Progress & issues in Strangeness NP

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- $\mathcal{S} = -1$: **dynamics of Λ hypernuclei ($^{A}_{\Lambda}Z$)**
  (i) Λ few-body & (ii) neutron-rich systems
  (iii) Λ and other hyperons in neutron stars?
- **$\Lambda\Lambda$ hypernuclei: long-lived H dibaryon?**
- **Hyperons (Λ, Σ, Ξ) in nuclear matter**
  $|\mathcal{S}| \to \infty$: **strange hadronic matter?**
- **Kaons in nuclei: K^- quasibound states?**

- **SNP Special Issue: Nucl. Phys. A 881 (2012)**
  Proc. HYP 2012: Nucl. Phys. A 914 (2013)

Λ hypernuclear dynamics

Studies of Λ hypernuclei

- (K^-, π^-) – emulsions, CERN, BNL, KEK, LNF (FINUDA)
- (π^+, K^+) – BNL, KEK
- $(\pi^+, K^+ \gamma)$ at KEK and $(K^-, \pi^- \gamma)$ at BNL, with Hyperball
- $(e, e' K^+)$ – JLab, Hall A and Hall C; now also at MAMI
- DCX – (π^-, K^+) (KEK) & $(K^-_{\rm stop}, \pi^+_{\rm prod}\, \pi^-_{\rm decay})$ (LNF)

At J-PARC, two of these research directions will be followed:

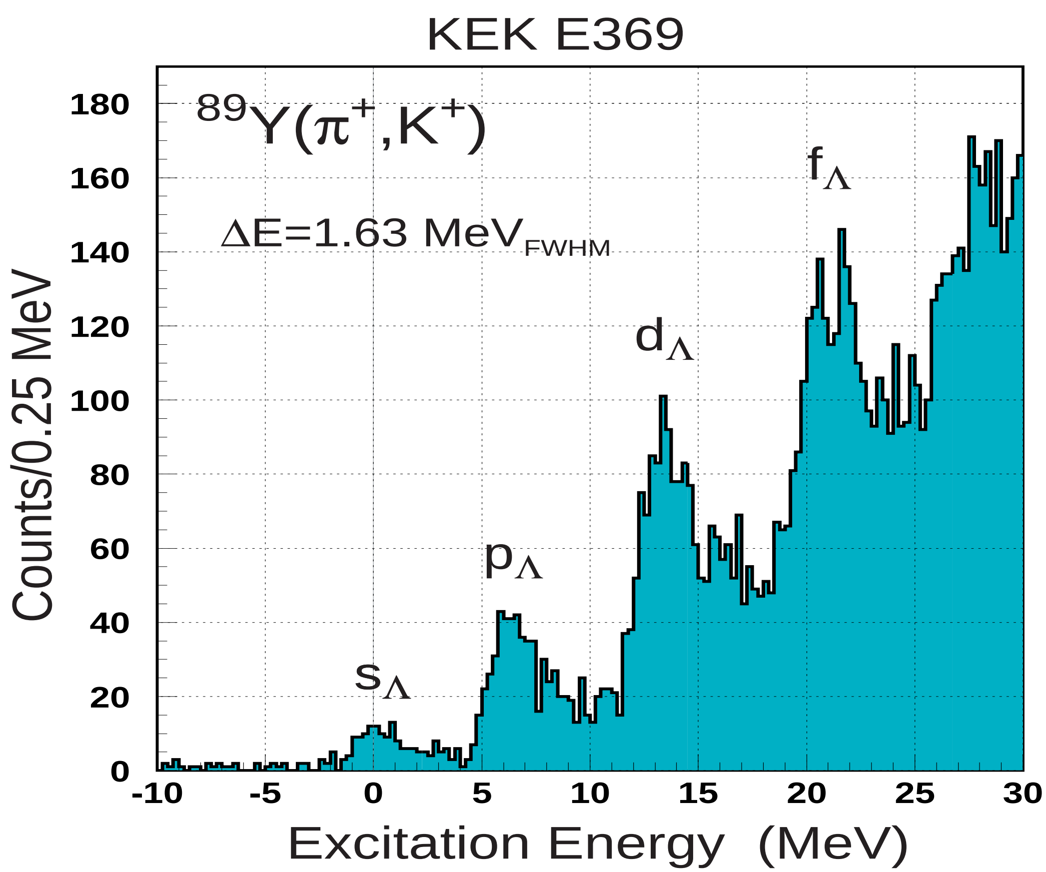
- E13: γ-ray spectroscopy of Λ hypernuclei
- E10: DCX studies of neutron-rich ${}^{A}_{\Lambda}Z$ (^{6}Li, ^{9}Be & ^{10}B targets)

plus two experiments on weak interactions:

- E18: ${}^{12}_{\Lambda}$C weak decays
- E22: weak interactions in ${}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}$.

In GSI, the HypHI Experiment: ^{6}Li on C at 2 A GeV.

Observation of Λ single-particle states

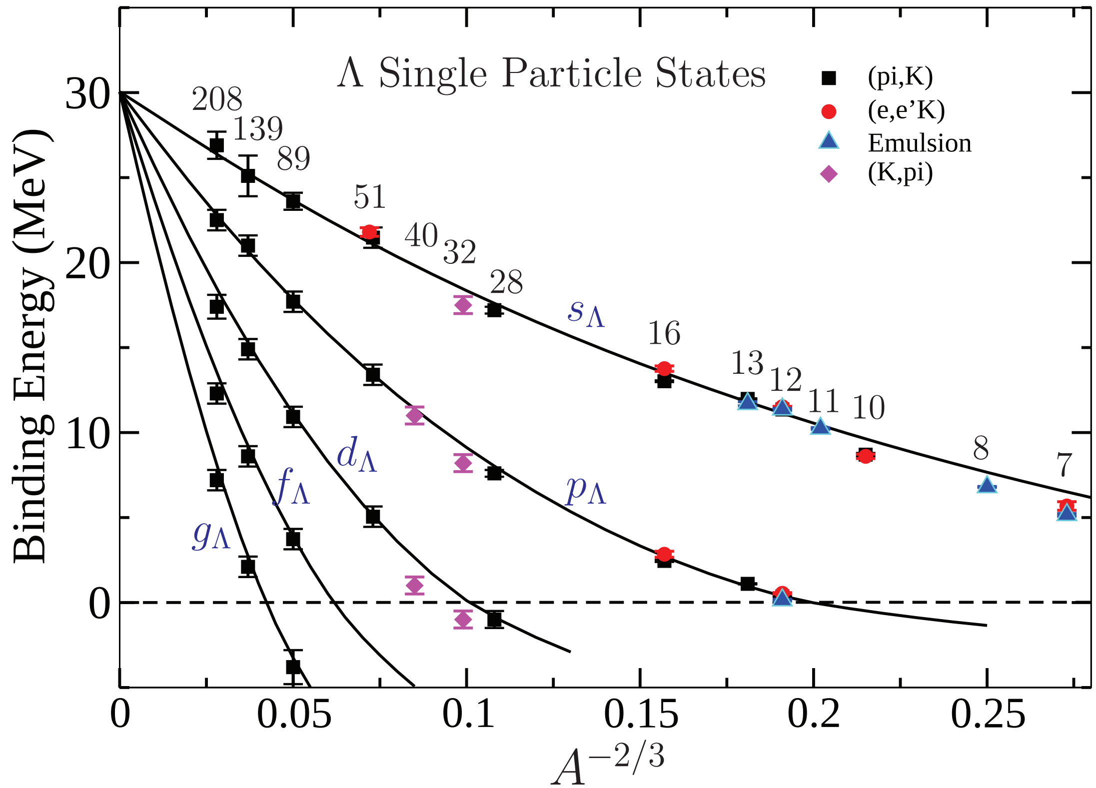


H. Hotchi et al., Phys. Rev. C 64 (2001) 044302 $B_\Lambda = 23.11 \pm 0.10$ MeV

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)

