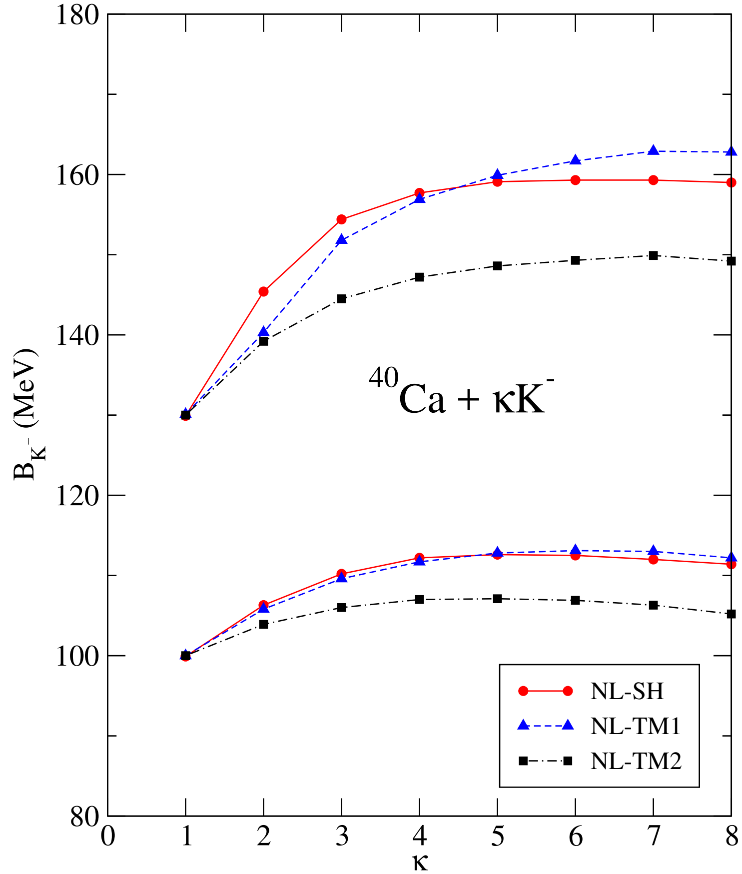
Λ^*(1405)N & Σ^*(1385)N dibaryons?

- $\Lambda(1405)N$ **is a doorway to a I=1/2, J^P=0$^-$** $\bar{K}NN$**, found quasibound in all calculations & in E15. It is coupled to** $\pi\Lambda N$ **and** $\pi\Sigma N$**, but** $\pi\Lambda N$ **cannot support any strongly attractive meson-baryon s-wave interaction.**

- **The** $\pi\Lambda N$ **system can benefit from strong meson-baryon** p**-wave interactions fitted to** $\Delta(1232) \to \pi N$ **and** $\Sigma(1385) \to \pi\Lambda$ **form factors. Maximize isospin and angular momentum couplings by full alignment: I=3/2, J^P=2$^+$, a good example of a Pion Assisted Dibaryon.**

  Gal-Garcilazo, NPA 897 (2013) 167

Λ^*: do antikaons condense on earth?



D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

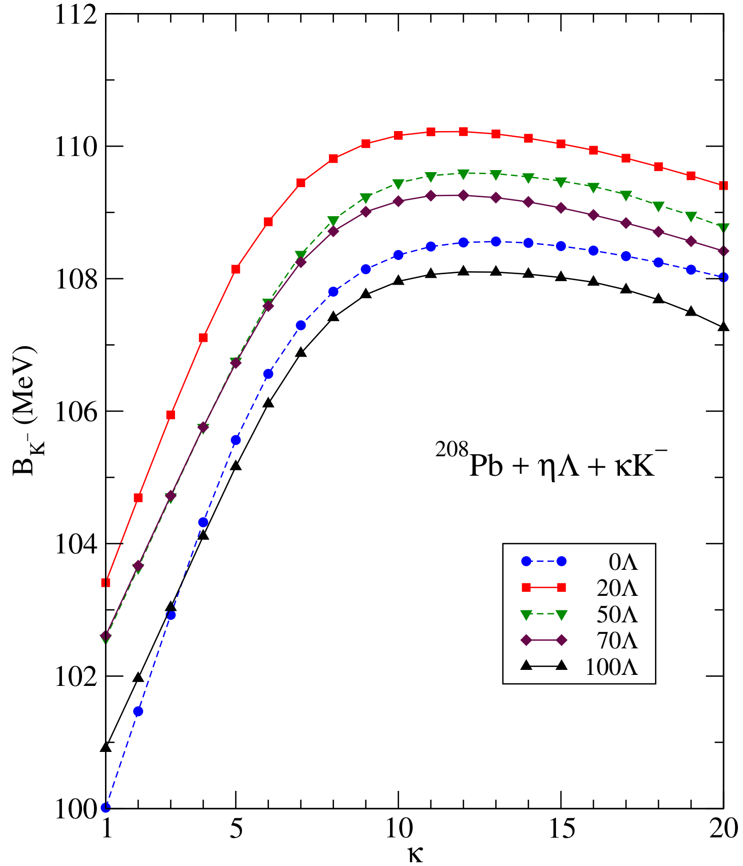
RMF: B$_{\bar{K}}$ saturates in multi-K^- ^{40}Ca nuclei

Large binding of 100, 130 MeV assumed for κ=1

Vector-meson repulsion among $\bar{K}$ mesons

$B_{\bar{K}}(\kappa \rightarrow \infty) << (m_K + M_N - M_\Lambda) \approx 320$ **MeV**

