Unresolved Issues in Hypernuclear Physics

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- 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?

- Strangeness Nuclear Physics reviews:
  (i) Nucl. Phys. A, Vol. 881 (2012) & 954 (2016)
  A. Gal, J. Pochodzalla, Eds.
  (ii) Rev. Mod. Phys. 88 (2016) 035004
  A. Gal, E.V. Hungerford, D.J. Millener

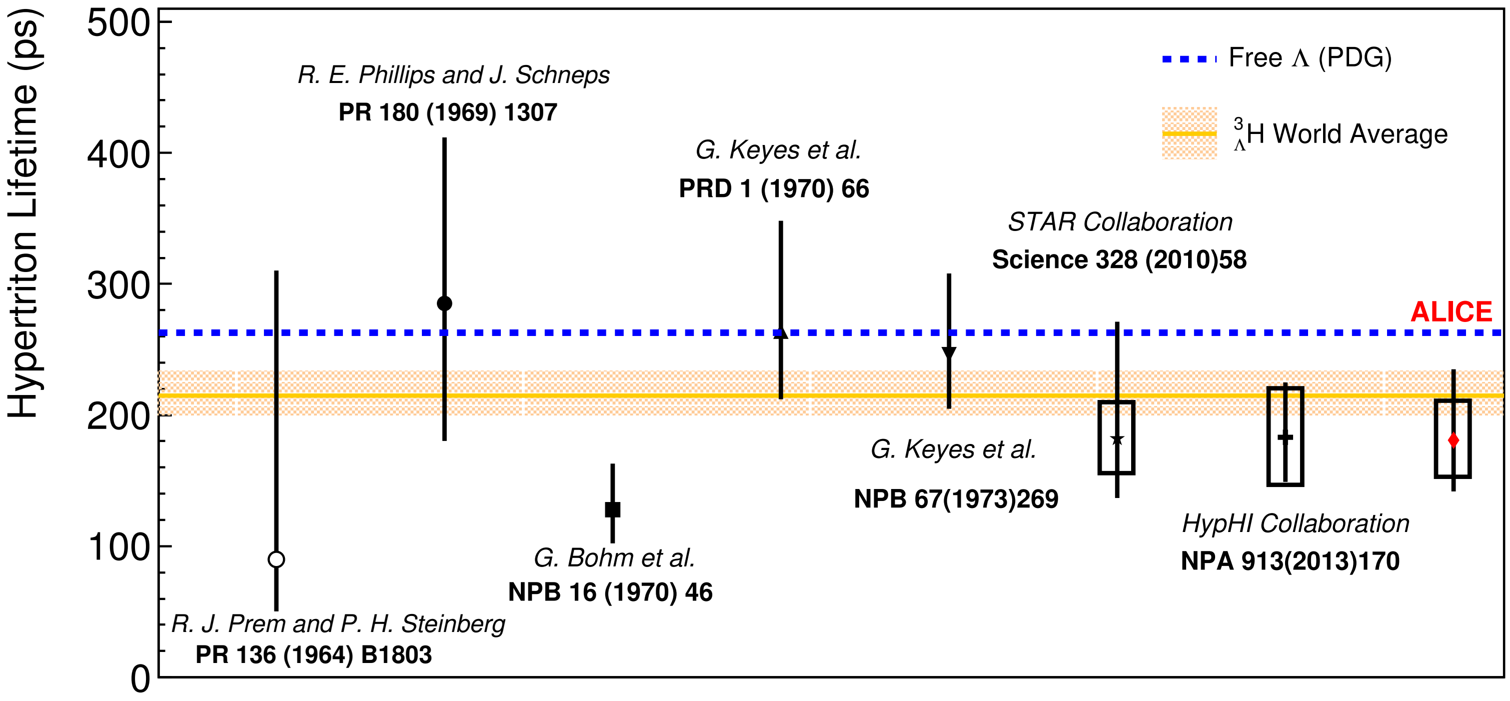
Λ hypernuclear dynamics

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^+	2.04(4)–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.**
- **$\Delta B_{\Lambda}({}^{4}_{\Lambda}\text{He}–{}^{4}_{\Lambda}\text{H})=0.35(5)$ MeV: very large CSB.**
- **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.**
    D. Gazda, A. Gal, PRL 116 (2016) 122501.
    ab-initio Jacobi-NCSM (chiral LO).

${}^{3}_{\Lambda}$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 $\approx 30\%$. ALICE, PLB 754 (2016) 360.

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... (1966)	closure	–	1.05 ± 0.01
Congleton (1992)	Λd w.f.	0.33 ± 0.02	1.12
Kamada... (1998)	Fad.	0.379	1.03

- $R_3=\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+{}^3\mathrm{He})/\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+\mathrm{all})$
  favors $J=\frac{1}{2}$ over $J=\frac{3}{2}$.
- 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 much slower than a free Λ.
- A bound ${}^3_\Lambda\mathrm{H}(J=\frac{1}{2},T=1)$, analog of Λnn, would decay to Λd or by γ(M1) to ${}^3_\Lambda\mathrm{H}(J=\frac{1}{2},T=0)$.

${}^{4}_{\Lambda}$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, R$_4$=0.7

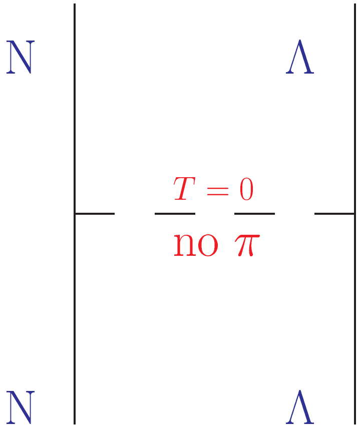
$\frac{2}{3}$ & $\frac{1}{3}$ for either π^- or π^0 with ^{4}He, $\Gamma_{\mathrm{n.m.}}/\Gamma_{\Lambda} \approx$ 0.25

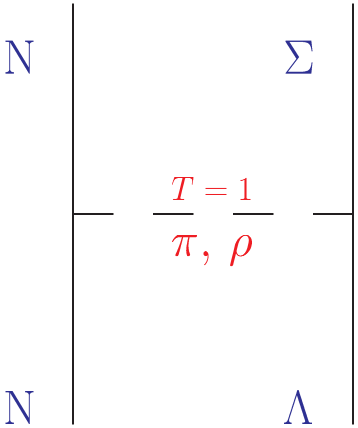
$$\Rightarrow \ \tau({}^{4}_{\Lambda}\mathrm{H}) \approx 190\,\mathrm{ps}, \quad \tau({}^{4}_{\Lambda}\mathrm{He}) \approx 250\,\mathrm{ps}$$

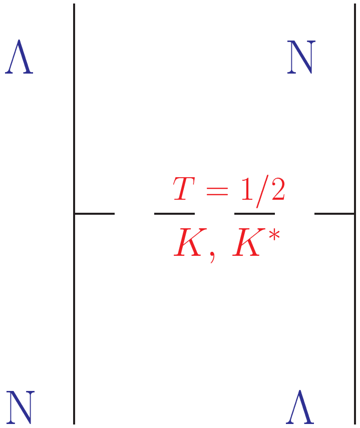
in rough agreement with measured lifetimes.

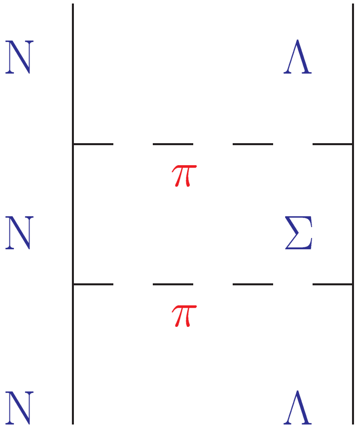
- **Looks like Lifetime Puzzle is limited to ${}^{3}_{\Lambda}$H.**