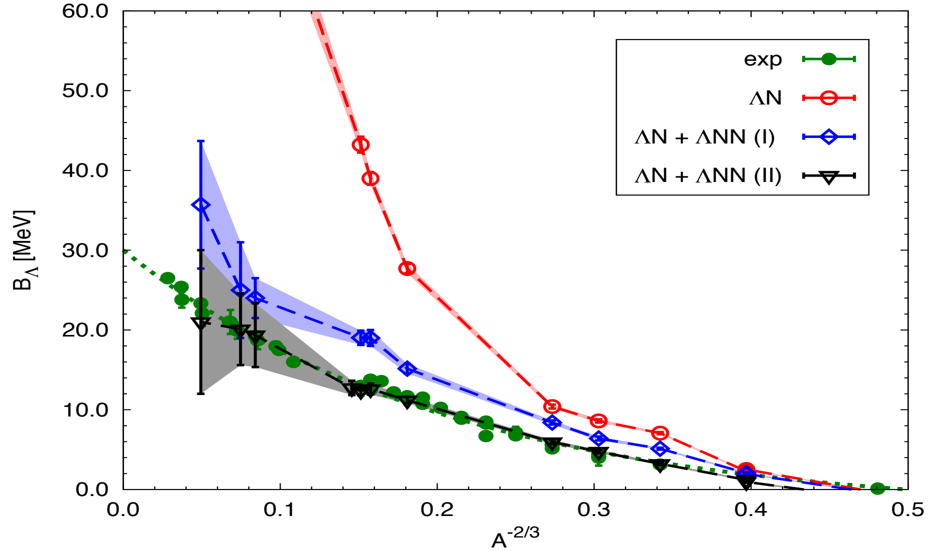


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

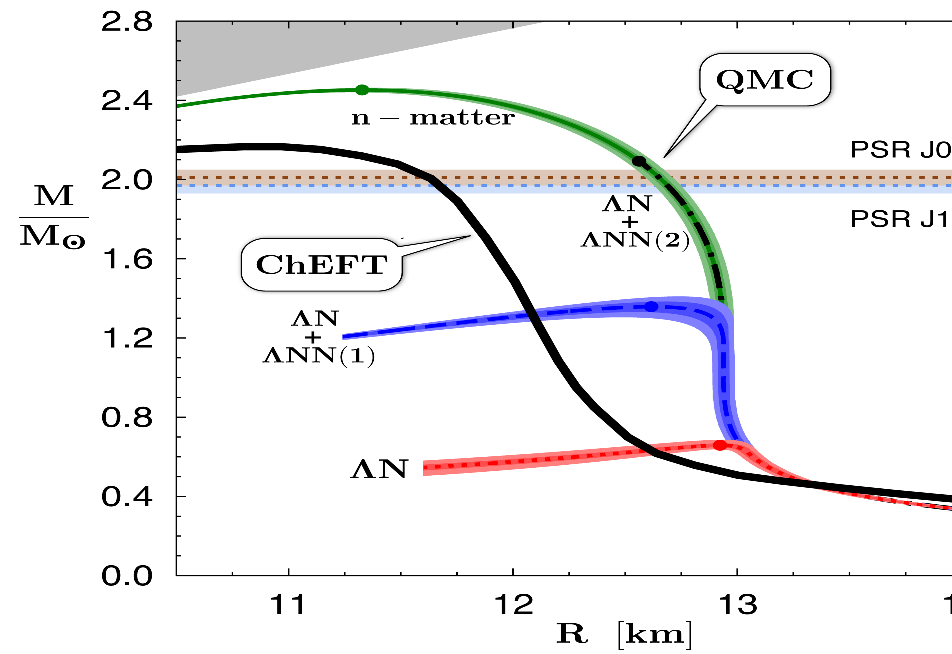
Textbook example of shell model at work.

SHF studies suggest ΛNN repulsion.

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314



PRL 114 (2015) 092301

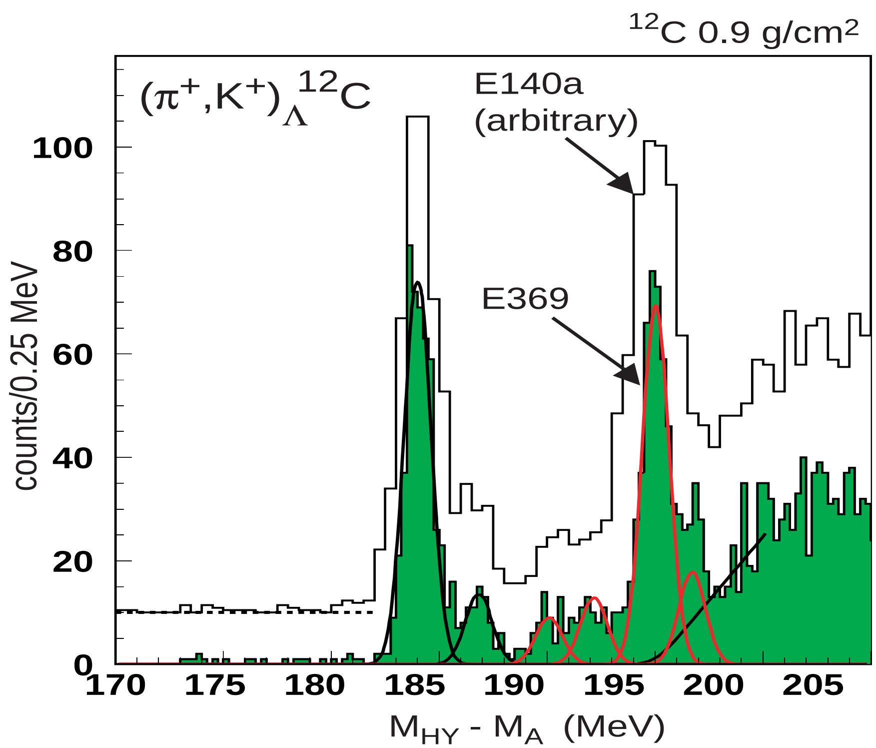
ΛNN effect on B_Λ(g.s.)

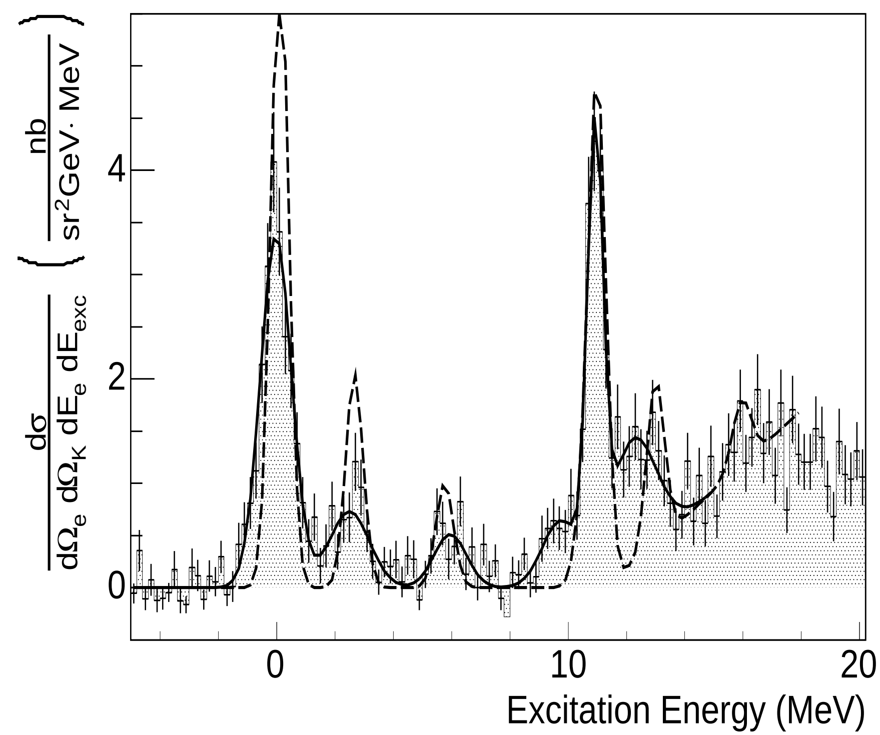
ΛNN effect on neutron stars

Adding ΛNN stiffens EOS of neutron stars.

Other hyperons besides Λ need to be considered too.

Room for hypernuclear spectroscopy





H. Hotchi et al., PRC 64 (2001) 044302

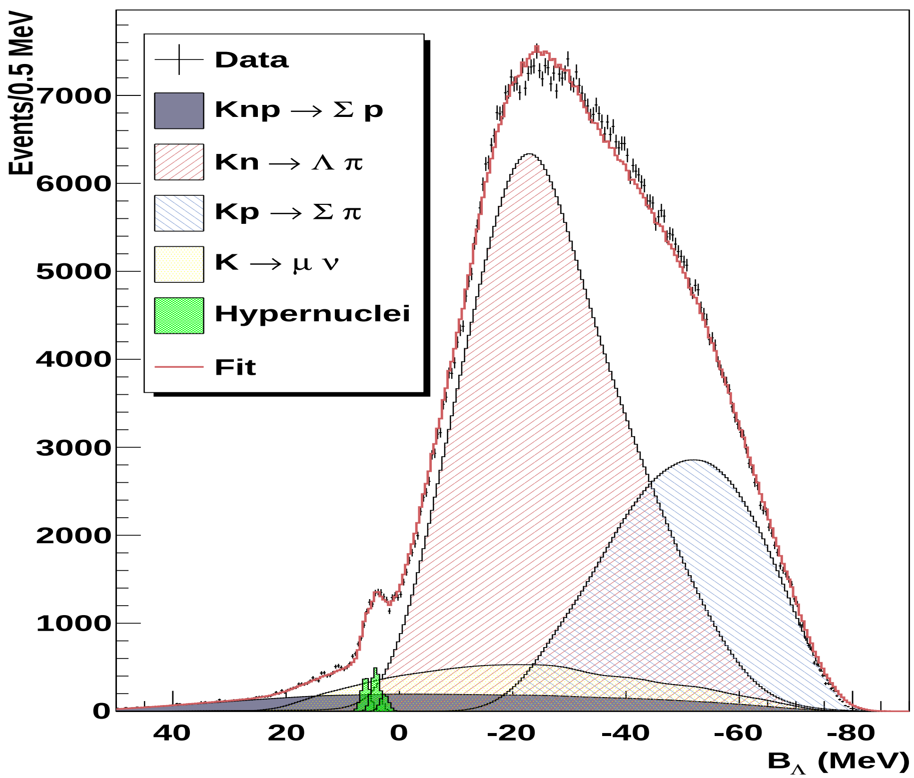
$1s_\Lambda - 1p_\Lambda$ intermediate structure

