Open Questions in Hypernuclear Physics

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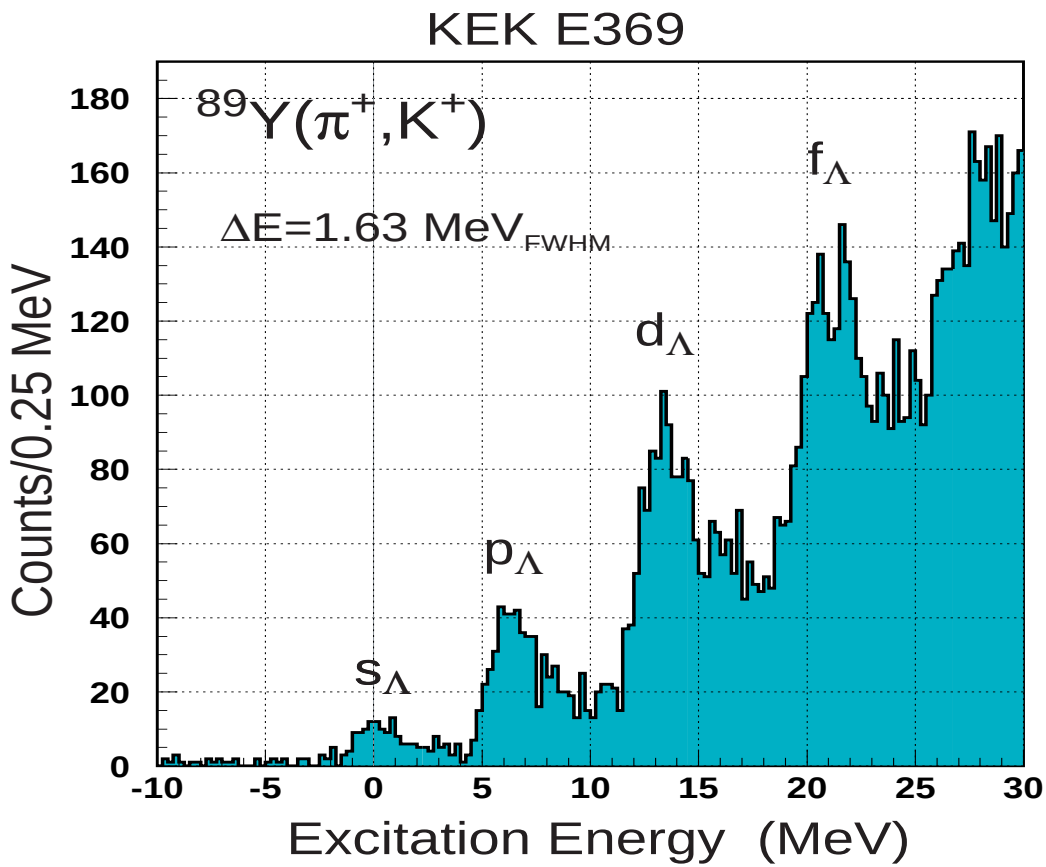
- **Dynamics of Λ hypernuclei ($^{A}_{\Lambda}Z$)**
  (i) Λ few-body & (ii) neutron-rich systems
- **$\Lambda\Lambda$ hypernuclei: long-lived H dibaryon?**
- **Hyperons (Λ, Σ, Ξ) in nuclear matter & beyond**
  (i) $|\mathcal{S}| \to \infty$: strange hadronic matter?
  (ii) hyperons in neutron stars?
  (iii) competition with $\bar{K}$ condensation?
- **Strangeness Nuclear Physics reviews:**
  (i) Nucl. Phys. A Special Issues 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

Observation of Λ single-particle states

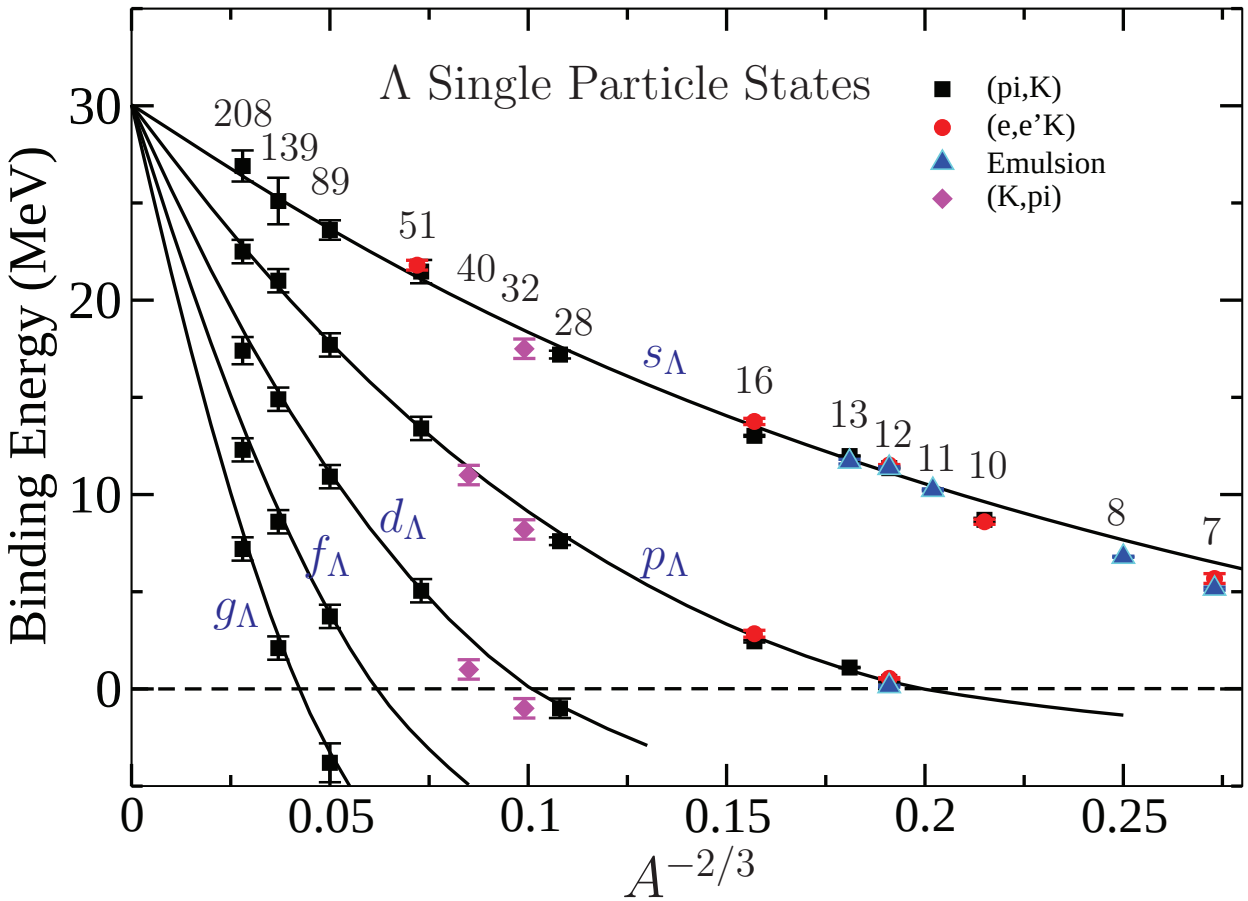


H. Hotchi et al., Phys. Rev. C 64 (2001) 044302 $B_\Lambda = 23.11 \pm 0.10$ MeV

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)