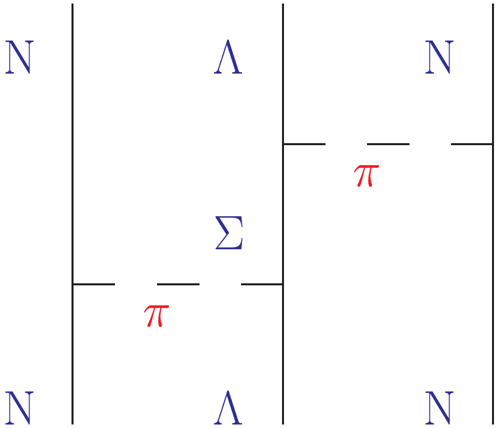
T=1/2 hyperon-nucleon interaction





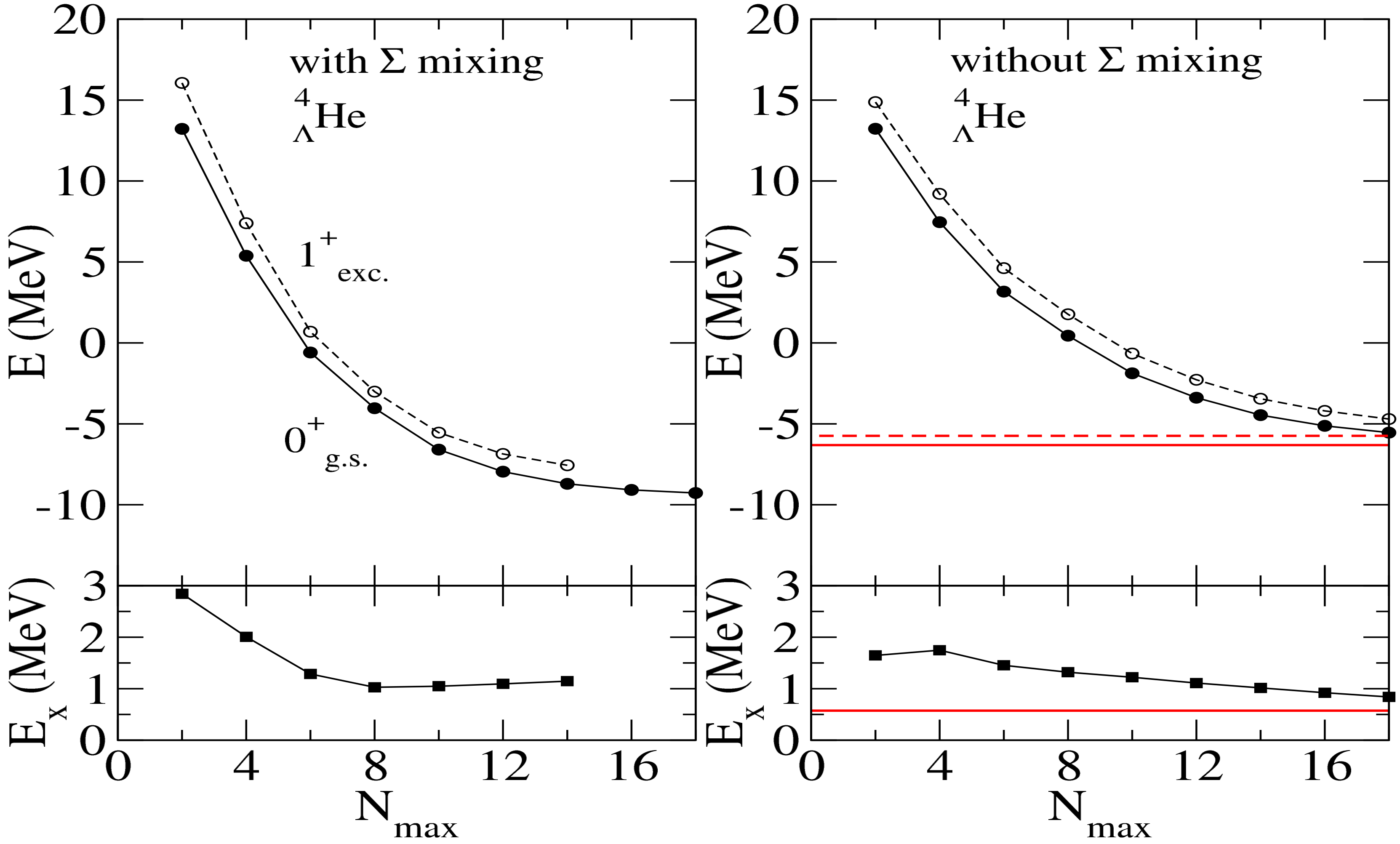






LO χEFT YN model: PS meson exchange + 5 contact terms

[Polinder-Haidenbauer-Meißner, NPA 779, 244 (2006)].

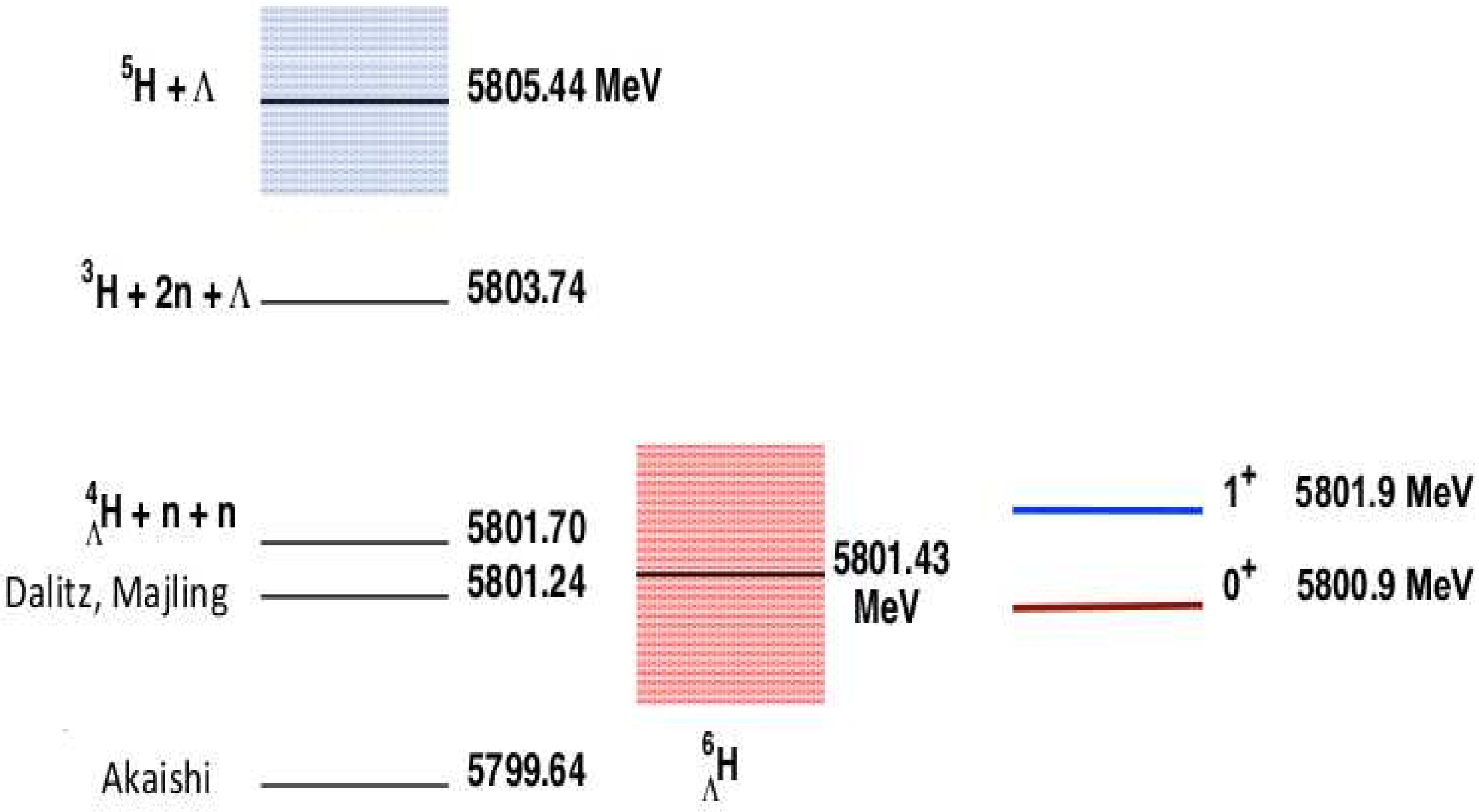


ΛN-ΣN ($\Lambda\Sigma$) coupling provides ≈1/3 of E_x

$^4_\Lambda$He levels severely underbound without $\Lambda\Sigma$ coupling

D. Gazda et al., FBS 55, 857 (2014) R. Wirth et al., PRL 113, 192502, using LO chiral potentials [H. Polinder et al., NPA 779, 244 (2006)].

FINUDA+Gal (2012) [PRL 108, 042501; NPA 881, 269]



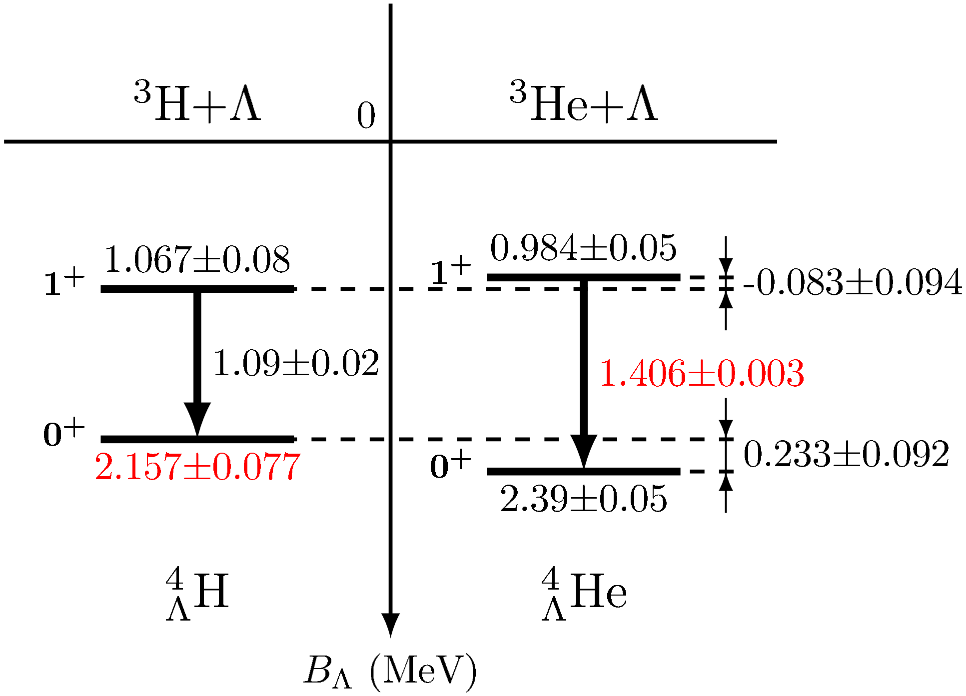
Three $(K^-_{\rm stop}, \pi^+)$ $^6_\Lambda$H events out of 2.7 x 10^7 $K^-_{\rm stop}$