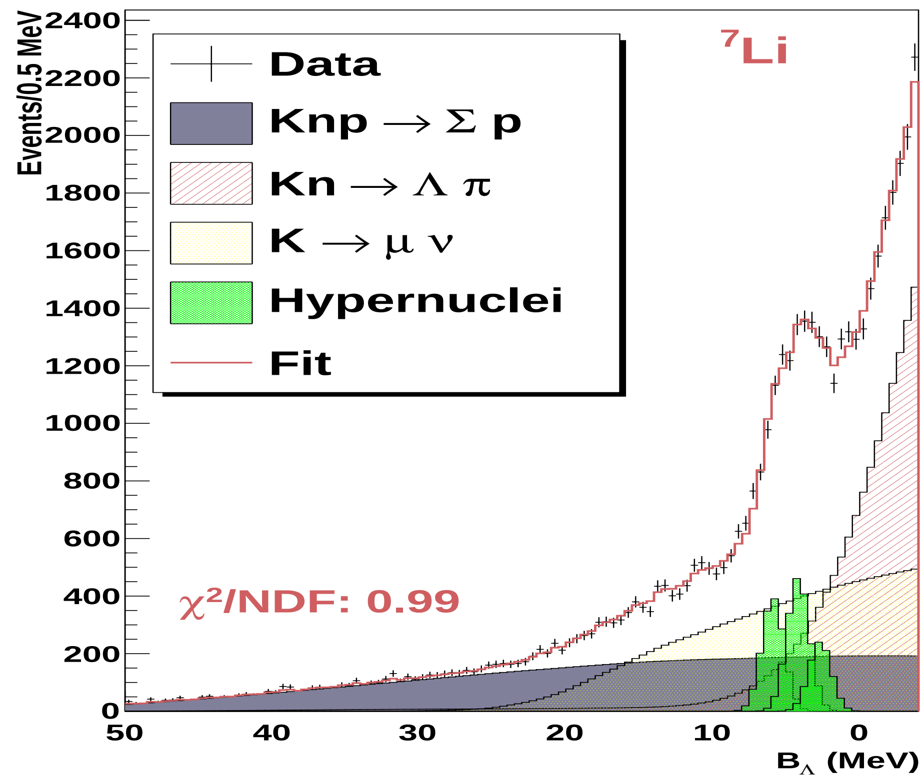
M. Iodice et al., PRL 99 (2007) 052501

$^{12}_{\Lambda}$B in $(e, e'K^+)$, Jlab Hall A

energy resolution 1.6 MeV → 0.6 MeV [PRC 90 (2014) 034320]

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





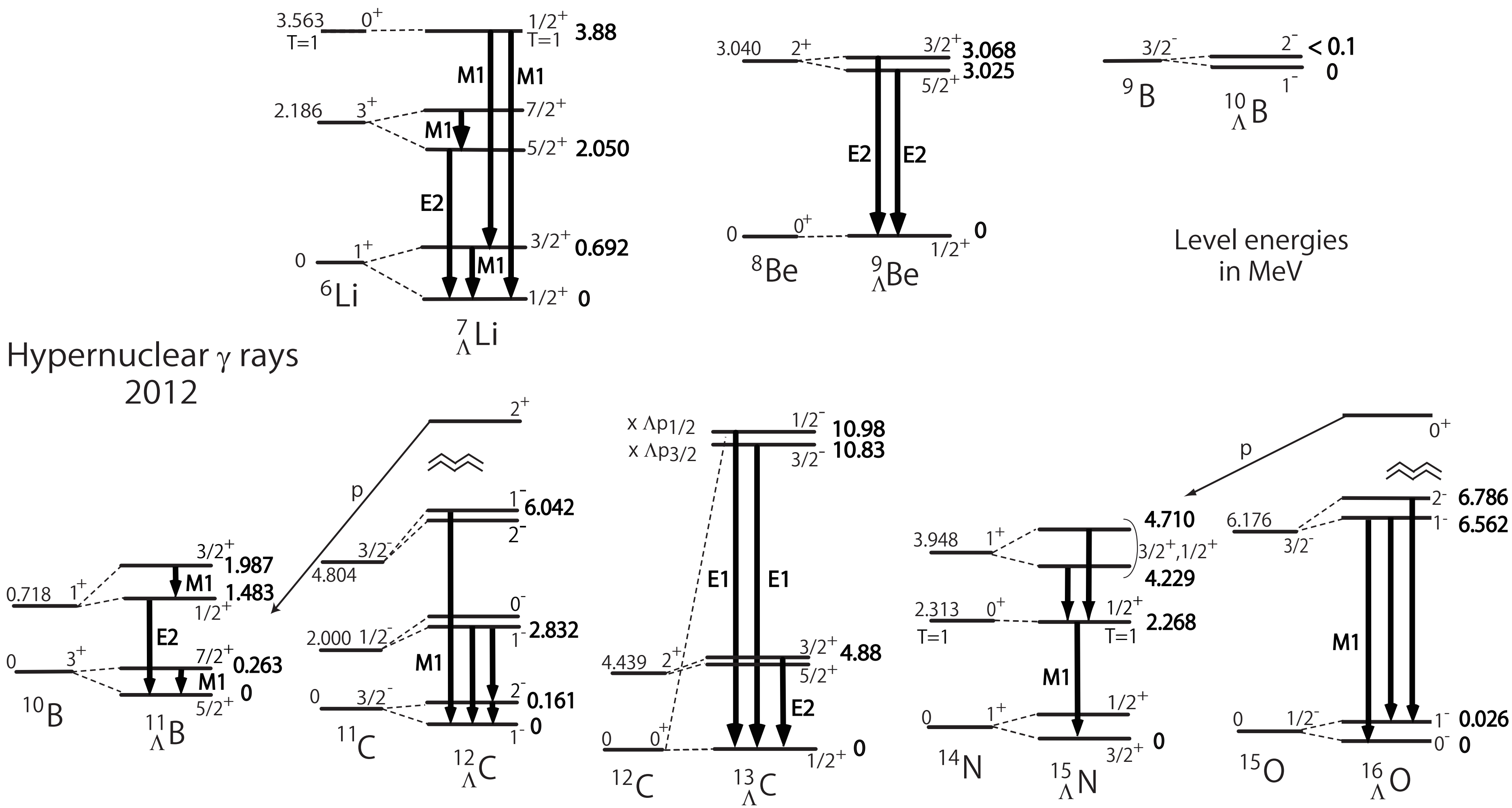
Production spectrum on ^{7}Li

FINUDA, DAΦNE, Frascati

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

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

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



Hypernuclear level schemes from γ-ray measurements (BNL, KEK)

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

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

Λ spin dependence parameters Δ, S_Λ, T determined by doublet spacings

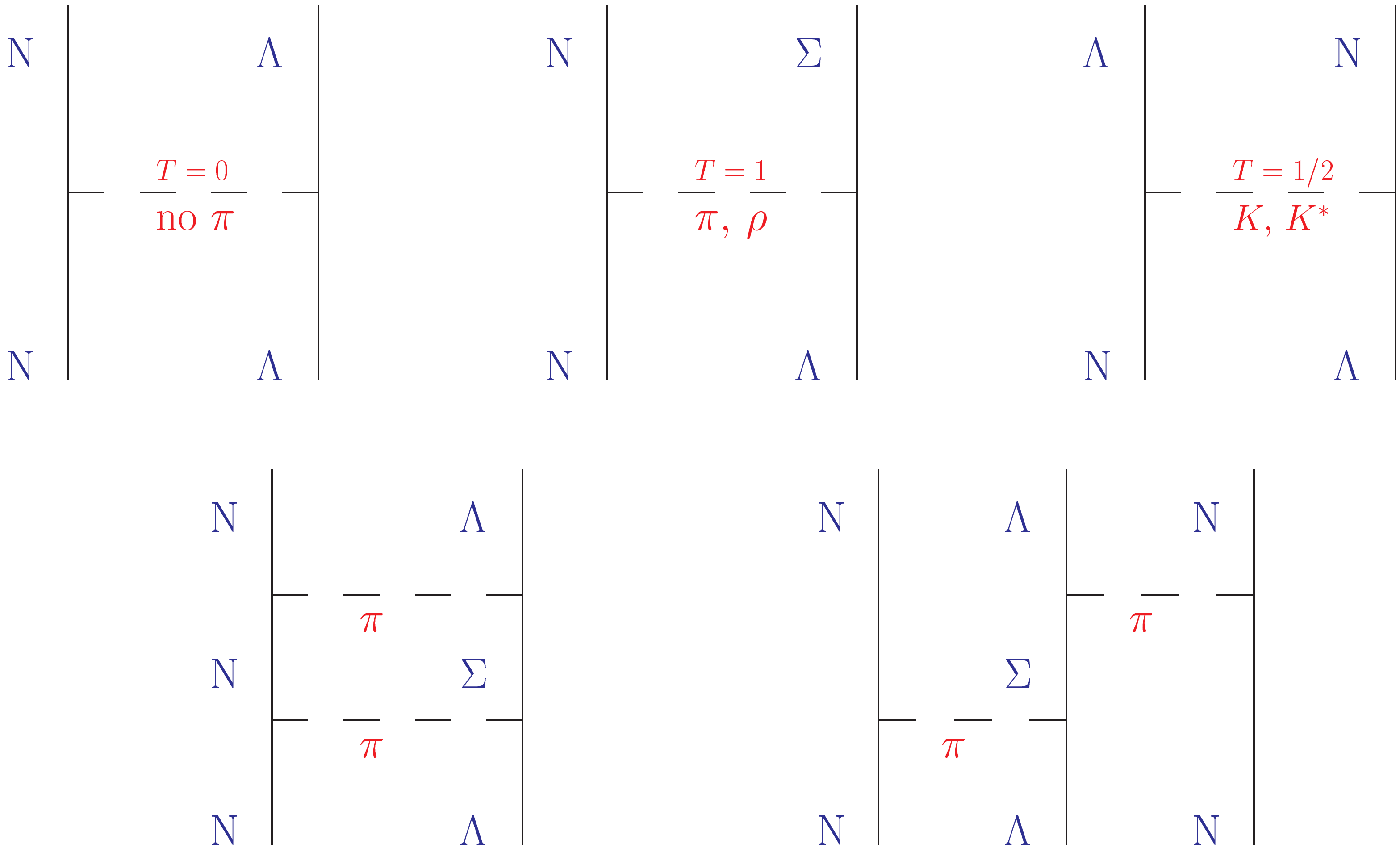
ΛN interaction matrix elements in Nijmegen BB models