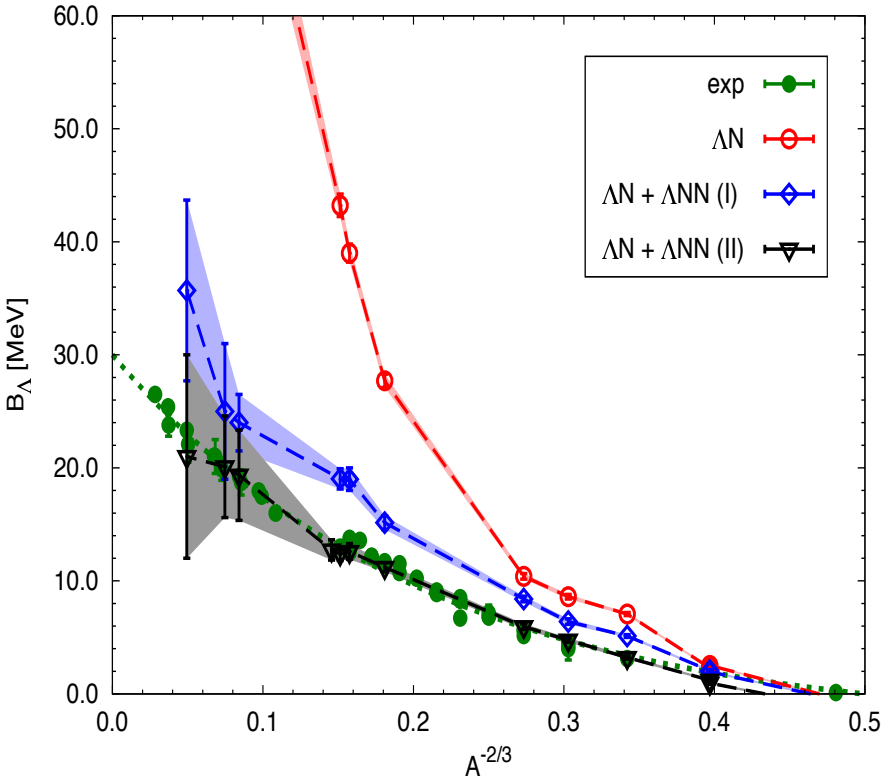


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

Textbook example of shell model at work.

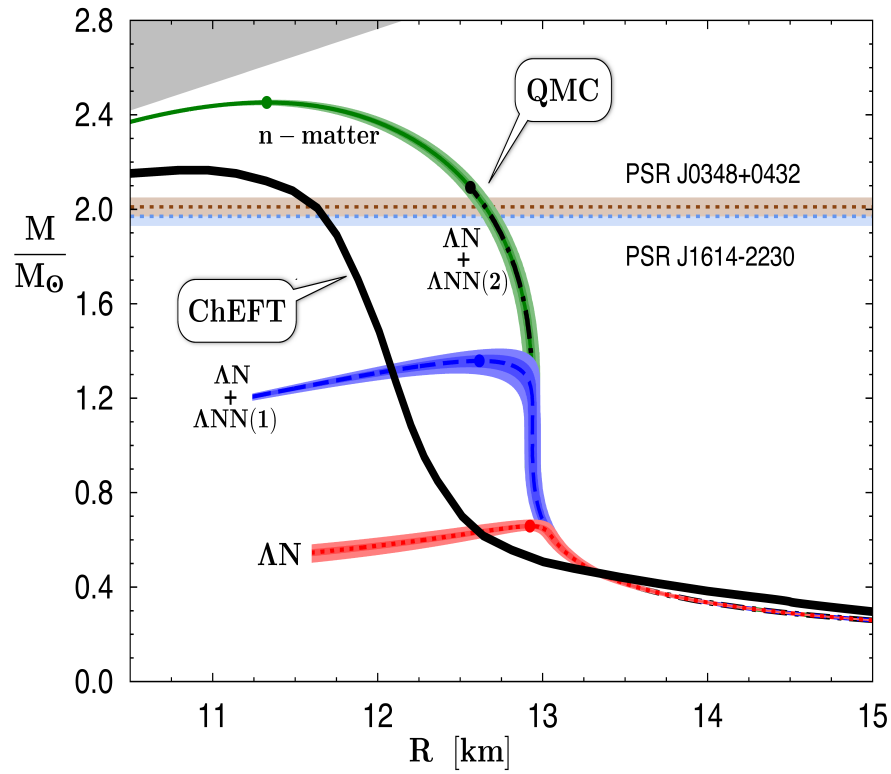
Skyrme-Hartree-Fock studies suggest ΛNN repulsion.

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314

ΛNN effect on B_Λ(g.s.)

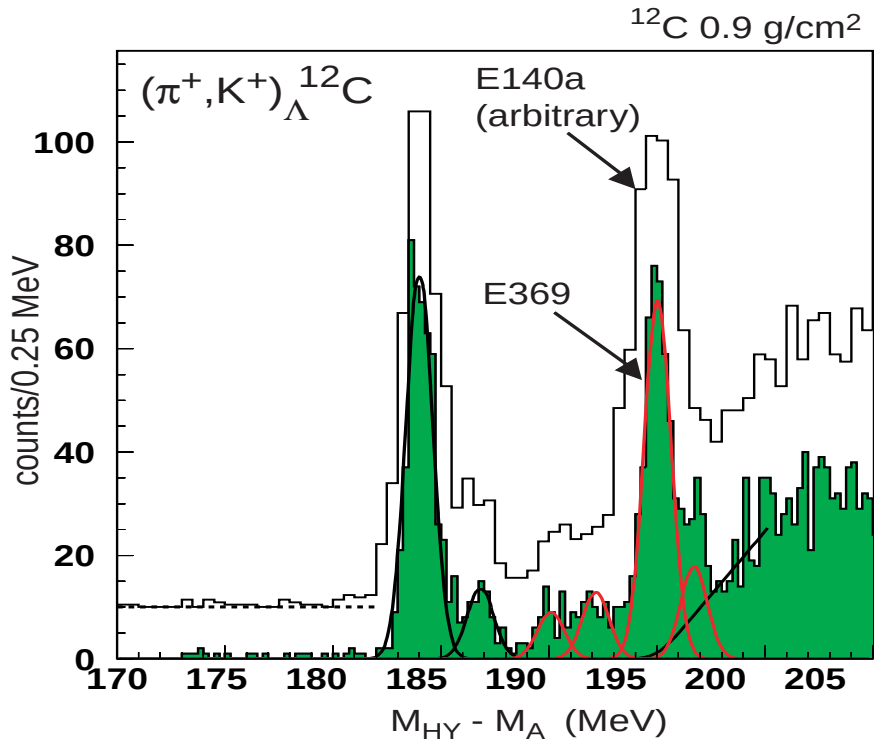


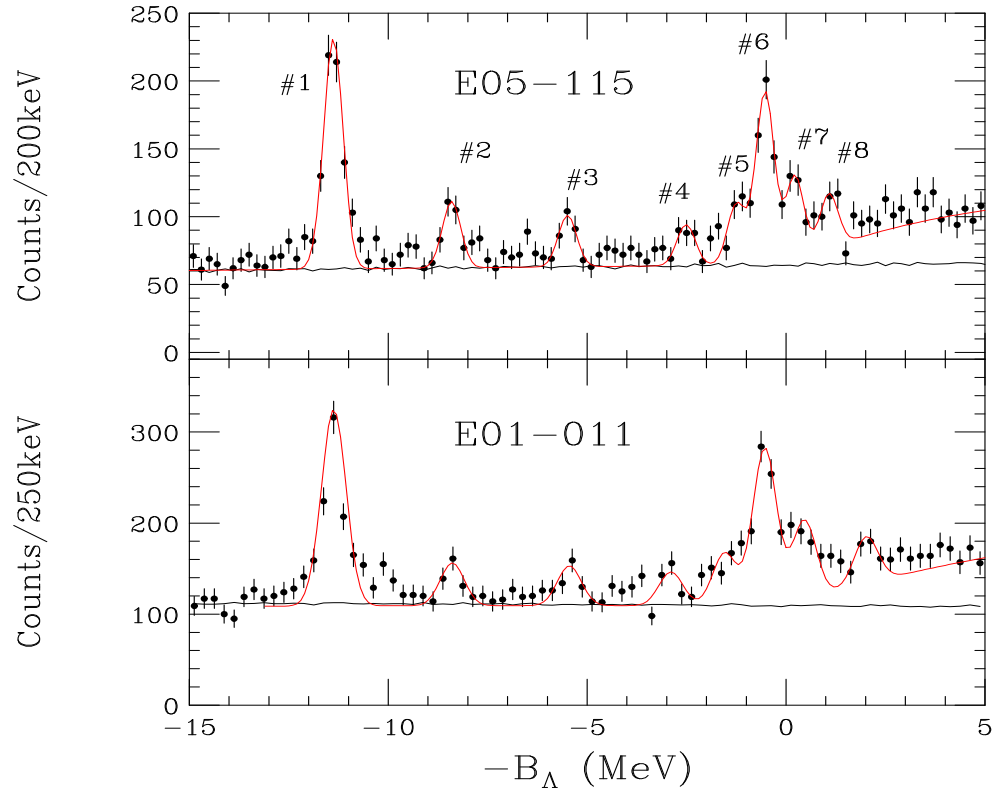
PRL 114 (2015) 092301

ΛNN effect on neutron stars

- **Adding ΛNN stiffens EOS of neutron stars.**
- **Other hyperons need to be considered too.**