- **$B_\Lambda(^6_\Lambda$H) & $\Delta E(1^+ - 0^+)$ constrain $\Lambda N \leftrightarrow \Sigma N$ in n-rich $^A_\Lambda Z$,** **A. Gal, D.J. Millener, PLB 725 (2013) 445.**

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

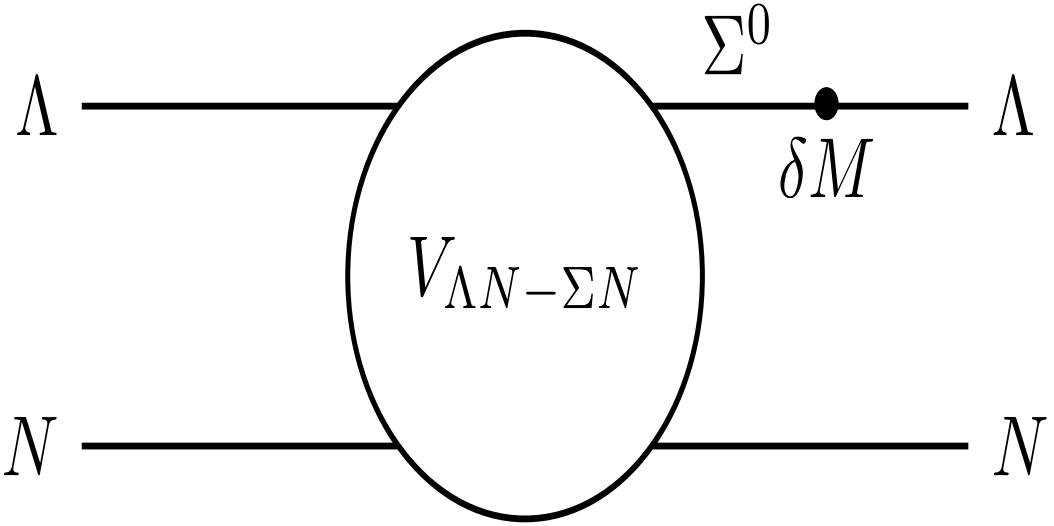
MAMI's A1, ${}^{4}_{\Lambda}\mathrm{H}\rightarrow{}^{4}\mathrm{He}+\pi^{-}$, PRL 114 (2015) 232501

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. Remeasure ${}^{4}_{\Lambda}\mathrm{He}_{\mathrm{g.s.}}$ (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.**

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

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

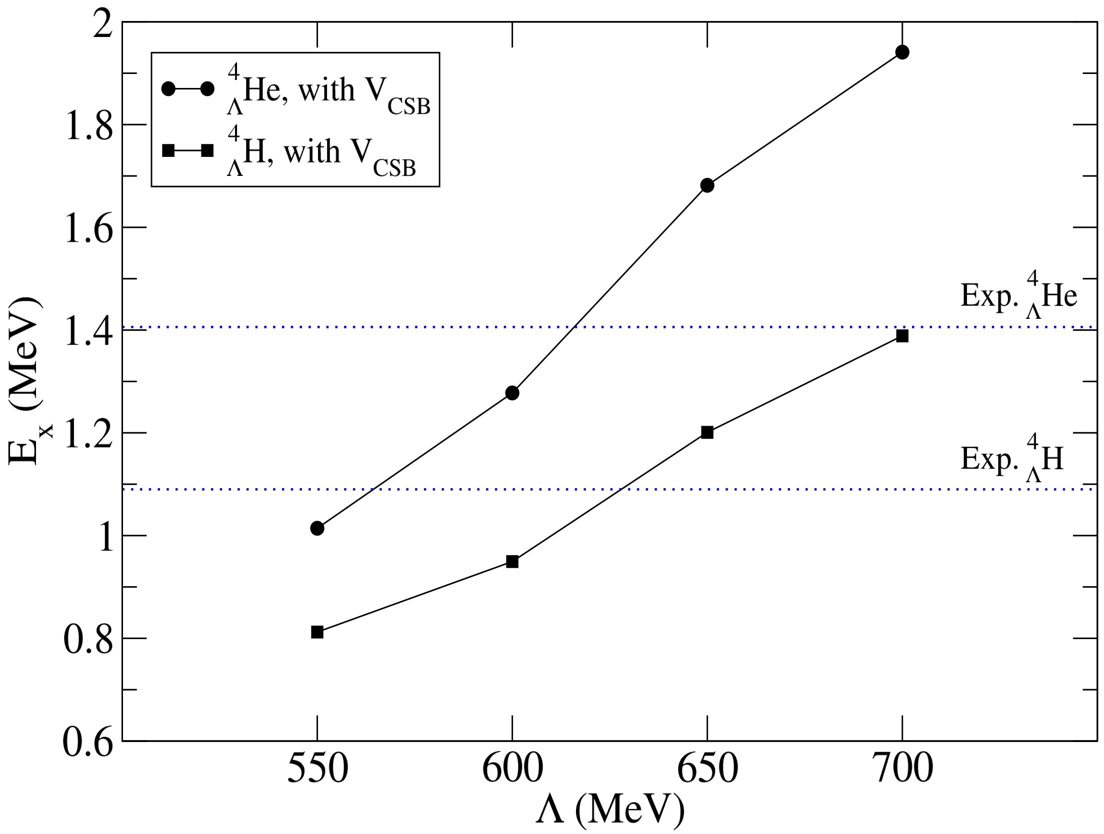
D.Gazda, A.Gal (2016): PRL 116 122501; NPA 954 161.

Latest summary in arXiv:1708.04791.

Recent NCSM calculations

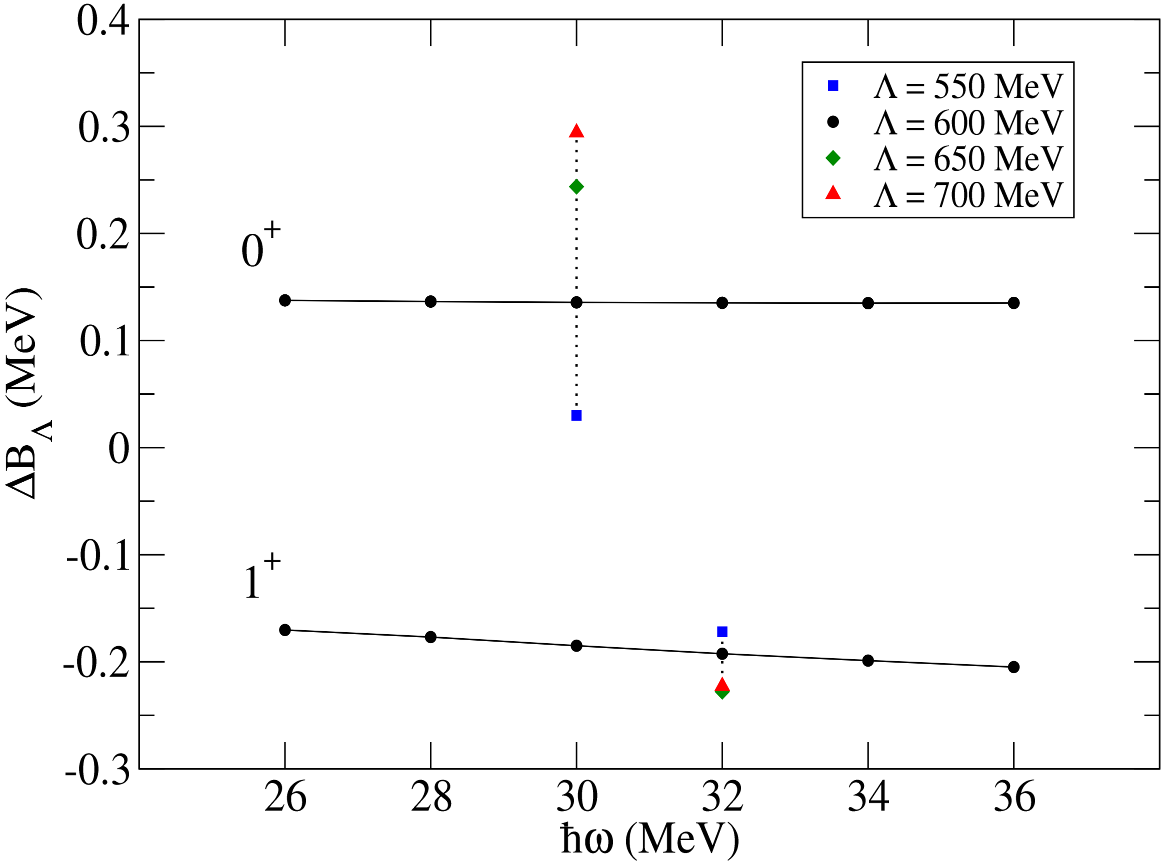
- **No-Core Shell-Model (NCSM) 4-body calculation in a translationally invariant Jacobi-coordinate harmonic oscillator (HO) basis, antisymmetrized for nucleons.**
- **χEFT interactions: N3LO NN & N2LO NNN, LO YN (Bonn-Jülich) with CSB introduced by relating Λ–Σ^0 mixing to ΛN–ΣN strong-interaction coupling.**
- **Diagonalize Hamiltonian in finite four-body HO bases, admitting all HO excitation energies $N\hbar\omega$, $N \leq N_{\rm max}$. Extrapolated energy values $E(\omega)$, $N_{\rm max} \to \infty$, obtained by fitting an exponential function to $E(N_{\rm max}, \omega$ fixed) sequences in the vicinity of the variational minima with respect to ω.**