- 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 using Woods-Saxon 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	−1.387	0.497
	${}^{16}_{\Lambda}$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.

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



YN interaction contributions to g.s. binding energies

	${}^{7}_{\Lambda}$Li	${}^{8}_{\Lambda}$Li	${}^{9}_{\Lambda}$Li	${}^{10}_{\Lambda}$B	${}^{11}_{\Lambda}$B	${}^{11}_{\Lambda}$Be	${}^{12}_{\Lambda}$B	${}^{13}_{\Lambda}$C	${}^{15}_{\Lambda}$N	${}^{16}_{\Lambda}$N
keV	$1/2^+$	1^-	$3/2^+$	1^-	$5/2^+$	$1/2^+$	1^-	$1/2^+$	$3/2^+$	1^-
Λ-Σ	78	160	183	35	66	99	103	28	59	62
Δ	419	288	350	125	203	2	108	-4	40	94
S_Λ	0	-6	-10	-13	-20	0	-14	0	12	6
S_N	94	192	434	386	652	540	704	841	630	349
T	-2	-9	-6	-15	-43	0	-29	-1	-69	-45
sum	589	625	952	518	858	641	869	864	726	412
Exp	5.58	6.80	8.50	8.89	10.24		11.37	11.69		13.76
MeV		6.84	8.29	9.11						
$\overline{V}$	-0.94	-1.02	-1.06	-1.05	-1.04		-1.05	-0.96		-0.93

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

Improve fit by adding a spin-independent ΛNN term,

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

The lightest, s-shell, Λ hypernuclei

${}^{A}_{\Lambda}$Z	T	$J^{\pi}_{\rm g.s.}$	B_{Λ} (MeV)	$J^{\pi}_{\rm exc.}$	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^+	1.04(5)–1.15(4)
${}^{5}_{\Lambda}$He	0	$1/2^+$	3.12(2)		

- **No Λnn bound state is 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

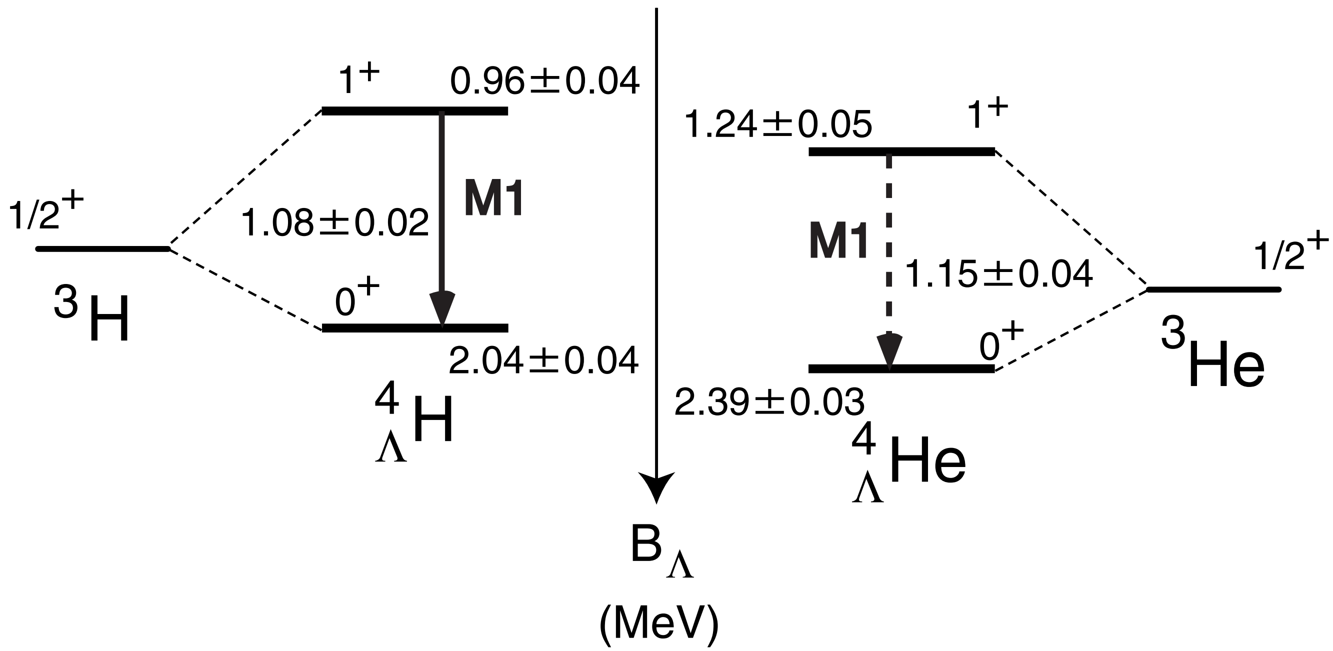
- **A. Nogga, NPA 914 (2013) 140**
  Faddeev & Faddeev-Yakubovsky (chiral LO & NLO).
- **E. Hiyama et al., PRC 89 (2014) 061302(R)**
  Jacobi-coordinates Gaussian basis (Nijmegen soft-core).
- **R. Wirth et al., PRL 113 (2014) 192502.**
  ab-initio no-core (chiral LO).

Is Λnn bound?

- **Neither Λn nor nn are bound.**
- 1st sound calculation resulting in **unbound** ${}^{3}_{\Lambda}$n is due to Downs-Dalitz, PR 114 (1959) 593. However, the HypHI Collaboration, Rappold et al. PRC 88 (2013) 041001(R), argued recently by observing $\pi^{-}+{}^{3}$H weak decay that ${}^{3}_{\Lambda}$n is **bound**.
- **Recent calculations agree on unbound ${}^{3}_{\Lambda}$n:**
  (i) Garcilazo-Valcarce, PRC 89 (2014) 057001
  (ii) Hiyama-Ohnishi-Gibson-Rijken, *ibid* 061302(R)
  (iii) Gal-Garcilazo, PLB 736 (2014) 93
- **A bound ${}^{3}_{\Lambda}$n is incompatible with existing data.**

- **The ΛN interactions required to bind ${}^{3}_{\Lambda}$n are inconsistent with Λp scattering cross sections at low energies, with ${}^{3}_{\Lambda}\mathrm{H}_{\mathrm{g.s.}}$ binding energy, and with the $0^{+}_{\mathrm{g.s.}}$–1^{+}_{exc} excitation energy of the $A = 4$ Λ hypernuclei.**
- **${}^{3}_{\Lambda}\mathrm{H}(\frac{3}{2}^{+})$ becomes g.s. well before ${}^{3}_{\Lambda}$n binds.**
- **The consequences of accepting a bound ${}^{3}_{\Lambda}$n for Λ hypernuclear data are sufficiently strong that the use of more refined interactions is unlikely to modify any of the conclusions reached here.**
- **Could ΛNN interactions bind ${}^{3}_{\Lambda}$n? – unlikely.**
- **Could CSB bind ${}^{3}_{\Lambda}$n? – unlikely.**

The ${}^4_\Lambda$H–${}^4_\Lambda$He mirror hypernuclei



- $\Delta B_\Lambda({}^4_\Lambda\mathrm{He}–{}^4_\Lambda\mathrm{H})$=0.35(5) MeV, a very large charge symmetry breaking (CSB).
- MAMI (Esser et al. arXiv:1501.06823) $B_\Lambda({}^4_\Lambda\mathrm{H})$=2.12±0.01±0.09 MeV, consistent with emulsion's 2.04±0.04 MeV.