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

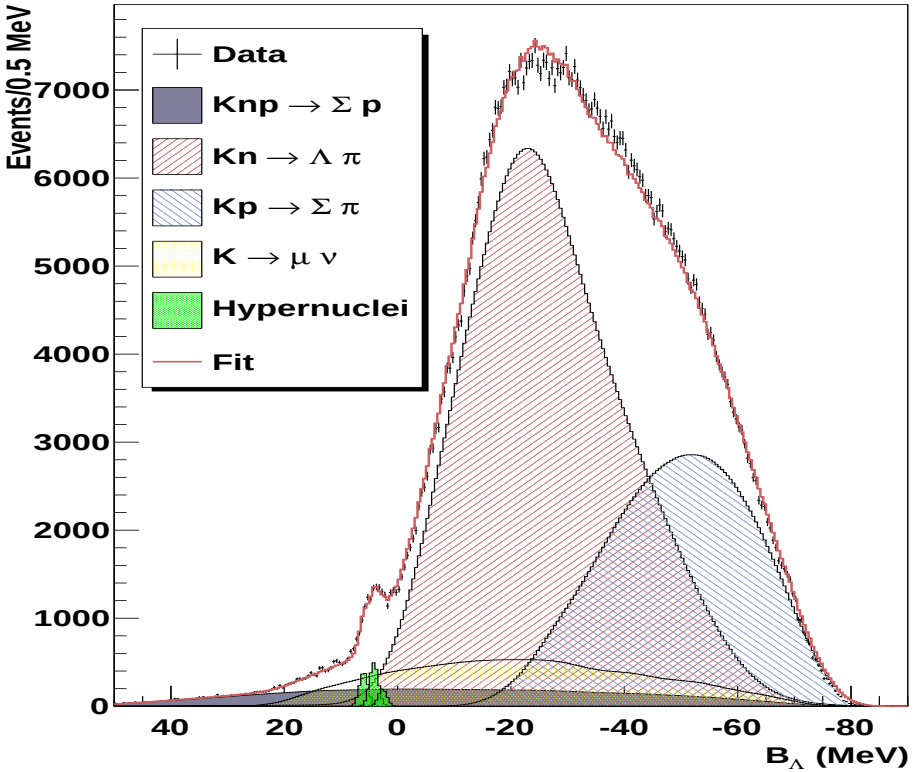
Jlab: ^{12}C$(e,e'K^+)^{12}_\Lambda$B (HKS)

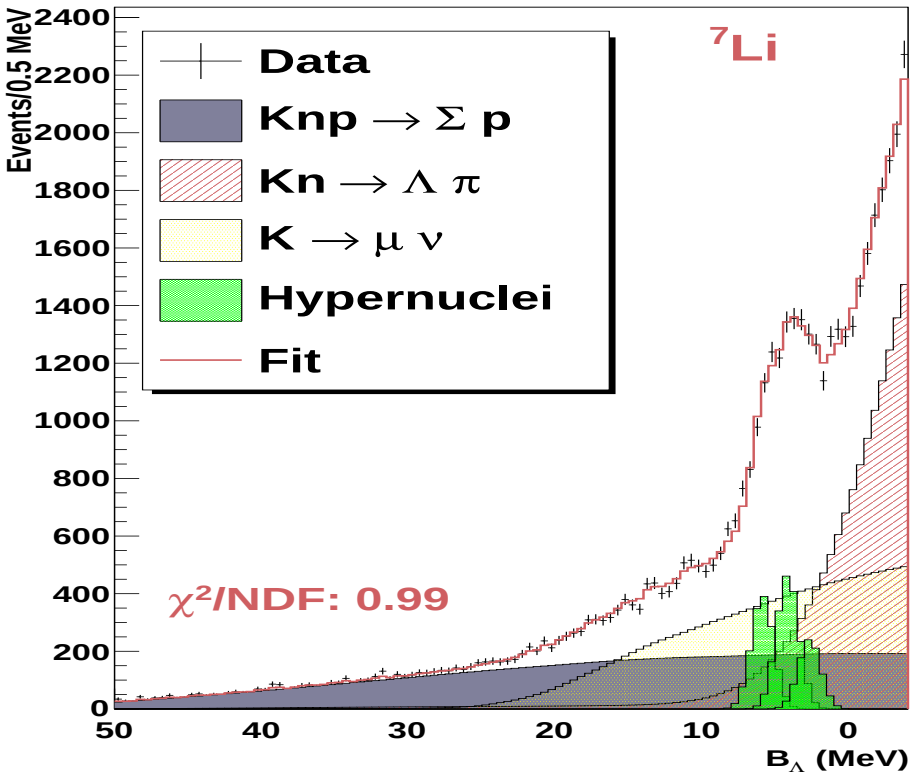
Spin-nonflip exc., ΔS=0

Spin-flip excitations, ΔS=1

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

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





Production spectrum on ^{7}Li

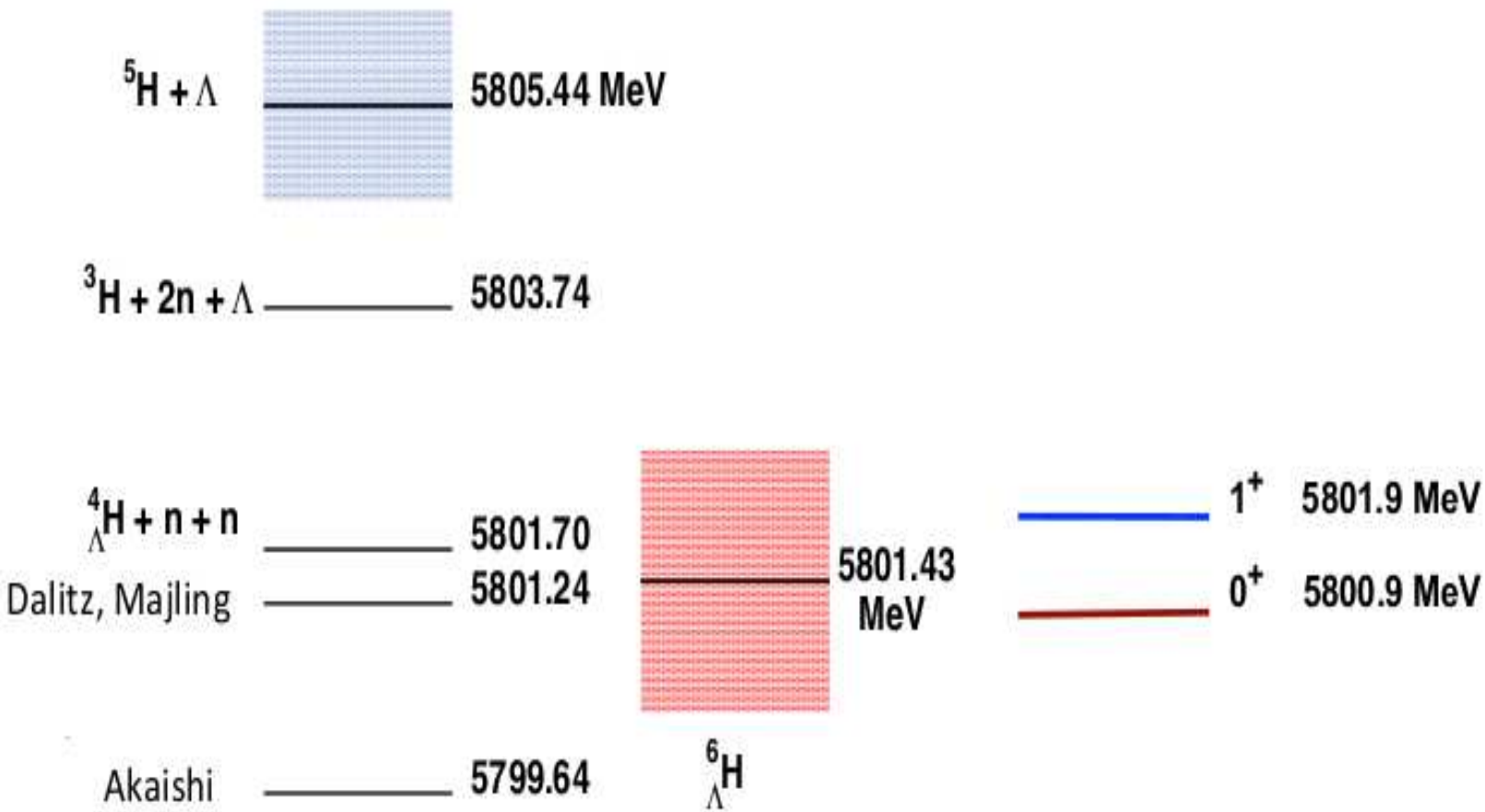
Three $^7_\Lambda$Li levels, δB_Λ=0.4 MeV