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



$E_x(0^+ \rightarrow 1^+)$ **in LO χEFT for $^4_\Lambda$H & $^4_\Lambda$He**

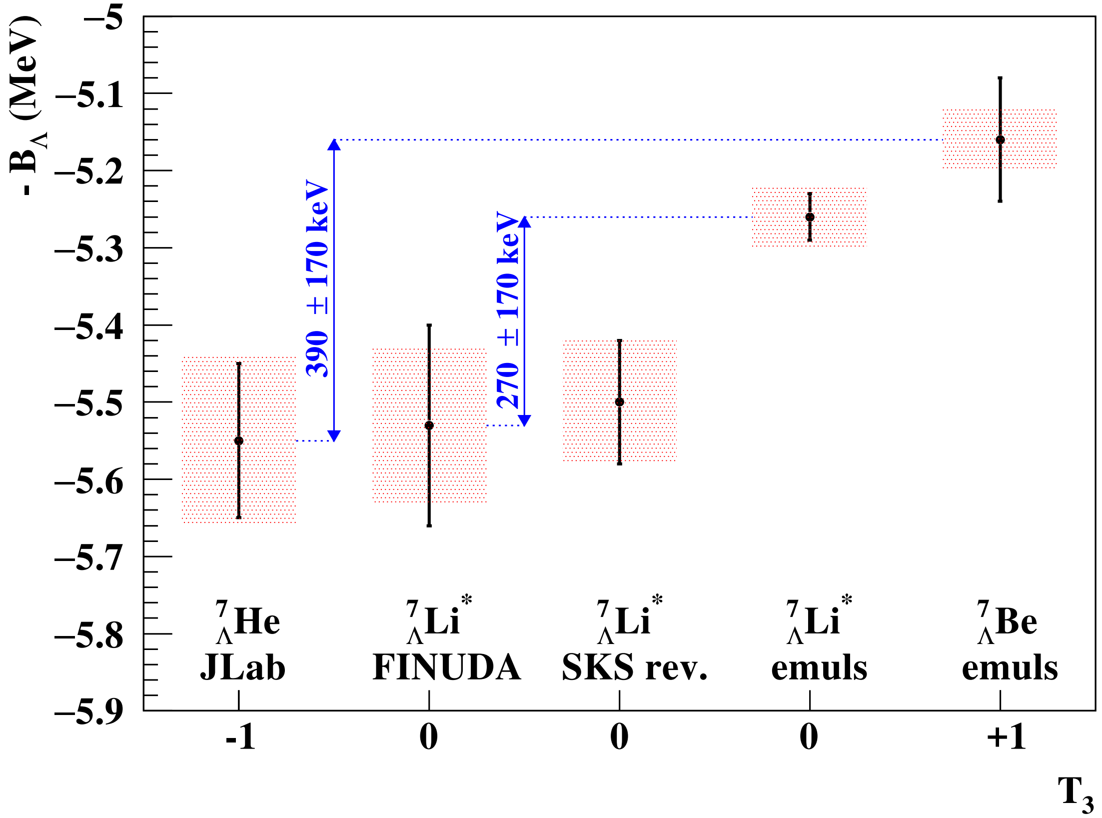
- **N3LO NN + N2LO NNN + LO/NLO YN**
- **E_x^{CS}=1.3$^{+0.5}_{-0.4}$ MeV (LO, Gazda-Gal with CSB)**
  Nogga: 1.05±0.25 (LO), 0.71±0.04 (NLO)
- **E_x^{CS}(NLO) $\ll$ E_x^{CS}(exp) $\approx$ 1.25 MeV**



NCSM HO $\hbar\omega$ dependence of $\Delta B_\Lambda({}^4_\Lambda\text{He}–{}^4_\Lambda\text{H})$ for 0^+ & 1^+. Note ± sign pattern resulting from ${}^1S_0$ Λ-Σ contact term dominance at LO [see OPE discussion NPA 954 (2016) 161].

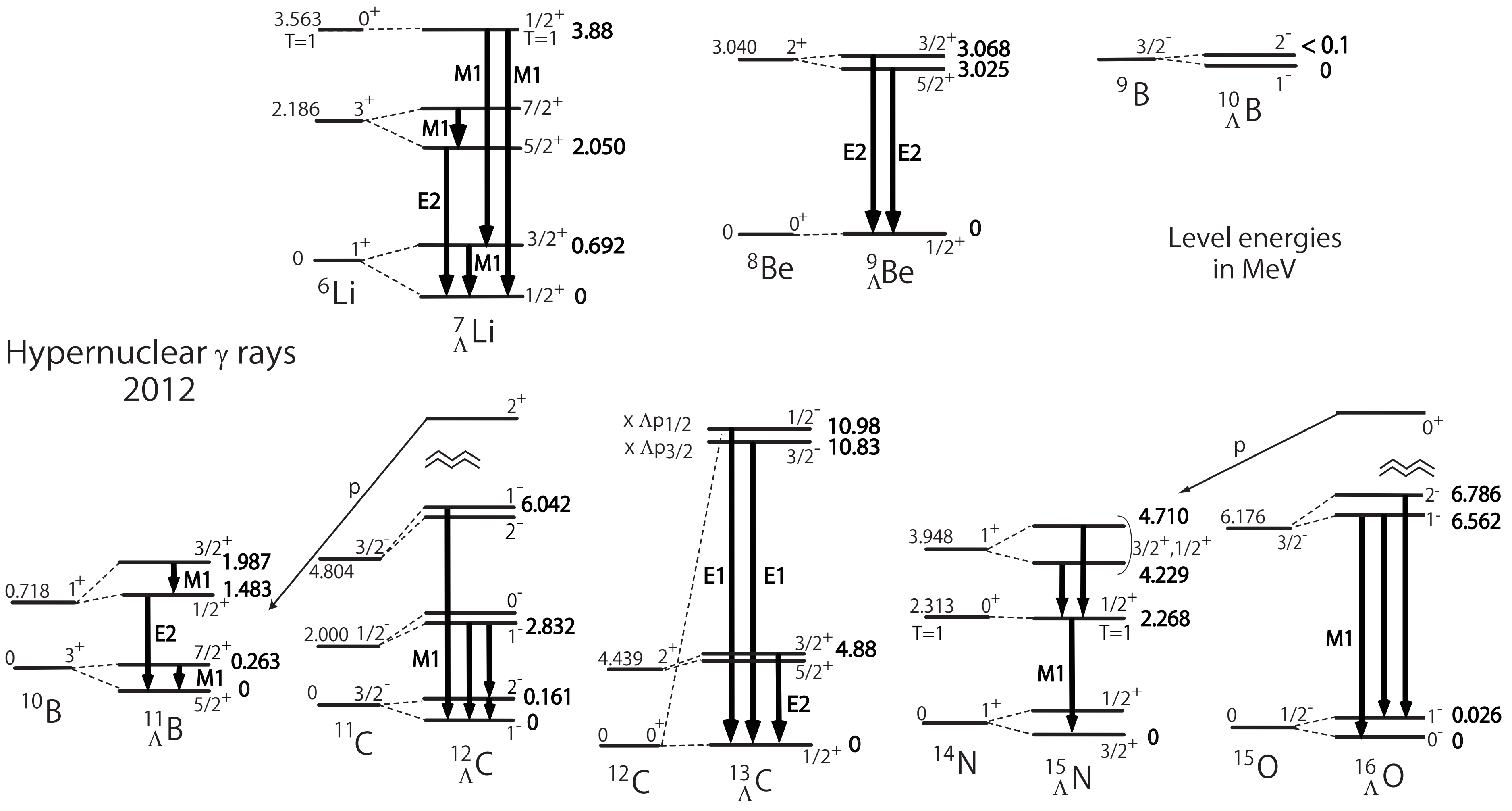
Λ=600 MeV: $\Delta E_\gamma = \Delta(\Delta B_\Lambda) = 0.33 \pm 0.03$ MeV compared to a measured $\Delta E_\gamma = 0.32 \pm 0.02$ MeV.

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.