$\Lambda - \Sigma$ coupling for ${}^4_\Lambda$H and ${}^4_\Lambda$He

Y. Akaishi et al., PRL 84 (2000) 3539

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

From ΛN$-\Sigma$N g matrix for 0s orbits

$v = \langle s^3 s_\Lambda | g | s^3 s_\Sigma \rangle$, $\Delta E \sim 80$ MeV ${}^3g_{ss} = 4.8$ ${}^1g_{ss} = -1.0$

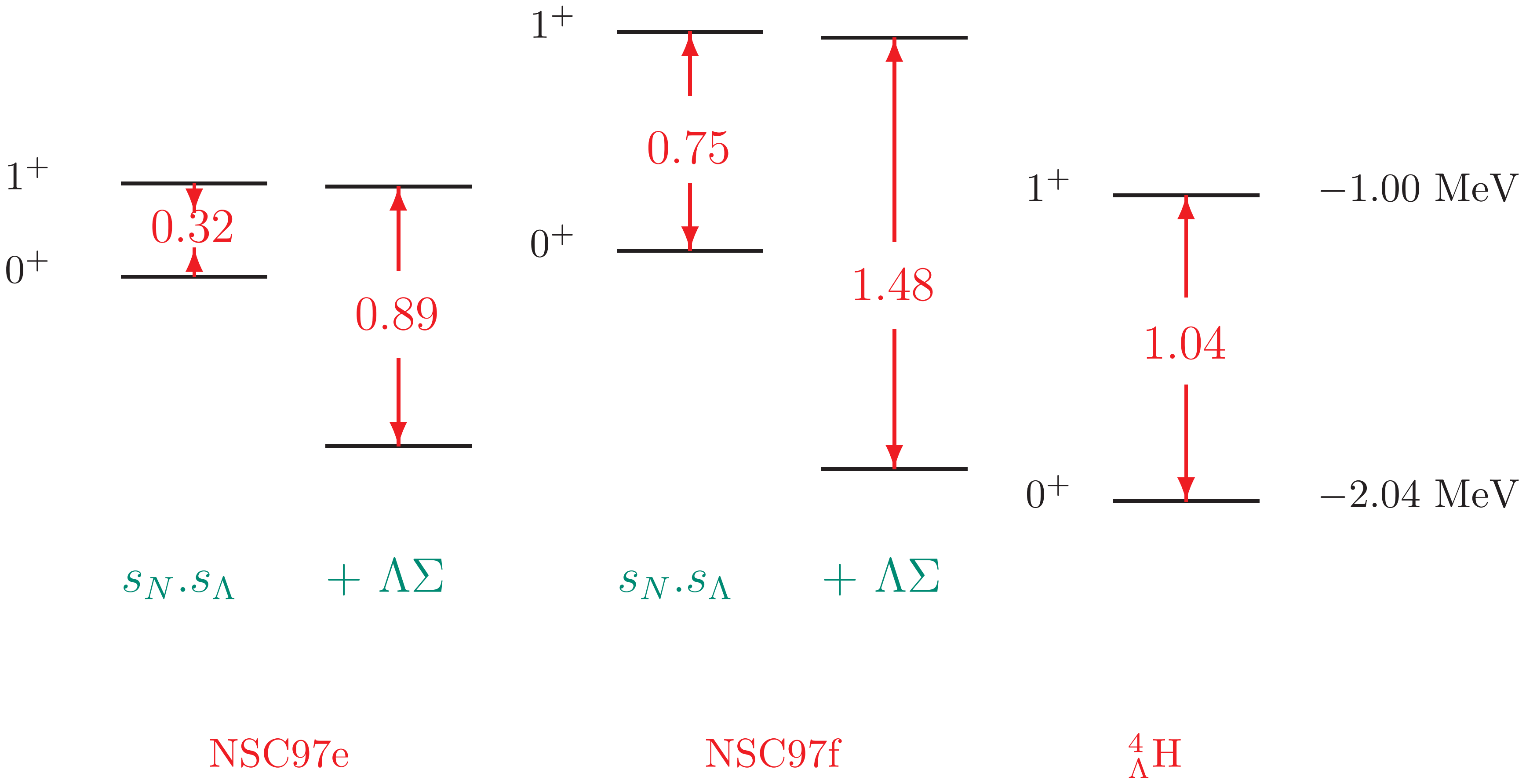
0^+	$v = \frac{3}{2}\,{}^3g_{ss} - \frac{1}{2}\,{}^1g_{ss}$	Admixture $\sim -v/\Delta E$
1^+	$v = \frac{1}{2}\,{}^3g_{ss} + \frac{1}{2}\,{}^1g_{ss}$	$E^{\mathrm{shift}} \sim v^2/\Delta E$

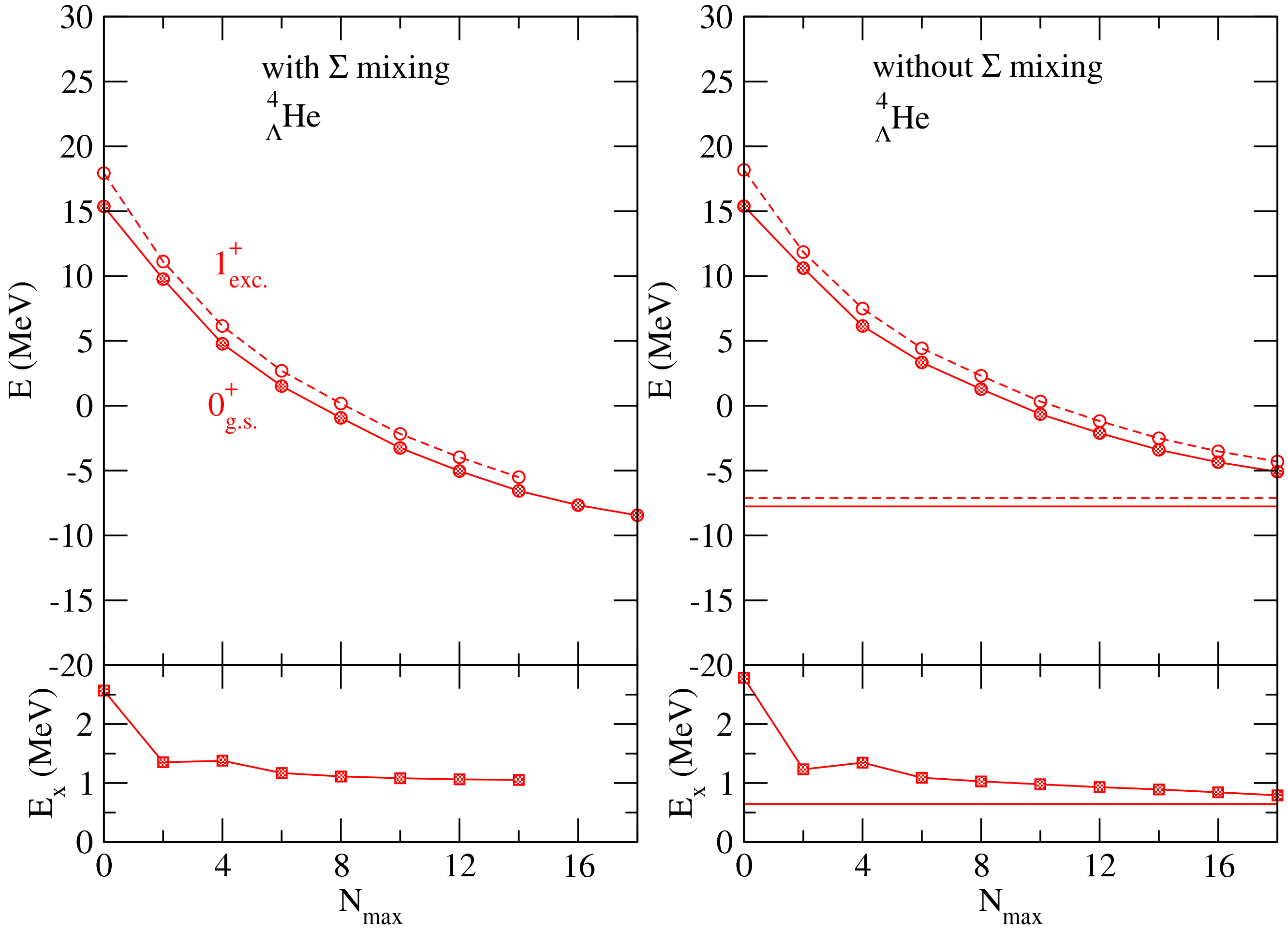
NSC97f: for 0^+ $v \sim 7.6$ MeV $\Rightarrow$ $E^{\mathrm{shift}} \sim 0.72$ MeV

comparable to genuine ΛN splitting $\Delta_s = 0.75$ MeV

(s-shell ΛN interaction: $\bar{V}_s + \Delta_s s_N . s_\Lambda$)

$\Lambda - \Sigma$ Nijmegen model dependence





LO chiral potentials, private communication Daniel Gazda, from joint work by R. Wirth et al., PRL 113 (2014) 192502.