FINUDA, DAΦNE, Frascati

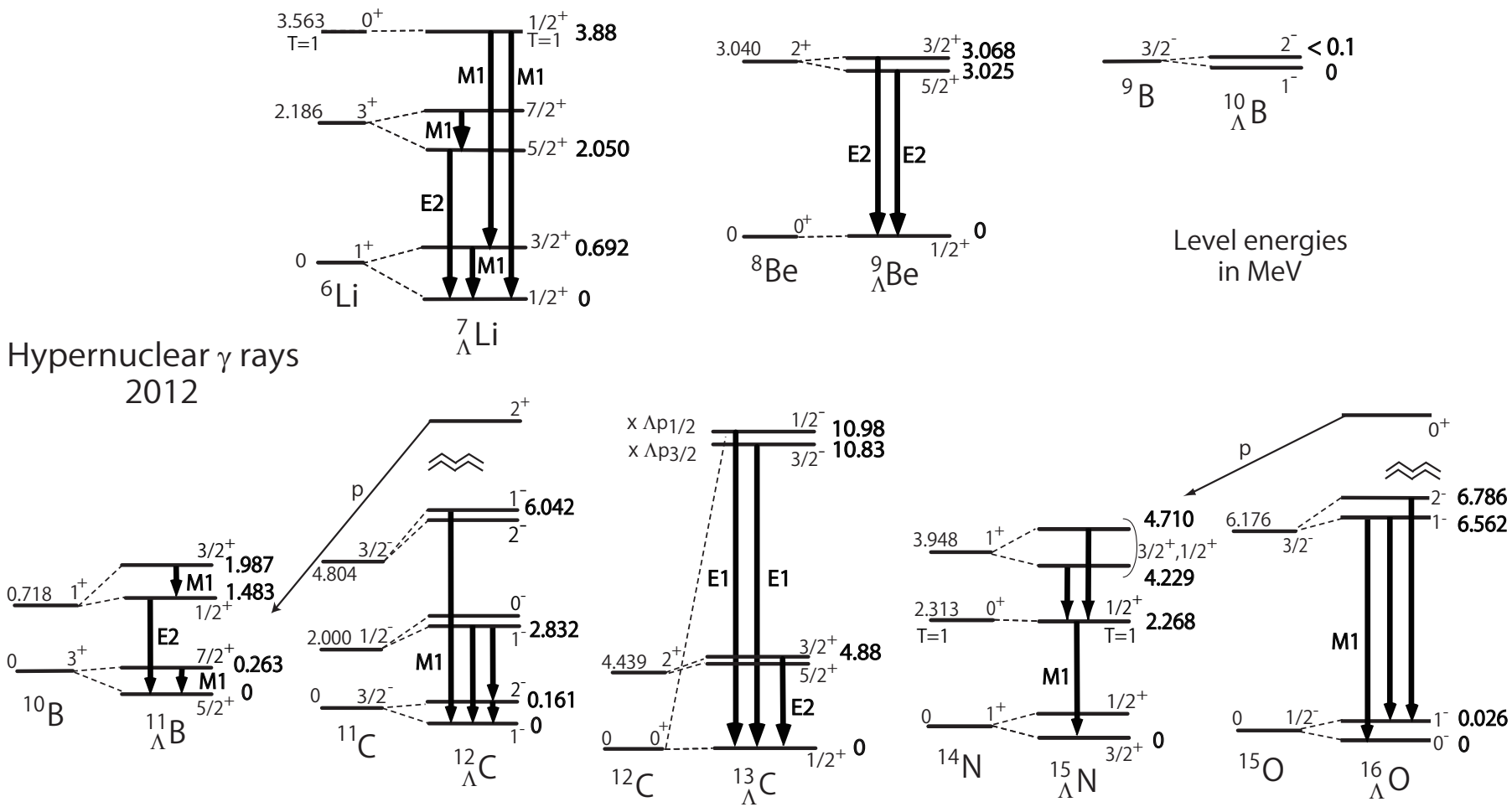
Formation rate $1 \cdot 10^{-3}/K^-_{\rm stop}$

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

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** $^A_\Lambda Z$.



Λ hypernuclear spectra from γ-ray measurements

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

Λ spin-orbit splitting (keV): 150 in $^{13}_{\Lambda}$C & related 43 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	(MeV)
$A = 7 - 9$	(-1.32)	0.430	-0.015	-0.390	0.030	
$A = 11 - 16$	(-1.32)	0.330	-0.015	-0.350	0.024	
$N\Lambda$-$N\Sigma$	1.45	3.04	-0.085	-0.085	0.157	

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	$\Delta E^{\rm th}$	$\Delta E^{\rm exp}$
${}^{7}_{\Lambda}$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 parameters Δ, S_Λ, T determined by doublet spacings

The lightest, s-shell, Λ hypernuclei

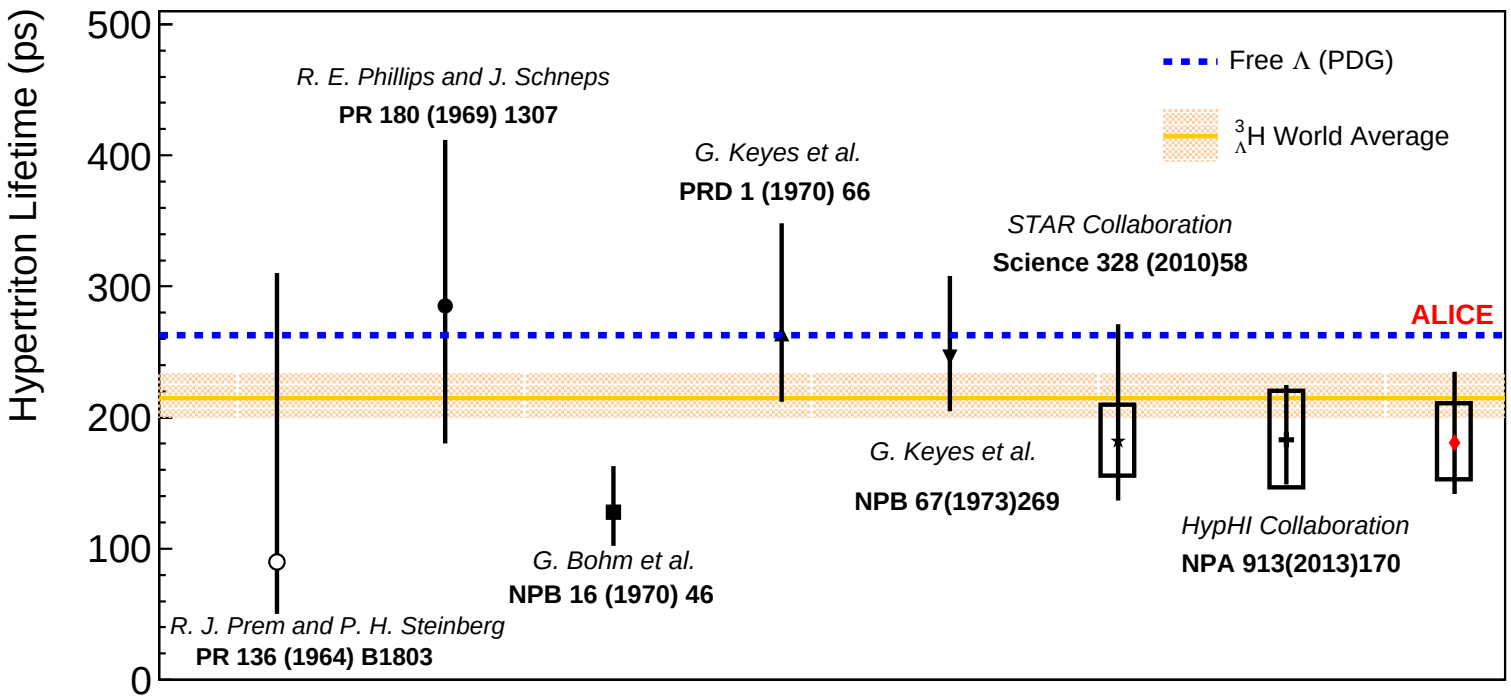
${}^{A}_{\Lambda}Z$	T	$J^{\pi}_{\text{g.s.}}$	B_Λ (MeV)	$J^{\pi}_{\text{exc.}}$	E_x (MeV)
${}^{3}_{\Lambda}H$	0	$1/2^+$	0.13(5)		
${}^{4}_{\Lambda}H$–${}^{4}_{\Lambda}He$	1/2	0^+	2.04(4)–2.39(3)	1^+	1.09(2)–1.406(3)
${}^{5}_{\Lambda}He$	0	$1/2^+$	3.12(2)		