Level schemes of Λ hypernuclei from γ-ray measurements

H. Tamura et al., Nucl. Phys. A 835 (2010) 3 [HYP09], updated at HYP12

Λ spin-orbit splitting: 150 keV in $^{13}_{\Lambda}$C & related 43 keV in $^{9}_{\Lambda}$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 $p_N s_Y$: $V_{\Lambda N} = \bar{V} + \Delta\, s_N \cdot s_\Lambda + S_\Lambda\, l_N \cdot s_\Lambda + S_N\, l_N \cdot s_N + T\, S_{12}$

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	from
$A = 7-9$	(-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

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

Λ spin dependence (Δ, S_Λ, T) determined by doublet spacings

p-shell CSB contributions in $(\Lambda\Sigma)_{\mathrm{e}}$ coupling model

${}^{A}_{\Lambda}\mathrm{Z}_{>}$–${}^{A}_{\Lambda}\mathrm{Z}_{<}$ pairs	I_C, J^{π}_C	P_Σ (%)	ΔT_{YN} (keV)	ΔV_C (keV)	ΔV_{YN} (keV)	$\Delta B^{\mathrm{calc}}_{\Lambda}$ (keV)	$\Delta B^{\mathrm{exp}}_{\Lambda}$ [D] (keV)
${}^{4}_{\Lambda}\mathrm{He}$–${}^{4}_{\Lambda}\mathrm{H}$	$\frac{1}{2}, 0^+$	0.72	39	−45	232	226	+350±60
${}^{7}_{\Lambda}\mathrm{Be}$–${}^{7}_{\Lambda}\mathrm{Li}^*$	$1, \frac{1}{2}^+$	0.12	3	−70 [HYMK]	50	−17	−100±90
${}^{8}_{\Lambda}\mathrm{Be}$–${}^{8}_{\Lambda}\mathrm{Li}$	$\frac{1}{2}, 1^-$	0.20	11	−81 [HKMYY]	119	+49	+40±60
${}^{9}_{\Lambda}\mathrm{B}$–${}^{9}_{\Lambda}\mathrm{Li}$	$1, \frac{3}{2}^+$	0.23	10	−145 [M]	81	−54	−210±220
${}^{10}_{\Lambda}\mathrm{B}$–${}^{10}_{\Lambda}\mathrm{Be}$	$\frac{1}{2}, 1^-$	0.053	3	−156 [M]	17	−136	−220±250

Davis, NPA 754 (2005) 3c. Millener, unpublished (2015).

Hiyama Yamamoto Motoba Kamimura PRC 80 (2009) 054321.

Hiyama Kamimura Motoba Yamada Yamamoto, PRC 66 (2002) 024007.

Negligible ΔT_{YN} no longer cancels ΔV_C. ΔV_{YN} is smaller than in s shell and, except for A=8, is dominated by the larger-size negative ΔV_C, so CSB becomes negative in the p shell as suggested by the data.

YN interaction contributions to g.s. binding energies

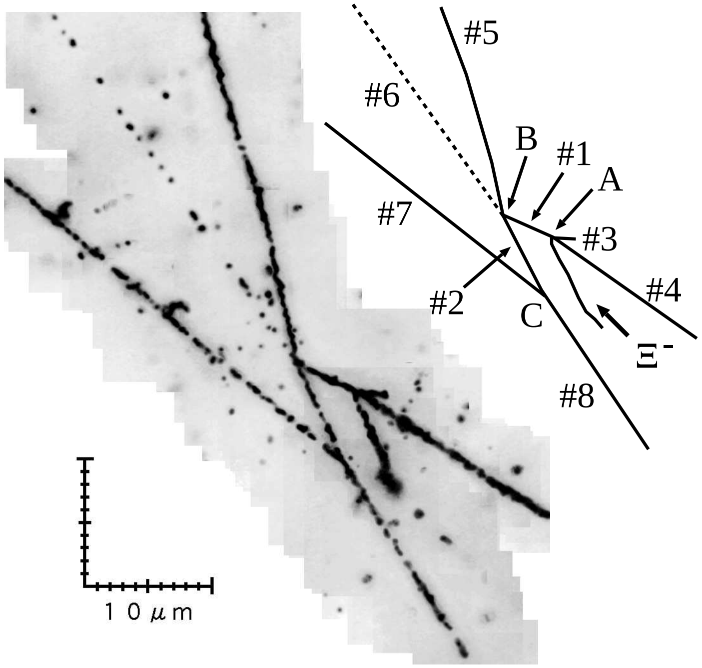
	${}^{7}_{\Lambda}$Li	${}^{8}_{\Lambda}$Li	${}^{9}_{\Lambda}$Be	${}^{9}_{\Lambda}$Li	${}^{10}_{\Lambda}$B	${}^{11}_{\Lambda}$B	${}^{12}_{\Lambda}$B	${}^{13}_{\Lambda}$C	${}^{15}_{\Lambda}$N	${}^{16}_{\Lambda}$N
keV	$1/2^+$	1^-	$1/2^+$	$3/2^+$	1^-	$5/2^+$	1^-	$1/2^+$	$3/2^+$	1^-
$\Lambda\Sigma$	78	160	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

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

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

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

$\Lambda\Lambda$ 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.

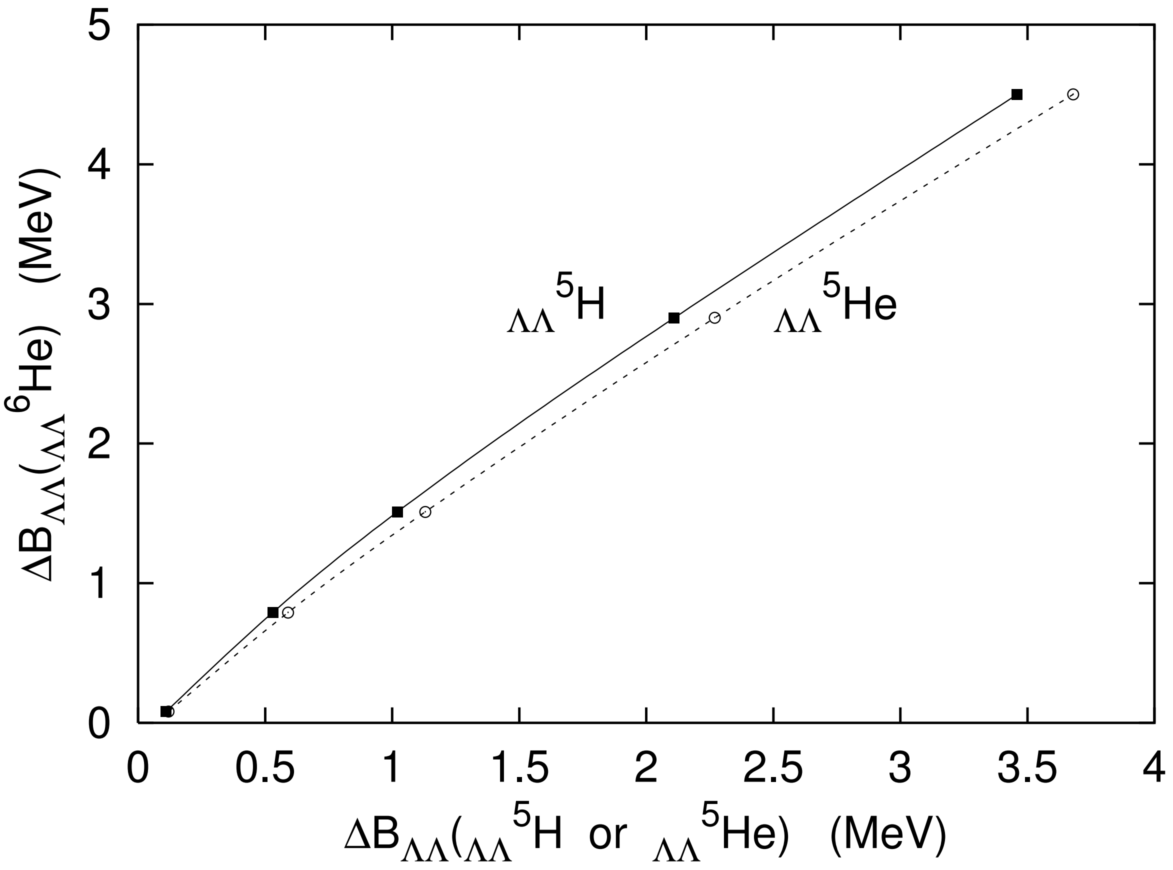
- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}^{\;6}\mathrm{He} + t + \alpha$
- **B:** **weak decay** ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-$ **(no** ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + H$**)**
- **C:** ${}_{\Lambda}^{5}\mathrm{He}$ **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$\rightarrow$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)$_{\mathrm{f}}$ breaking pushes it to $\approx N\Xi$ threshold, $\approx$26 MeV in $\Lambda\Lambda$ continuum [HALQCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].**
- **Experimental searches also rule out a bound H. J-PARC E42 will search for H in (K^-, K^+).**



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 $\Lambda\Lambda$ hypernuclei