$\Lambda - \Sigma$ Coherent Coupling

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

- $\Lambda\Sigma$ coupling: $\sqrt{4/3}\ (\ t_N \cdot t_Y\ \overline{V}' + \ s_N \cdot s_Y\ t_N \cdot t_Y\ \Delta'\ )$
  ($\sqrt{4/3}$ arises from t_Y changing Λ to Σ) **leading to Fermi & Gamow-Teller (GT) nuclear 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,**

  for example in models NSC97e(f):

$$\bar{V}_{\Lambda\Sigma} = 2.96\ (3.35), \quad \Delta_{\Lambda\Sigma} = 5.09\ (5.76)\ \text{MeV}.$$

CSB calculations for ${}^4_\Lambda$He–${}^4_\Lambda$H

${}^4_\Lambda$He–${}^4_\Lambda$H keV	$P_\Sigma(\%)$ $0^+_{\rm g.s.}$	ΔT_{YN} $0^+_{\rm g.s.}$	ΔV_C $0^+_{\rm g.s.}$	ΔV_{YN} $0^+_{\rm g.s.}$	ΔB_Λ $0^+_{\rm g.s.}$	ΔB_Λ $1^+_{\rm exc}$
ΛNNN	–	–	−42	91	49	−61
NSC97$_{\rm e}$	1.6	47	−16	44	75	−10
NSC97$_{\rm f}$	1.8				100	−10
NLO chiral	2.1	55	−9	–	46	
$(\Lambda\Sigma)_{\rm e}$	0.72	39	−45	232	226	30
$(\Lambda\Sigma)_{\rm f}$	0.92	49	−46	263	266	39

S.Coon,H.Han,J.Carlson,B.Gibson, arXiv:nucl-th/9903034.

A.Nogga, NPA 914 (2013) 140, and refs. to earlier work.

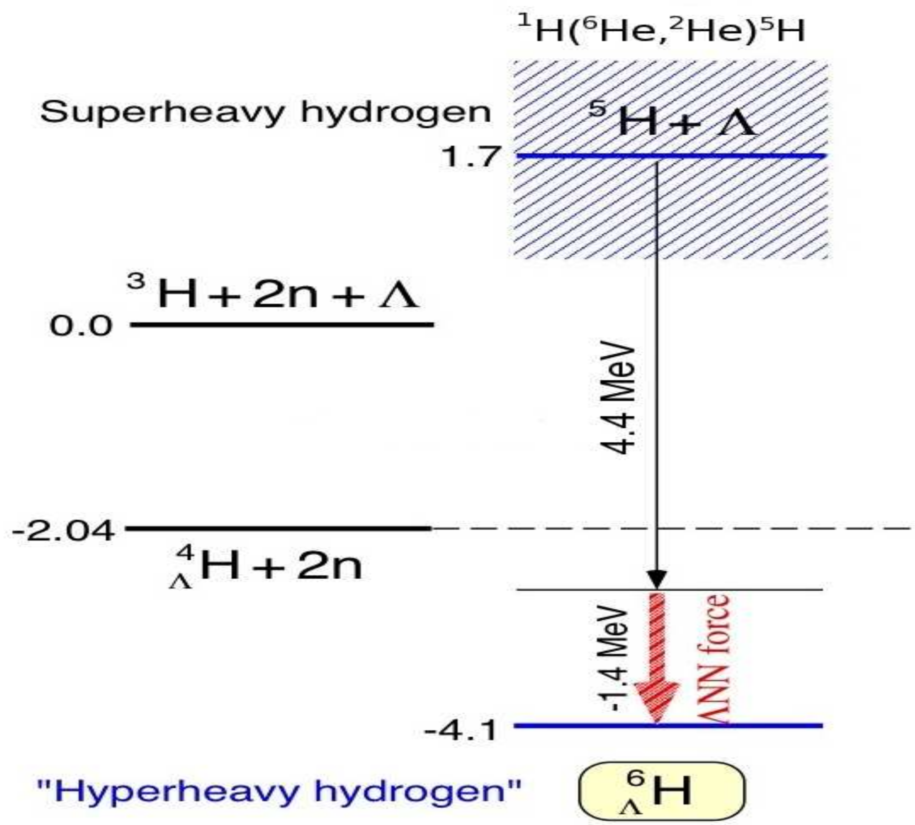
A.Gal, PLB 744 (2015) 352.

$\Lambda\Sigma^0$ **mixing:** $g_{\Lambda\Lambda\pi} = -2\,\frac{\langle\Sigma^0|\delta M|\Lambda\rangle}{M_{\Sigma^0}-M_\Lambda} g_{\Lambda\Sigma\pi} = -0.0297 g_{\Lambda\Sigma\pi}$

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

Adding neutrons: n-rich ${}^{6}_{\Lambda}$H

Y. Akaishi, Frascati Phys. Ser. XVI (1999) 59



$\Lambda - \Sigma$ coupling, resulting in "ΛNN force", lowers $0^{+}_{\rm g.s.}$ by 1.4 MeV and increases $\Delta E(0^{+}_{\rm g.s.} - 1^{+})$ from 1 MeV in ${}^{4}_{\Lambda}$H to 2.4 MeV in ${}^{6}_{\Lambda}$H

- If Akaishi is right, far-reaching consequences could follow for dense neutron-rich strange stellar matter.
- ${}^{6}_{\Lambda}$H was predicted by Dalitz & Levi Setti, NC 30 (1963) 489: $B_\Lambda^{\rm Dalitz}({}^{6}_{\Lambda}{\rm H})$=**4.2 MeV.**
Akaishi (1999) predicted $B_\Lambda^{\rm Akaishi}({}^{6}_{\Lambda}{\rm H})$=**5.8 MeV.**
- FINUDA found three ${}^{6}_{\Lambda}$H events in ${}^{6}{\rm Li}(K^-_{\rm stop}, \pi^+)$
Production rate: $R(\pi^+) = (5.9 \pm 4.0) \cdot 10^{-6}/K^-_{\rm stop}$
[PRL 108 (2012) 042501, NPA 881 (2012) 269].
$B_\Lambda({}^{6}_{\Lambda}{\rm H})$=**(4.0±1.1) MeV vs (3.9±0.1) MeV calc. by Gal-Millener, PLB 725 (2013) 445.**
- **E. Hiyama et al., tnnΛ calc.: unbound, NPA 908 (2013) 29.**
- **${}^{6}_{\Lambda}$H not seen in ^{6}Li(π^-, K^+), J-PARC E10.**

Coincident ${}^{6}_{\Lambda}\mathrm{H}$ production & decay

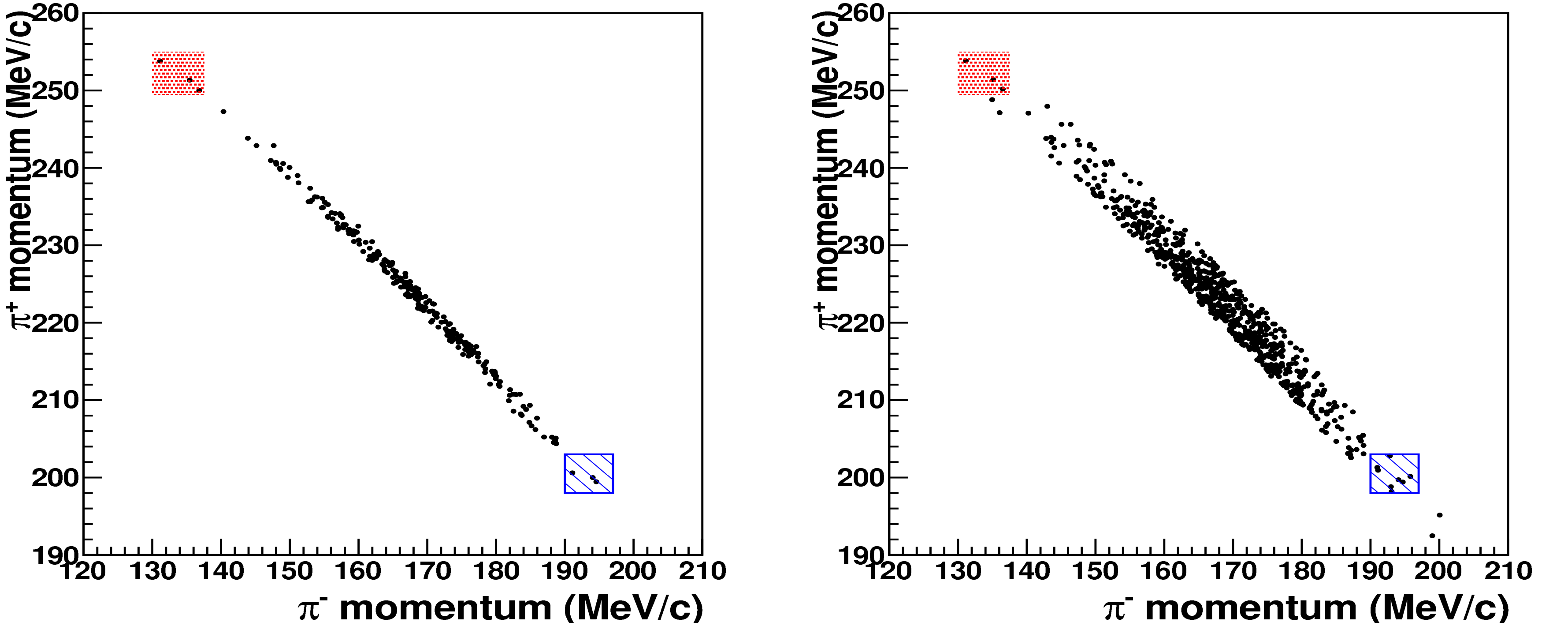
$$K^-_{\rm stop} + {}^{6}\mathrm{Li} \;\rightarrow\; {}^{6}_{\Lambda}\mathrm{H} + \pi^+ \quad (\sim 250 < p_{\pi^+} < 255 \ \mathrm{MeV/c})$$
$$\hookrightarrow {}^{6}\mathrm{He} + \pi^- \quad (\sim 130 < p_{\pi^-} < 137 \ \mathrm{MeV/c})$$

$$T(\pi^+) + T(\pi^-) \;= M(K^-) + M(p) - M(n) - 2M(\pi)$$
$$-B({}^{6}\mathrm{Li}) + B({}^{6}\mathrm{He}) - T({}^{6}\mathrm{He}) - T({}^{6}_{\Lambda}\mathrm{H})$$