- **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.**
  ab-initio Jacobi-NCSM (chiral LO).

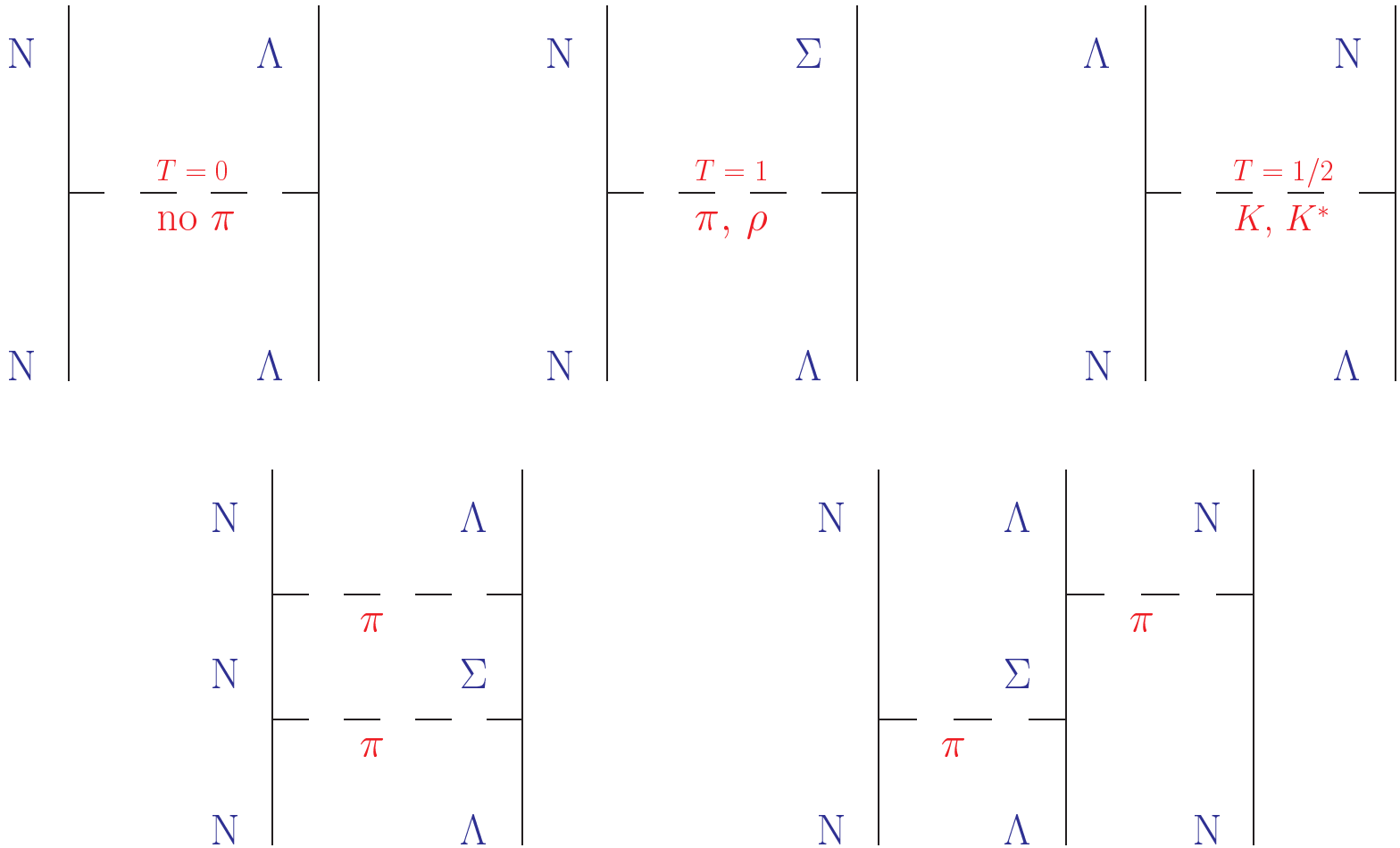
${}^{3}_{\Lambda}$H lifetime puzzle



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 ≈ 30%. ALICE, PLB 754 (2016) 360.

$S = -1 \quad T = 1/2 \qquad \Lambda N - \Sigma N$



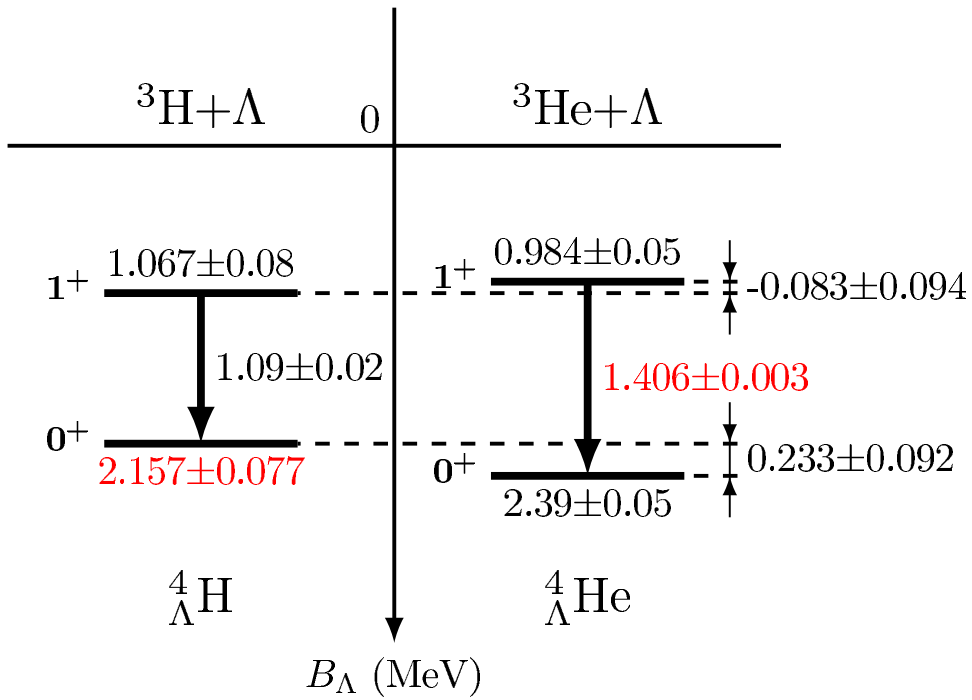
LO χEFT YN model: PS meson exchange + 5 contact terms