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

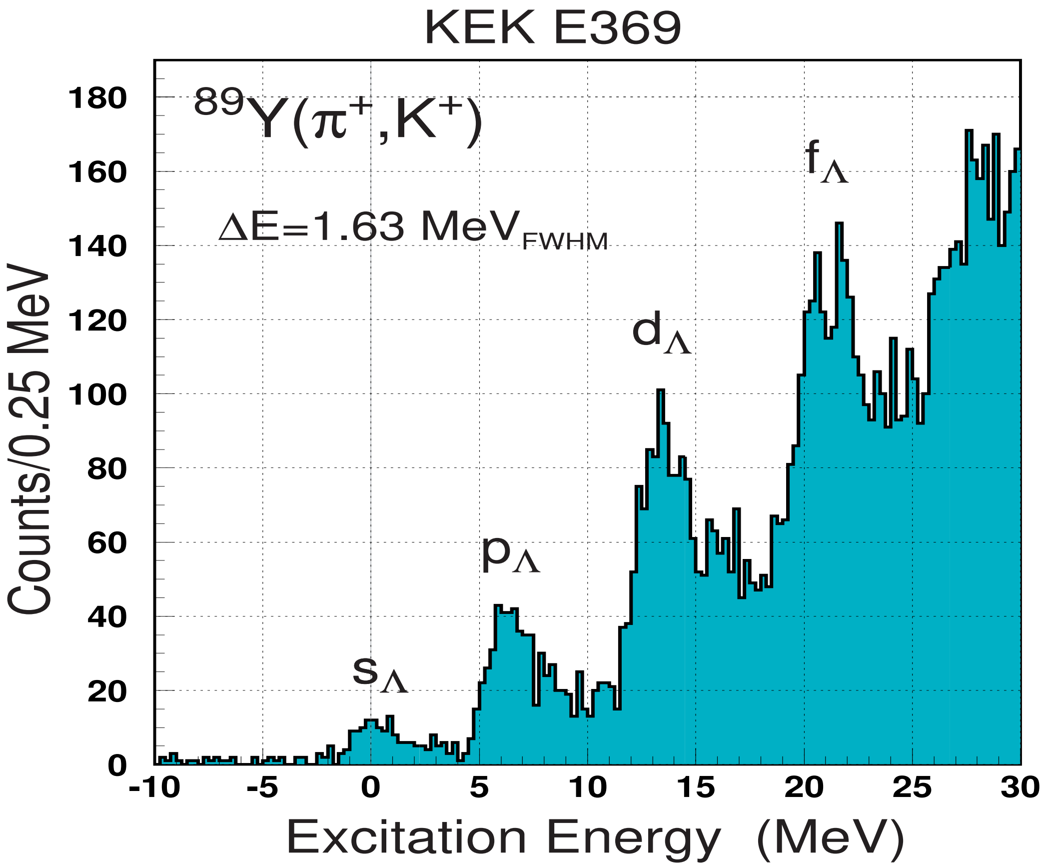
‡ **Assuming production in** ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ **non g.s.** $2^{+}(3.04\ \mathrm{MeV})$

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

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

Other Strange Hadrons in Matter

Observation of Λ single-particle states

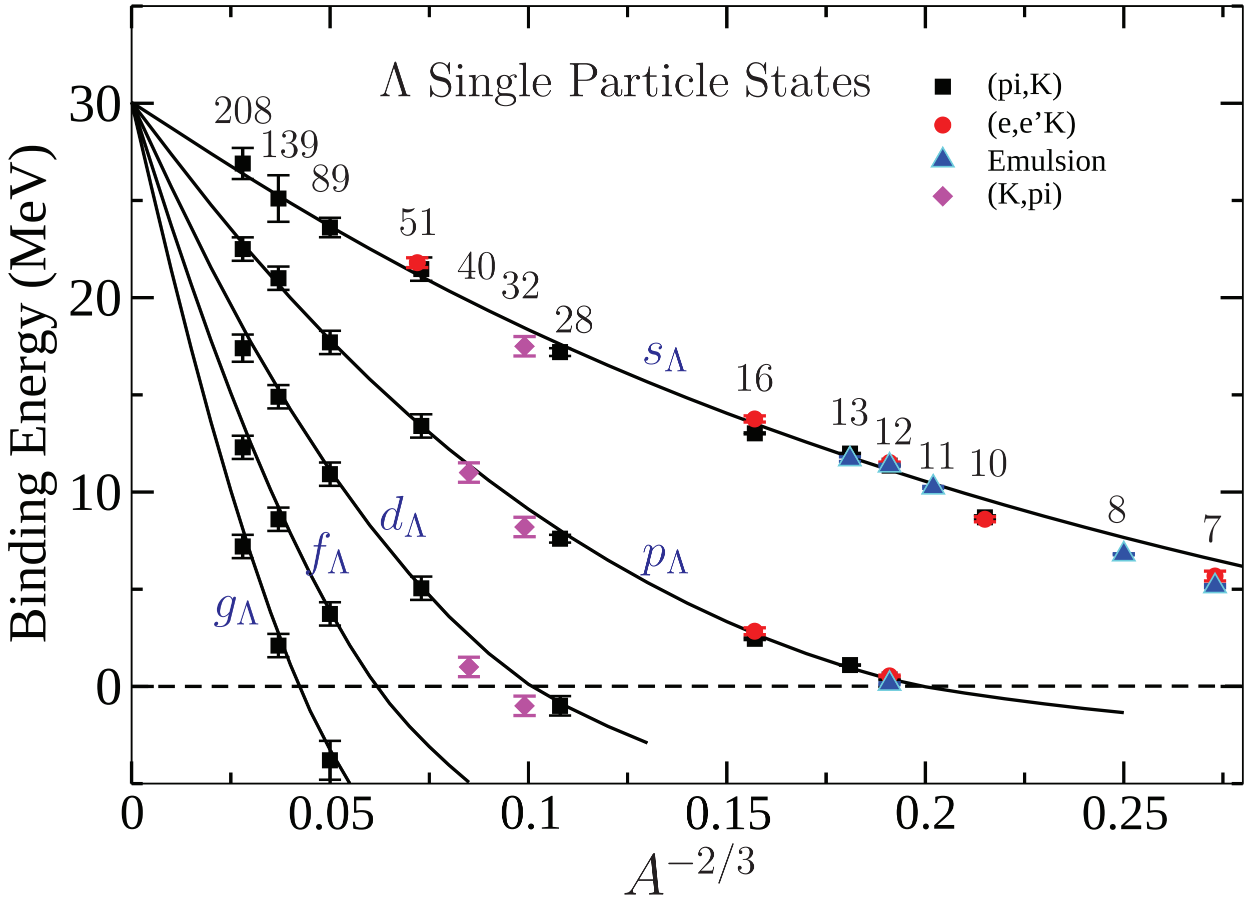


H. Hotchi et al., Phys. Rev. C 64 (2001) 044302 $B_\Lambda = 23.11 \pm 0.10$ MeV

T. Motoba, D.E. Lanskoy, D.J. Millener, Y. Yamamoto, NPA 804 (2008) 99:

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

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

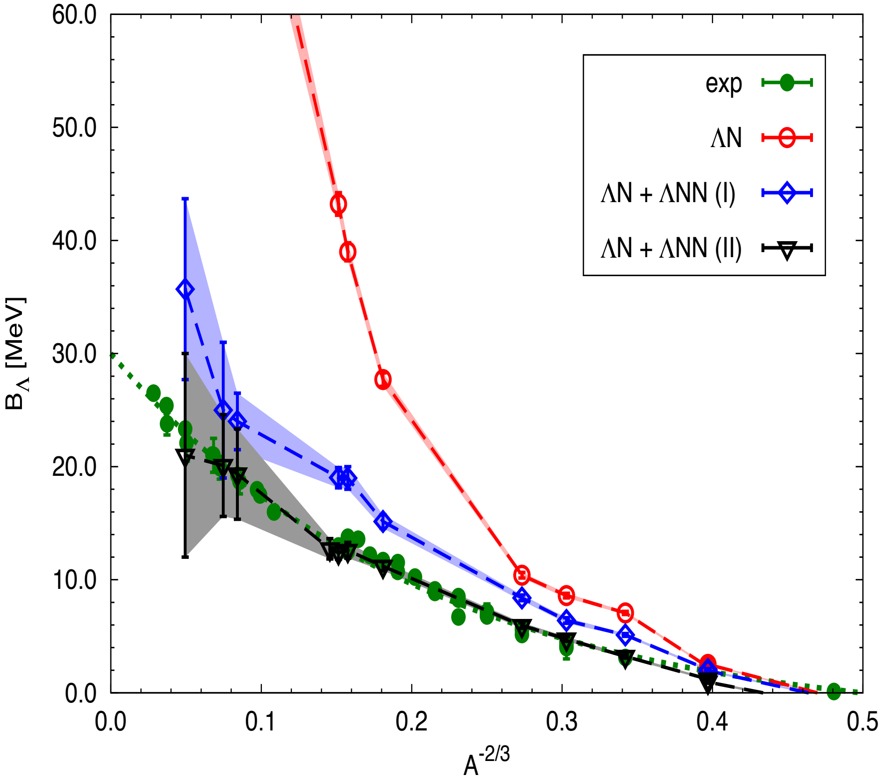


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

Textbook example of shell model at work.