- **Recoil uncertainty is 0.2 MeV for 6 MeV B interval**
- **Pions kinetic energy uncertainty is 1.3 MeV**
- **Altogether T(π^+) + T(π^-) = 203±1.3 MeV**
- **Three ${}^{6}_{\Lambda}\mathrm{H}$ candidate events out of 2.7$\cdot$ 10^7 $K^-_{\rm stop}$**

FINUDA+Gal (2012): PRL 108, 042501; NPA 881, 269.

p_{π^+} vs p_{π^-} in $K^-_{\rm stop}$ on ^{6}Li for given $T(\pi^+) + T(\pi^-)$ cuts



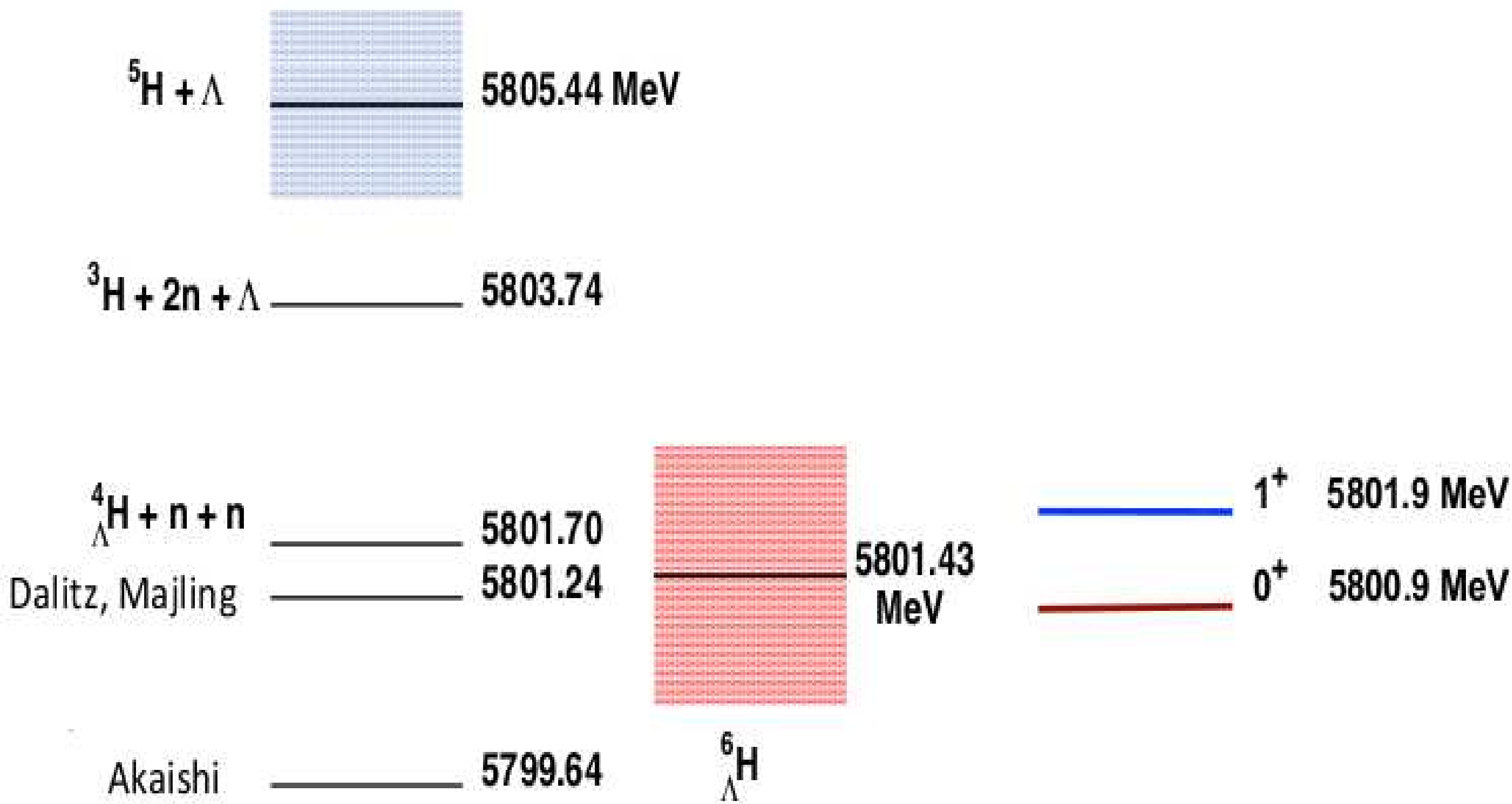
$T(\pi^+)+T(\pi^-)$=202–204 MeV (l.h.s.)   200–206 MeV (r.h.s.)

Red rectangles: p_{π^+}=250–255, p_{π^-}=130–137 MeV/c.

The 3 events in red are stable against $T(\pi^+)+T(\pi^-)$ cuts.

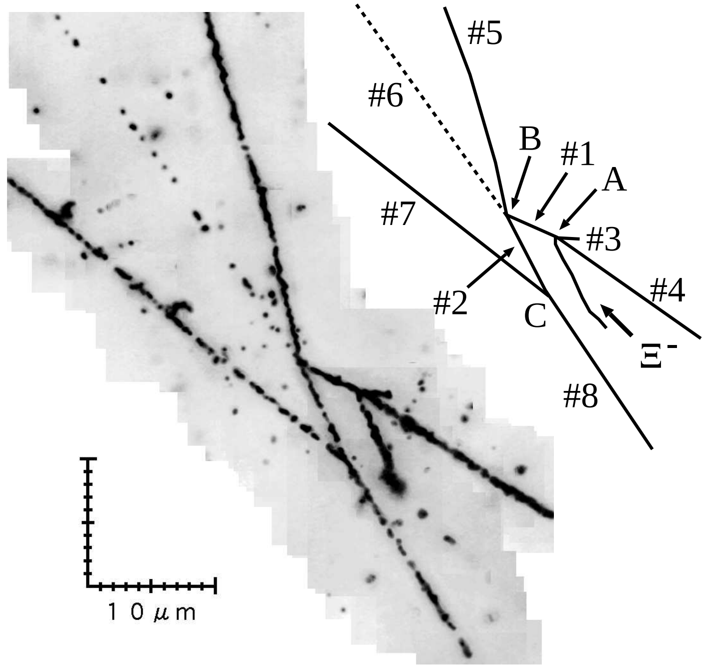
$B_\Lambda(^6_\Lambda\mathrm{H})$ constrains $\Lambda N \leftrightarrow \Sigma N$ effects in neutron-rich $^A_\Lambda Z$.

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



Note: $\Delta E(0^+_{\rm g.s.} - 1^+) = 1.0 \pm 0.7$ **MeV** (2σ **away from Akaishi)**

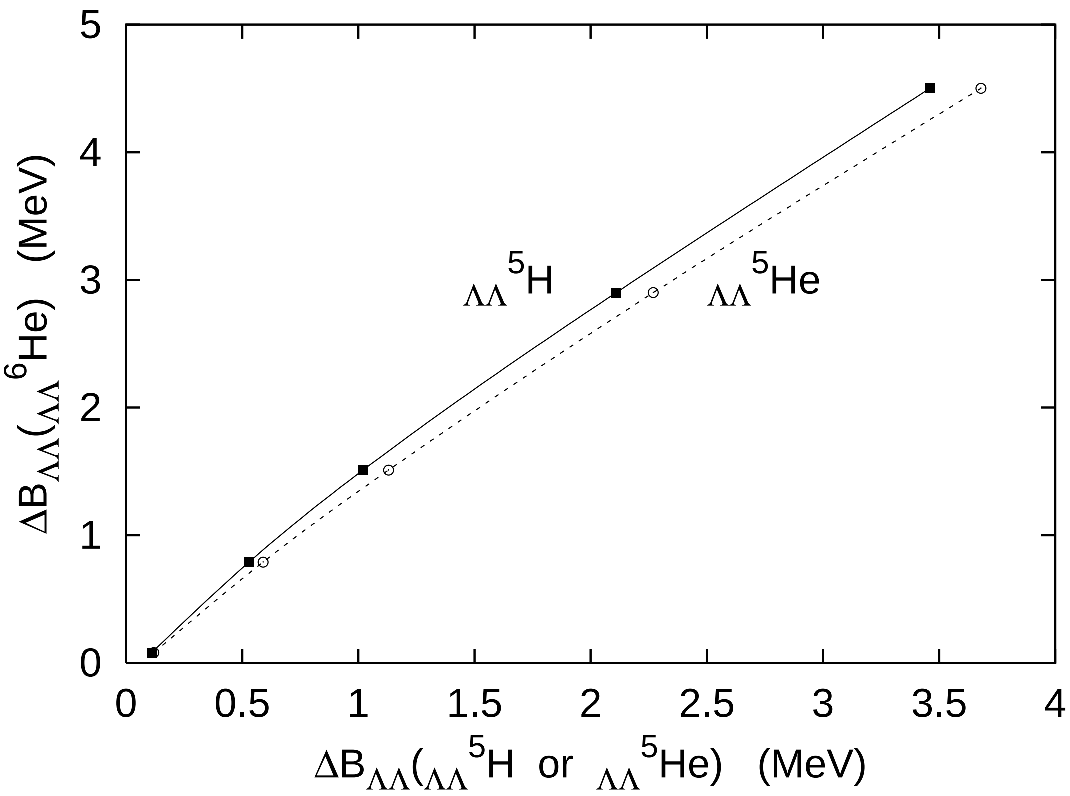
$\Lambda\Lambda$ hypernuclei



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

$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\mathrm{He}_{\mathrm{g.s.}}) = 6.91 \pm 0.16$ **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: nonmesonic weak decay of ${}_{\Lambda}^{5}\mathrm{He}$ to two $Z = 1$ recoils & neutron