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

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

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

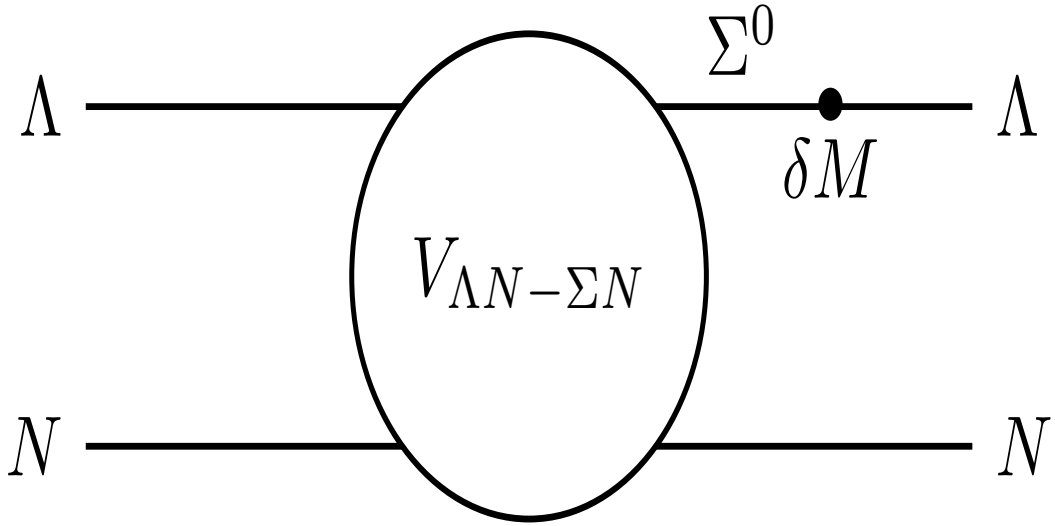
J-PARC's E13, ^{4}He($K^-, \pi^-\gamma$), PRL 115 (2015) 222501



CSB due to Λ-Σ^0 mixing, strongly spin dependent, dominantly in $0^+_{\text{g.s.}}$, large w.r.t. ≈−70 keV in ^{3}H-^{3}He.

Remeasure ${}^{4}_{\Lambda}$He$_{\text{g.s.}}$ (E13).

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

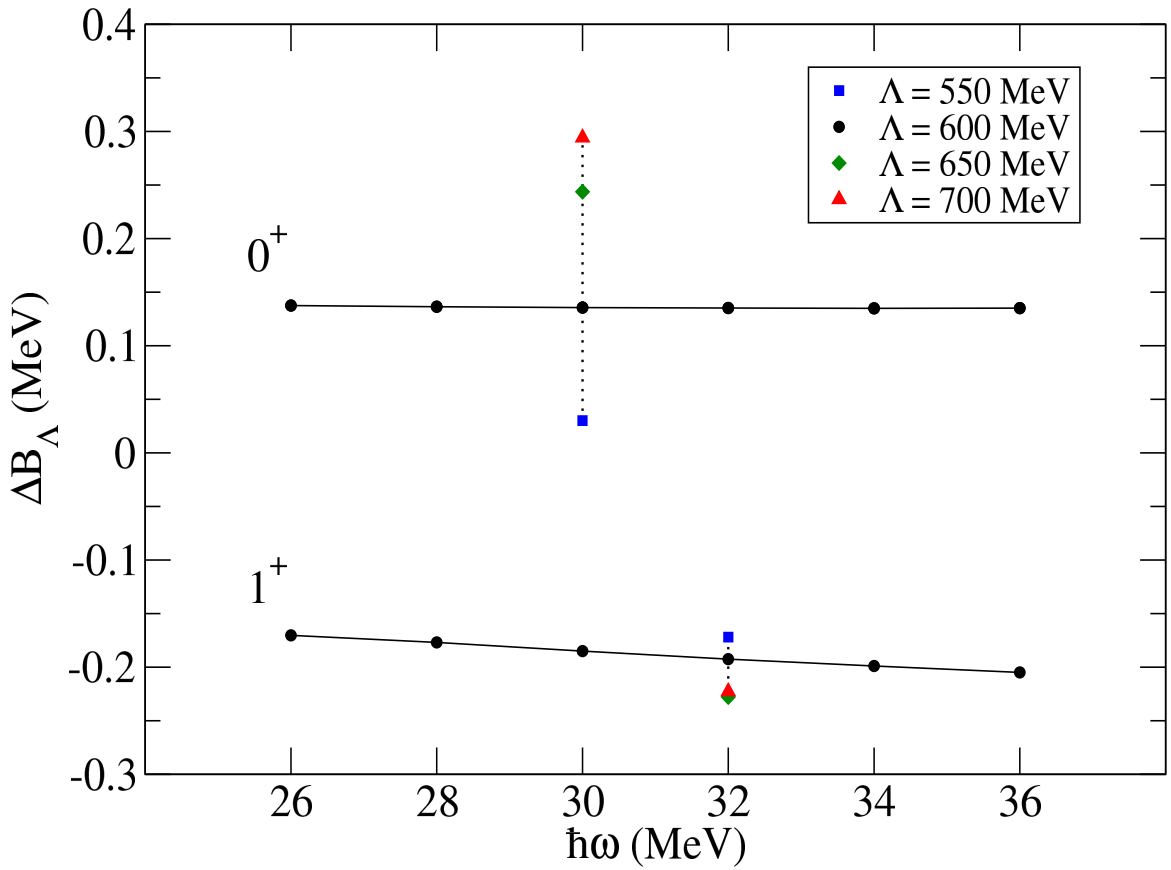


Dalitz-von Hippel (1964): "applies to any I=1 meson exchange, π, ρ..." & also to χEFT contact interactions.

Applied systematically in recent work by

A. Gal, PLB 744 (2015) 352 (also in p shell) and by

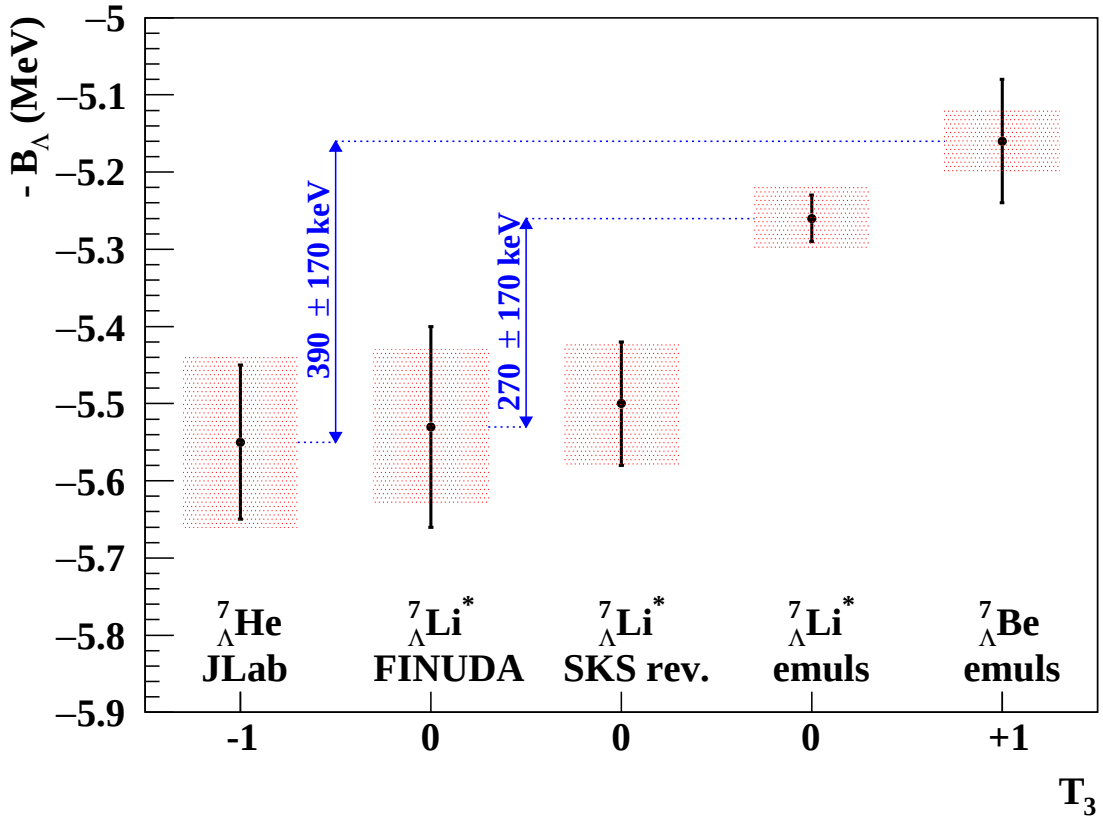
D. Gazda, A. Gal (2016) PRL 116, 122501; NPA 954, 161.