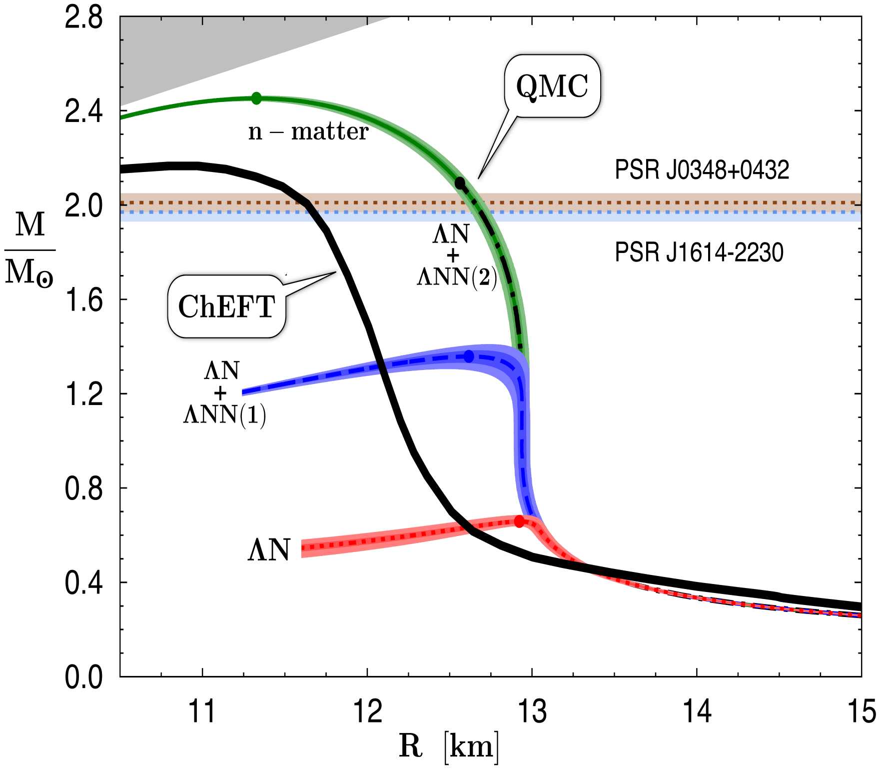
Skyrme-Hartree-Fock studies suggest ΛNN repulsion.

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314

ΛNN effect on B_Λ(g.s.)

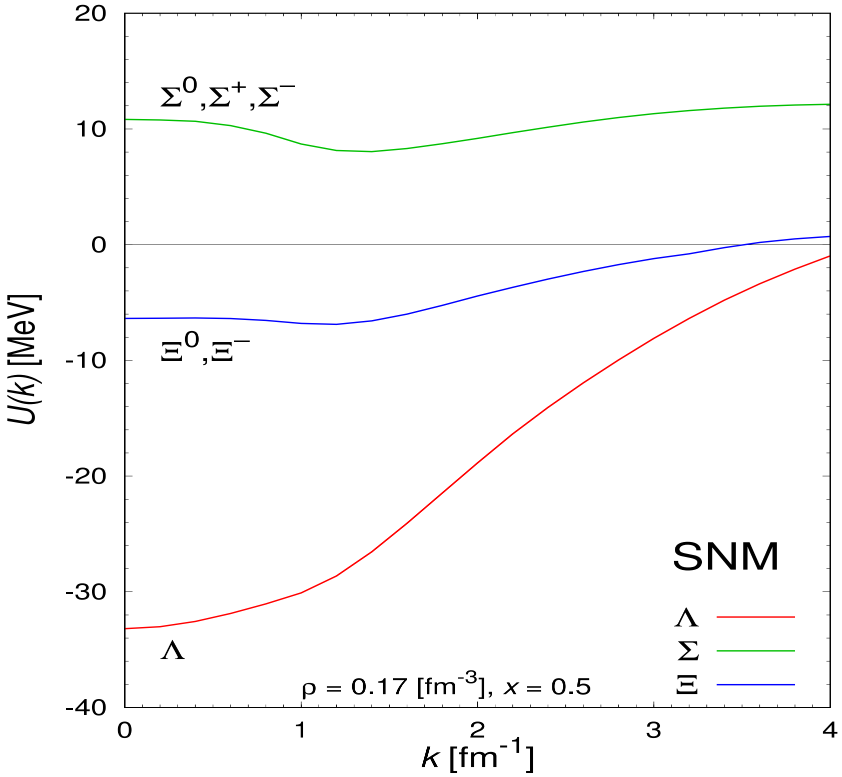


PRL 114 (2015) 092301

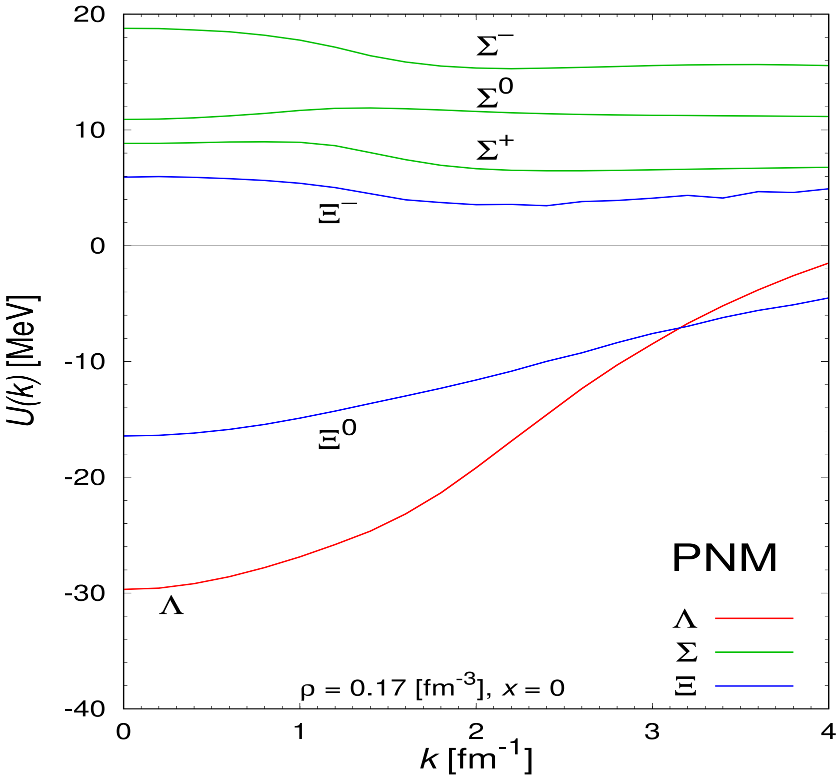
ΛNN effect on neutron stars

- **Adding ΛNN stiffens EOS of neutron stars.**
- **YY add 0.3M$_\odot$ to M$_{\mathrm{max}}$ (Rijken-Schulze 2016).**

Hyperon-Nucleus potentials from LQCD



Symmetric nuclear matter



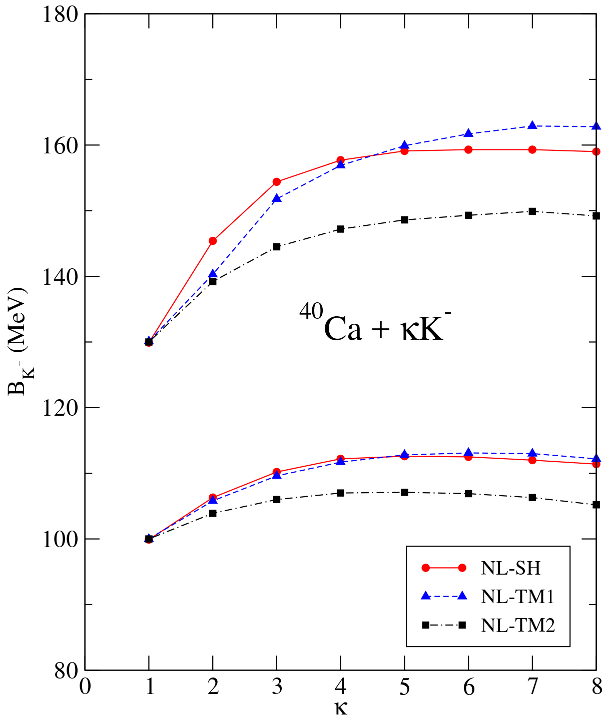
Pure neutron matter

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

BHF applied to Lattice YN potentials

Σ – repulsion, Ξ – weak attraction

Do antikaons condense on earth?



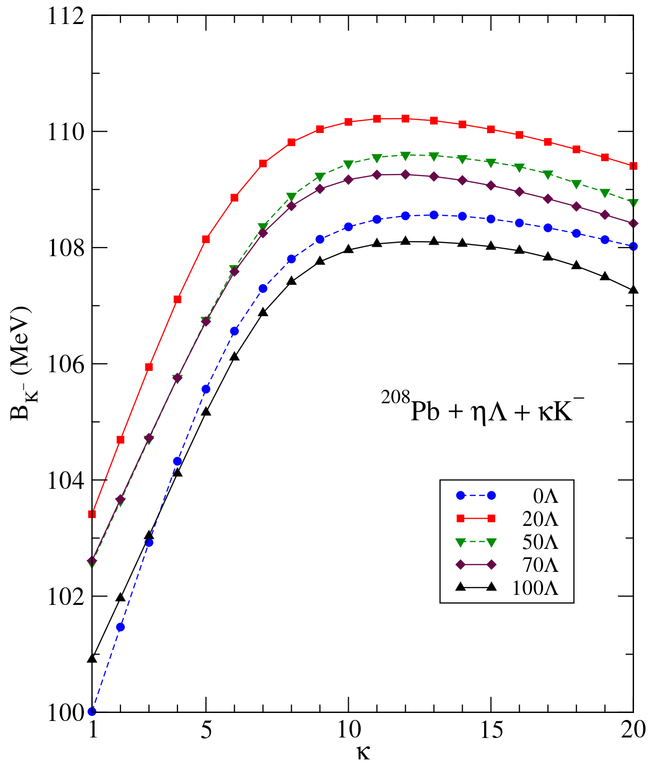
D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for multi-K^- ^{40}Ca nuclei

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

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

...and adding Λ hyperons



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

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for $^{208}\mathrm{Pb} + \eta\Lambda + \kappa\mathrm{K}^-$

Hyperons dominate stable self-bound strange matter

No kaon condensation on earth...