...and adding Λ hyperons

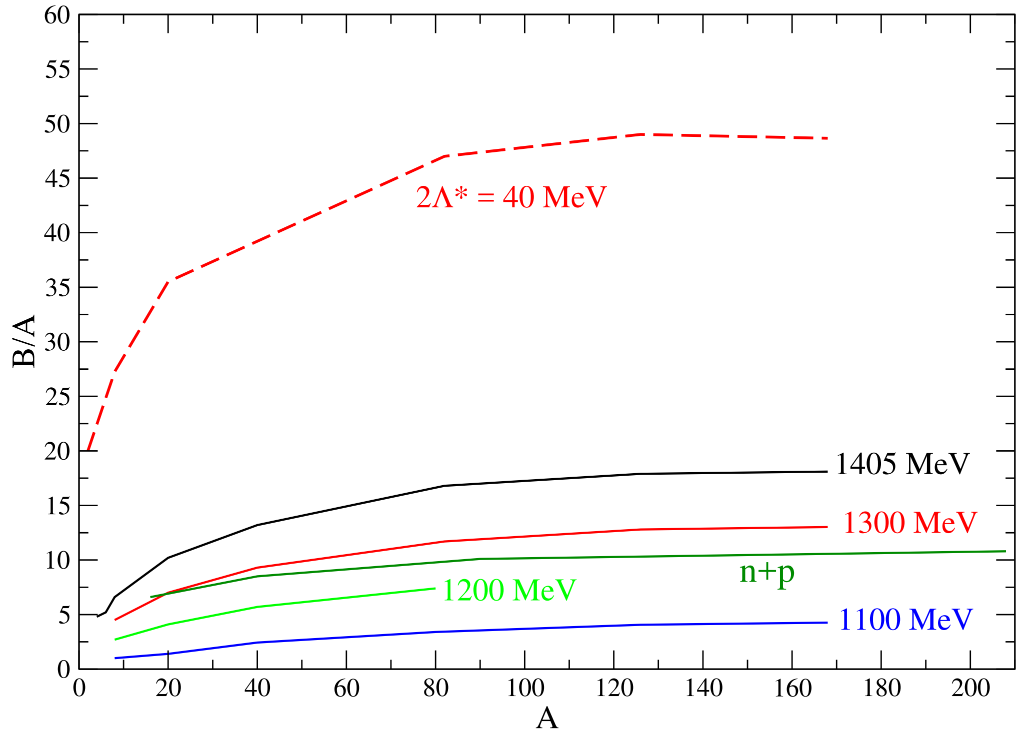


Gazda-Friedman-Gal-Mareš, Phys. Rev. C 80 (2009) 035205

Saturation of $B_{\bar{K}}$ in RMF for ^{208}Pb + $\eta\Lambda$ + κK^-

Hyperons dominate stable self-bound strange matter

No kaon condensation on earth...



$\Lambda^*(1405)$ matter: stable or unstable?

Stable: Y. Akaishi T.Yamazaki, PLB 774 (2017) 522
Unstable: J. Hrtánková et al., PLB 785 (2018) 90

- **RMF calculations demonstrate that B/A saturates, at values allowing $\Lambda^*\Lambda^* \to \Lambda\Lambda$ & $\Sigma\Sigma$ strong decays. Central densities saturate at about $2\rho_0$.**

Summary & Outlook

- ΛN **hypernuclear spin dependence deciphered.**
- **How small is Λ spin-orbit splitting and why?**
- **Role of 3-body ΛNN interactions in hypernuclei & neutron stars?**
- **Resolve the ${}^{3}_{\Lambda}$H lifetime puzzle from HIC.**
- **Re-measure the ${}^{4}_{\Lambda}$H–${}^{4}_{\Lambda}$He complex (E13→E63).**
- **Search for n-rich ${}^{A}_{\Lambda}$Z; (${}^{6}_{\Lambda}$H not seen in E10).**
- **Repulsive Σ-nuclear interaction; how repulsive? (relevant to neutron star matter scenarios).**
- **Search for H dibaryon in (K^-, K^+) (E42).**
- **Onset of $\Lambda\Lambda$ binding: ${}_{\Lambda\Lambda}{}^{4}$H or ${}_{\Lambda\Lambda}{}^{5}$Z? (E07).**

- **Shell model works well for g.s. beyond ${}_{\Lambda\Lambda}^{6}$He.**
- **Study excited states by slowing down Ξ^- from $\bar{p}p \to \Xi^-\bar{\Xi}^+$ in FAIR (PANDA).**
- **Do Ξ hyperons quasi-bind in nuclei ($\Xi N \to \Lambda\Lambda$)? No quasibound Ξ established yet (E05).**
- **Onset of Ξ stability: ${}_{\Lambda\Xi}^{6}\mathrm{He}$ or ${}_{\Lambda\Lambda\Xi}^{7}\mathrm{He}$?**
- **No $\bar{K}$ condensation in self-bound matter. $\{N, \Lambda, \Xi\}$ provides Strange-Hadronic-Matter g.s.**
- **Search for a Σ(1385)N (I=3/2, J^P=2$^+$) dibaryon $\mathcal{Y}$ at J-PARC or GSI in $\pi^- + d \to \mathcal{Y}^- + K^+, \quad \mathcal{Y}^- \to \Sigma^- + n.$**

Thanks for your attention!