NCSM HO $\hbar\omega$ dependence of $\Delta B_\Lambda({}^4_\Lambda\mathrm{He}-{}^4_\Lambda\mathrm{H})$ 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: $\Delta E_\gamma = \Delta(\Delta B_\Lambda) = 0.33 \pm 0.03$ MeV compared to a measured $\Delta E_\gamma = 0.32 \pm 0.02$ MeV.

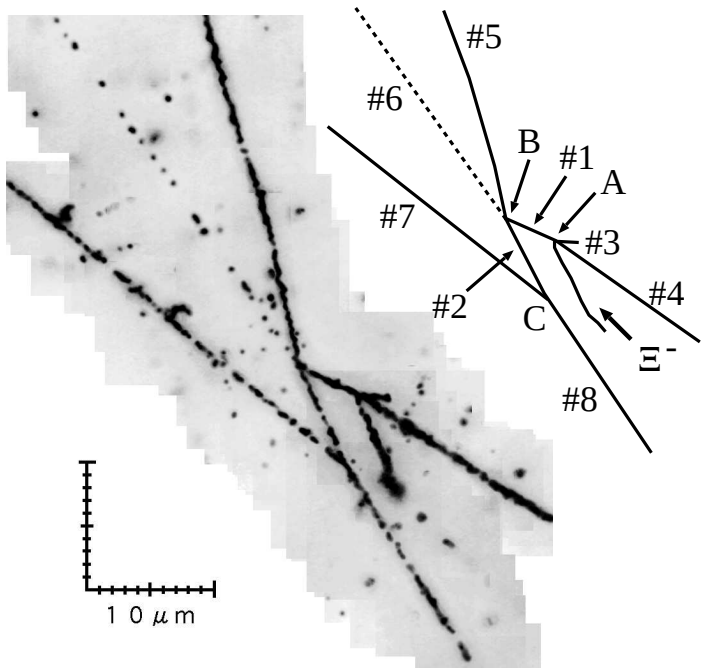
CSB in p-shell hypernuclei



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.

$\Lambda\Lambda$ 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.**

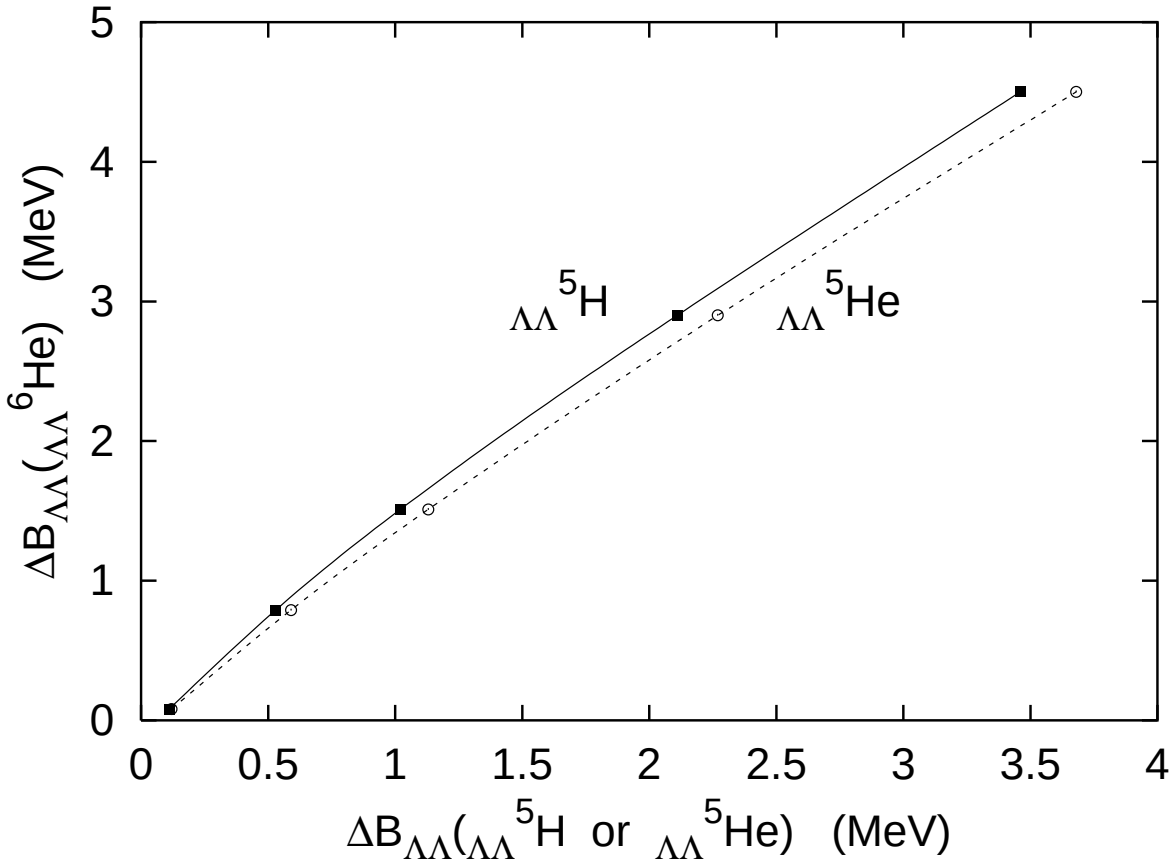
- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}^{6}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}_{\Lambda\Lambda}^{6}\mathrm{He} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-$ **(no** ${}_{\Lambda\Lambda}^{6}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + H$**)**
- **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→H+^{4}He, impose B(H)≤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 ≈$N\Xi$ threshold, ≈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

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

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

With ${}_{\Lambda\Lambda}^{4}$H likely unbound, ΛΛ 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**

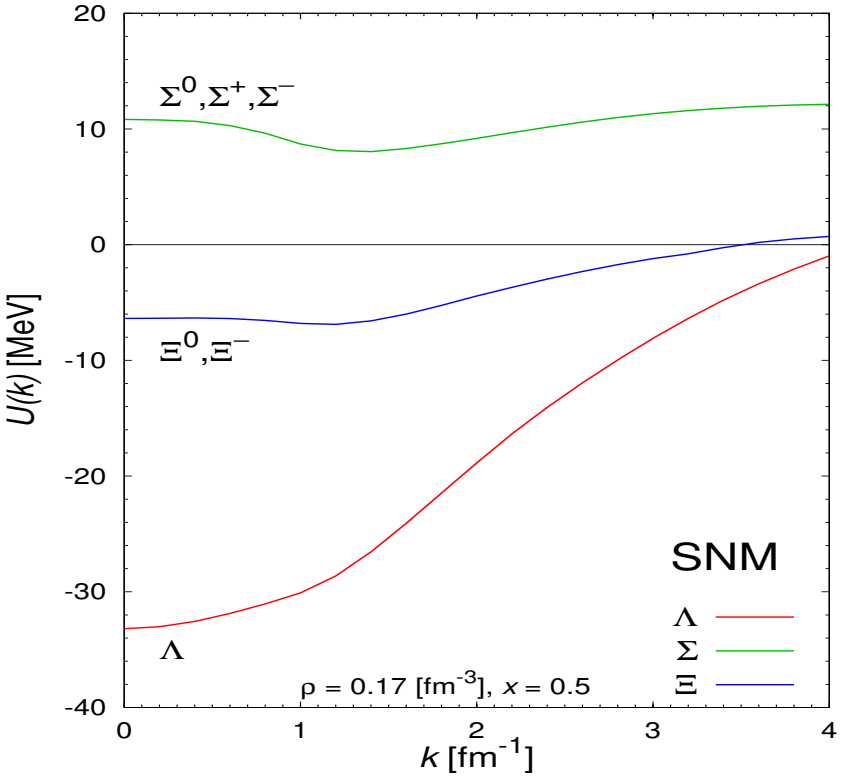
‡ **Assuming production in** ${}^{10}_{\Lambda\Lambda}$Be **non g.s.** $2^+(3.04\ \mathrm{MeV})$