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? (E10).**
- **Repulsive Σ-nuclear interaction; how strong? (relevant to neutron star matter & to strange hadronic matter).**
- **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.**

Thanks for your attention!

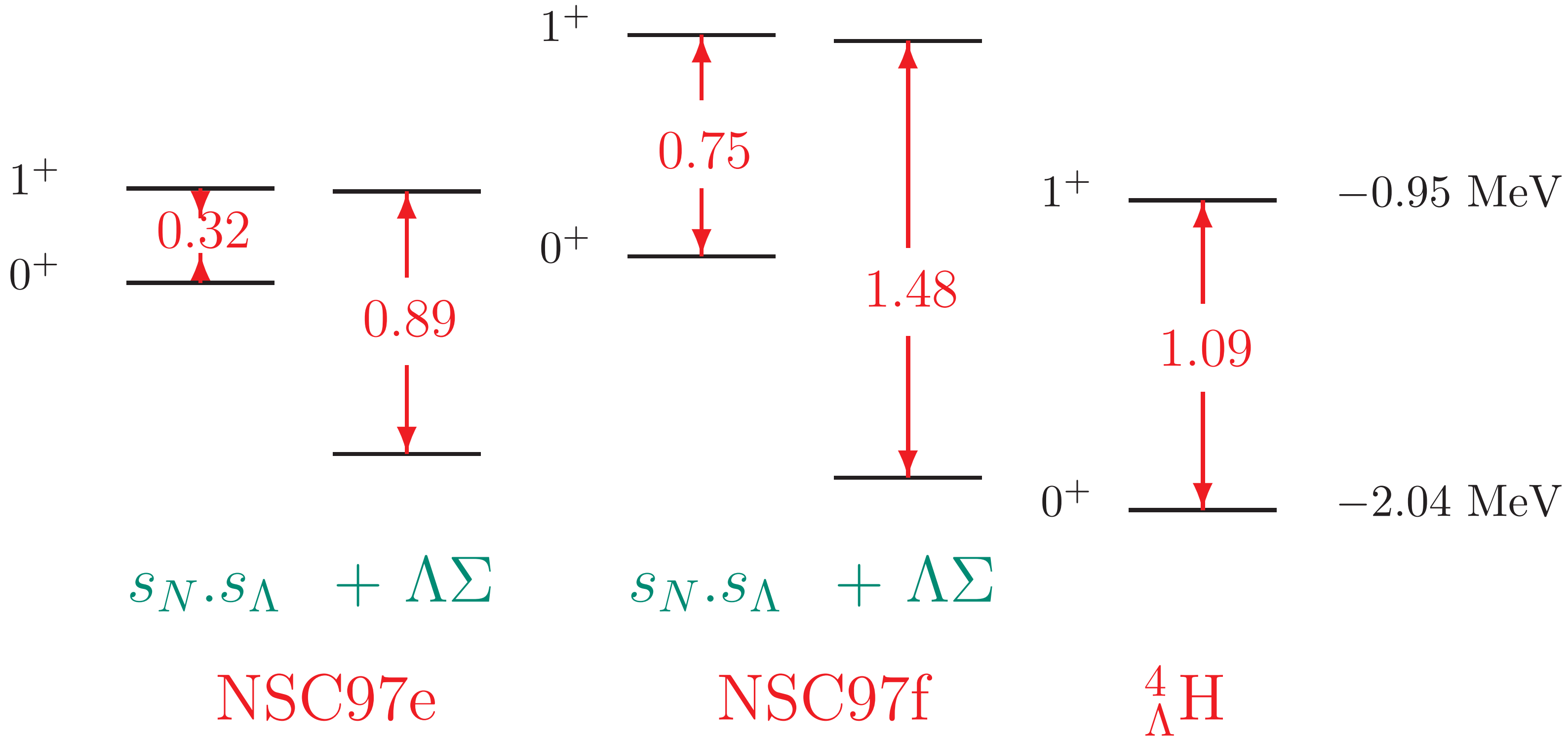
Related material

J-PARC SNP Experiments: Stage-1 Stage-2 Day-1

- **E03: X rays from Ξ^- atoms**
- **E05:** $^{12}\mathrm{C}(K^-,K^+)^{12}_{\Xi}\mathrm{Be}$ **textBlue**
- **E07: S=-2 emulsion-counter studies**
- **E10: DCX studies of neutron-rich $^{A}_{\Lambda}Z$**
- **E13: γ-ray spectroscopy of Λ hypernuclei →E63**
- **E15: search for K^-pp in $^3\mathrm{He}(K^-,n)$**
- **E18: $^{12}_{\Lambda}$C weak decays**
- **E19: search for Θ^+ pentaquark in $\pi^-p \to K^-X$**
- **E22: weak interactions in $^4_{\Lambda}\mathrm{H} - ^4_{\Lambda}\mathrm{He}$**
- **E27: search for K^-pp in $d(\pi^+,K^+)$**
- **E31: study of $\Lambda(1405)$ by in-flight $d(K^-,n)$**
- **E40: measurement of Σp scattering**
- **E42: search for H-dibaryon in (K^-,K^+) nuclear reactions**
- **E62: precision spectroscopy of X-rays from kaonic atoms with TES**

ΛN-ΣN coupling in NSC97 models

Akaishi et al., PRL 84 (2000) 3539



$\Lambda\Sigma$ coupling affects dominantly the 0^+ g.s.

Schematic $\Lambda\Sigma$ coupling model

($1s_\Lambda \to 1s_\Sigma$ & same nucleon orbital wavefunction)

- $\Lambda\Sigma$ coupling: $\sqrt{4/3}\, t_N \cdot t_{\Lambda\Sigma}\, (V_{\Lambda\Sigma} + s_N \cdot s_Y\, \Delta_{\Lambda\Sigma})$
  leading to Fermi (F) & Gamow-Teller (GT) nuclear transition matrix elements.

- **The important $\Lambda\Sigma$ coupling matrix elements involve Σ and Λ hyperons coupled to the same nuclear core, and nuclear states connected by a large GT matrix element to the dominant core state.**

- **Sizable $\Lambda\Sigma$ matrix elements arise in realistic models,**
  see Millener, Lect. Notes. Phys. 724 (2007) 31.

- $V_{\Lambda\Sigma} = 2.96\ (3.35), \quad \Delta_{\Lambda\Sigma} = 5.09\ (5.76)$ MeV,
  for s-shell baryons in simulated models NSC97e(f).

Schematic model A=4 matrix elements

$$|{}^4_\Lambda\mathrm{Z}(\mathrm{T}=1/2)\rangle = \alpha s^3 s_\Lambda + \beta s^3 s_\Sigma$$

$$v_{\Lambda\Sigma} = \sqrt{4/3}\,\vec{t}_N \cdot \vec{t}_{\Lambda\Sigma}\,(V_{\Lambda\Sigma} + \Delta_{\Lambda\Sigma}\,\vec{s}_N \cdot \vec{s}_Y)$$

$$v(0^+_{\mathrm{g.s.}}) = V_{\Lambda\Sigma} + \frac{3}{4}\Delta_{\Lambda\Sigma}, \quad v(1^+_{\mathrm{exc}}) = V_{\Lambda\Sigma} - \frac{1}{4}\Delta_{\Lambda\Sigma}$$

$$\delta E_\downarrow(J^+) = v^2(J^+)/(M_\Sigma - M_\Lambda)$$

NSC97	$V_{\Lambda\Sigma}$	$\Delta_{\Lambda\Sigma}$	$\delta E_\downarrow(0^+_{\mathrm{g.s.}})$	$\delta E_\downarrow(1^+_{\mathrm{exc}})$	$\Delta E_{\Lambda\Sigma}$	$\Delta E(0^+_{\mathrm{g.s.}} - 1^+_{\mathrm{exc}})$		
model	**as calculated in models** $(\Lambda\Sigma)_{\mathrm{e,f}}$					NKG	AHSM	NAS
NSC97$_\mathrm{e}$	2.96	5.09	0.574	0.036	0.539	0.75	0.89	1.13
NSC97$_\mathrm{f}$	3.35	5.76	0.735	0.046	0.689	1.10	1.48	1.51

Nogga, Kamada, Glöckle, PRL 88 (2002) 172501.

Akaishi, Harada, Shinmura, Myint, PRL 84 (2000) 3539.

Nemura, Akaishi, Suzuki, PRL 89 (2002) 142504.