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

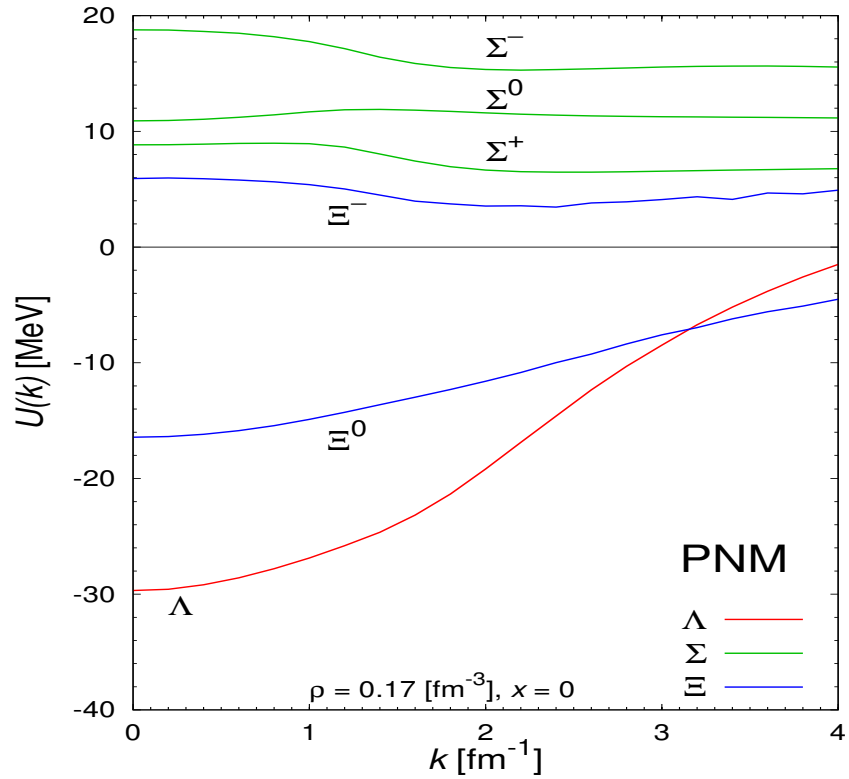
- **Unassigned Hida event [PTPS 185 (2010) 335]**
- $B^{\rm SM}_{\Lambda\Lambda} \approx B^{\rm CM}_{\Lambda\Lambda}$**, but SM spans a wider** A **range**

Other Strange Hadrons in Matter

Hyperon-Nucleus potentials from LQCD



Symmetric nuclear matter

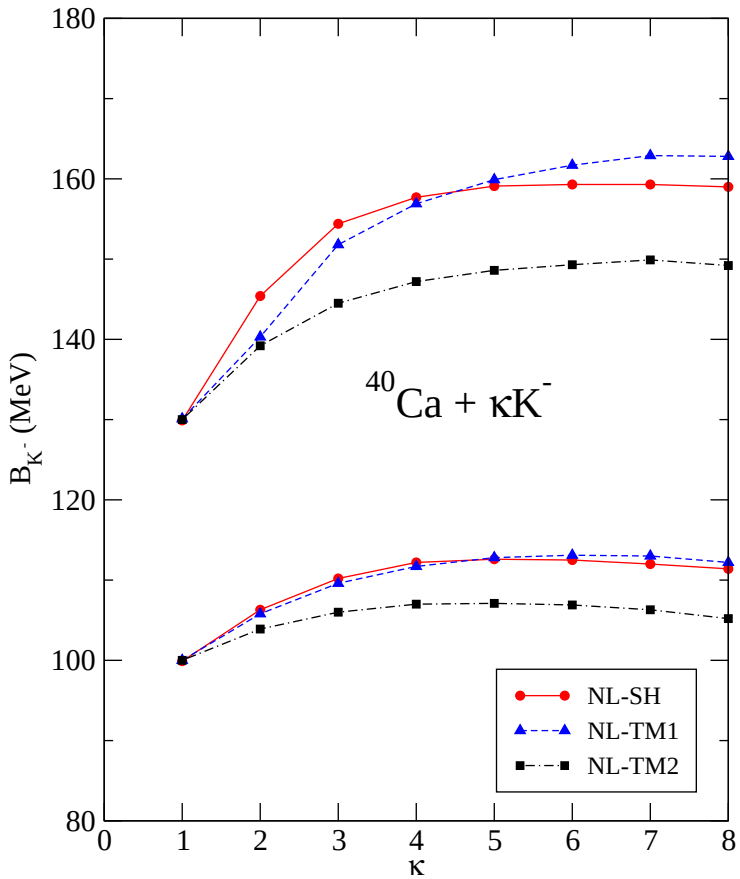


Pure neutron matter

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

BHF applied to Lattice YN potentials

Σ – repulsion, Ξ – weak attraction

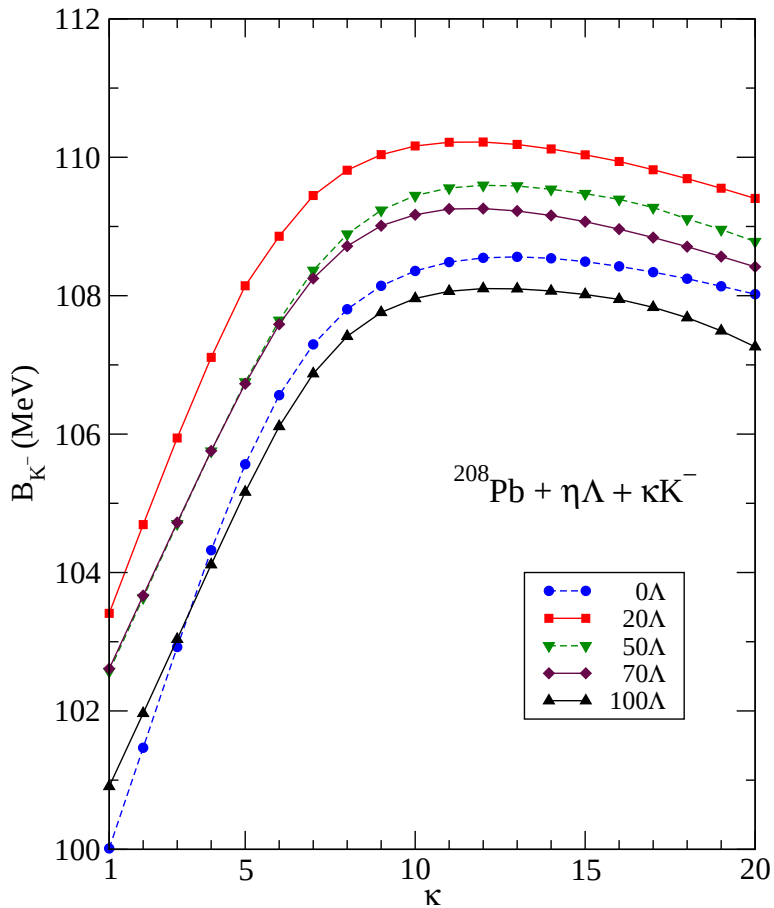


D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

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.**



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

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for $^{208}\mathrm{Pb} + \eta\Lambda + \kappa K^-$. $\bar{K}$ mesons do not replace hyperons in 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).
- Search for n-rich ${}^{A}_{\Lambda}$Z; ${}^{6}_{\Lambda}$H? (E10).
- Repulsive Σ-nuclear interaction; how repulsive? (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.**

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**
- **E15: search for K^-pp in $^3\mathrm{He}(K^-, n)$**
- **E18: $^{12}_{\Lambda}\mathrm{C}$ 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**