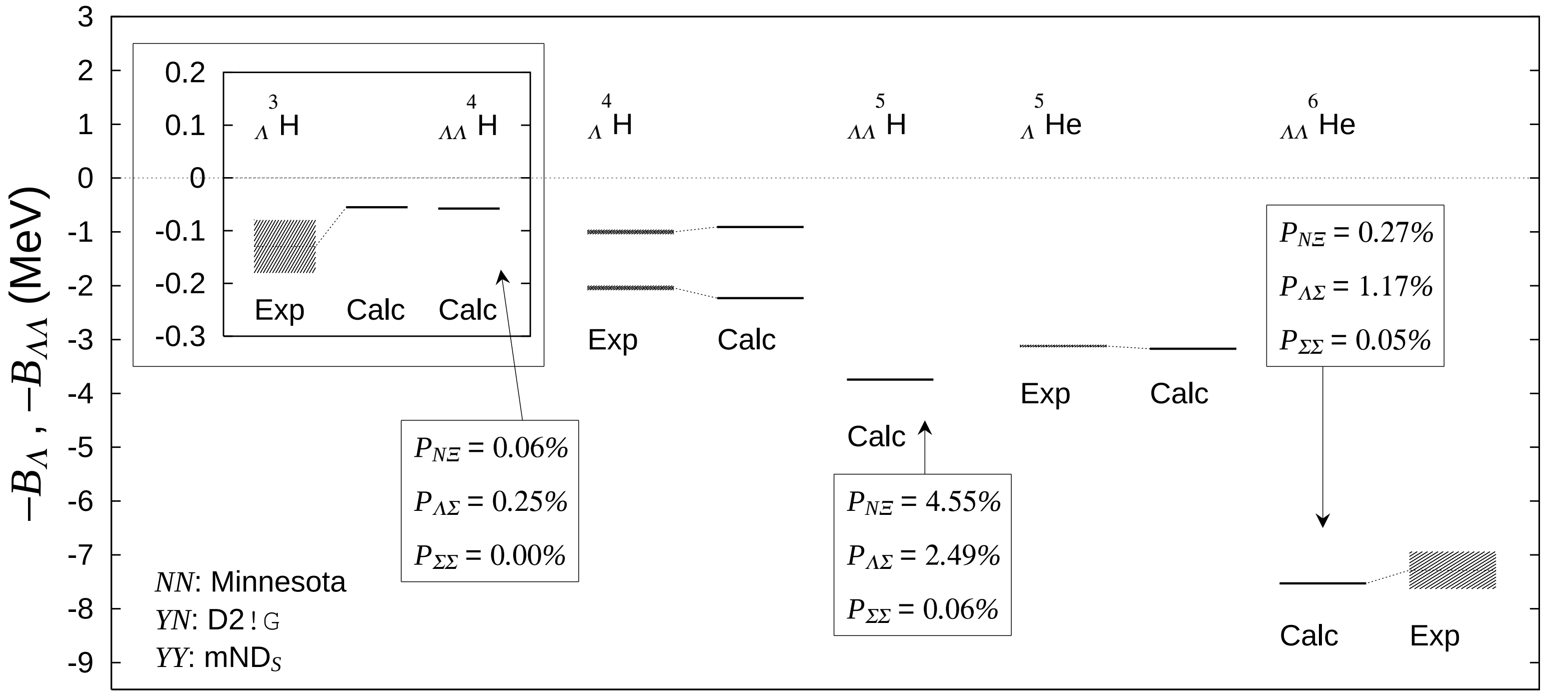
I.N. Filikhin, A. Gal, Nucl. Phys. A **707** (2002) 491

s-wave Faddeev calculations of $\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\text{He})$ vs. $\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{5}\text{H},\ {}_{\Lambda\Lambda}^{5}\text{He})$

$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\text{He}) \equiv \text{B}_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\text{He}) - 2\text{B}_{\Lambda}({}_{\Lambda}^{5}\text{He})$

$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\text{He}) \approx 1$ MeV implies that ${}_{\Lambda\Lambda}^{5}$H & ${}_{\Lambda\Lambda}^{5}$He are also bound

${}_{\Lambda\Lambda}^{5}$H & ${}_{\Lambda\Lambda}^{5}$He may mark the onset of $\Lambda\Lambda$ binding



H. Nemura, S. Shinmura, Y. Akaishi, K.S. Myint, PRL **94** (2005) 202502

Calculated Λ & $\Lambda\Lambda$ separation energies of s-shell hypernuclei

$\Lambda N - \Sigma N$ and $\Lambda\Lambda - \Xi N$ mixings are important

$^{6}_{\Lambda\Lambda}$He: the only uniquely determined $\Lambda\Lambda$ hypernucleus

$^{4}_{\Lambda\Lambda}$H unlikely bound [Filikhin-Gal, PRL 89 (2002) 172502]

Binding energy consistency of ΛΛ hypernuclei

event	${}^{A}_{\Lambda\Lambda}Z$	$B^{exp}_{\Lambda\Lambda}$	$B^{CM}_{\Lambda\Lambda}$ †	$B^{SM}_{\Lambda\Lambda}$ ††
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 production in ${}^{10}_{\Lambda\Lambda}$Be 1st excited state 2^+(3.04 MeV)

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

- Hida-event [PTPS **185** (2010) 335] offers no clue
- $B^{SM}_{\Lambda\Lambda} \approx B^{CM}_{\Lambda\Lambda}$, but SM spans a wider A range

$\Lambda\Lambda$ conclusions

- Relatively weak $\Lambda\Lambda$ interaction
  $< V_{\Lambda\Lambda} > \approx 0.6$ MeV, $|a_{\Lambda\Lambda}| < 1$ fm
- Onset of $\Lambda\Lambda$ binding likely with ${}^{5}_{\Lambda\Lambda}$H & ${}^{5}_{\Lambda\Lambda}$He
- Shell model works well beyond ${}^{6}_{\Lambda\Lambda}$He
- No sound SM or CM interpretation for Hida event
- Need more data for systematics and for studying possible continuum effects from H dibaryon
- J-PARC E07: $\mathcal{S} = -2$ emulsion-counter studies
- J-PARC E42: search for H dibaryon in (K^-, K^+)
- FAIR (PANDA): slowing down Ξ^- from $\bar{p}p \to \Xi^-\bar{\Xi}^+$

The elusive H dibaryon

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

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

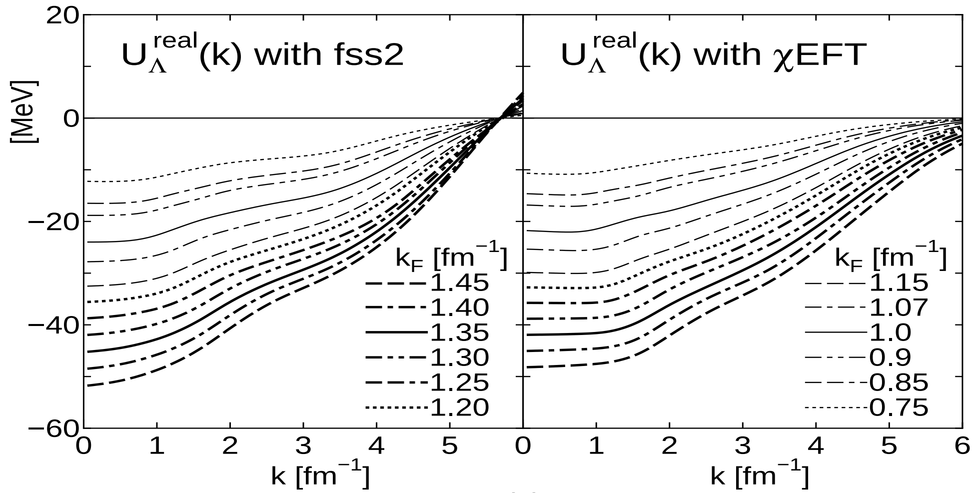
- **To forbid $^{6}_{\Lambda\Lambda}$He$\rightarrow$H$+^{4}$He, impose B(H)$\leq$7 MeV. A bound H most likely overbinds $^{6}_{\Lambda\Lambda}$He** **[Gal, PRL 110 (2013) 179201].**

- **Weakly bound H in Lattice QCD calculations. SU(3)$_{\rm f}$ breaking pushes it to $\approx N\Xi$ threshold, $\approx$26 MeV in $\Lambda\Lambda$ continuum** **[HALQCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].**

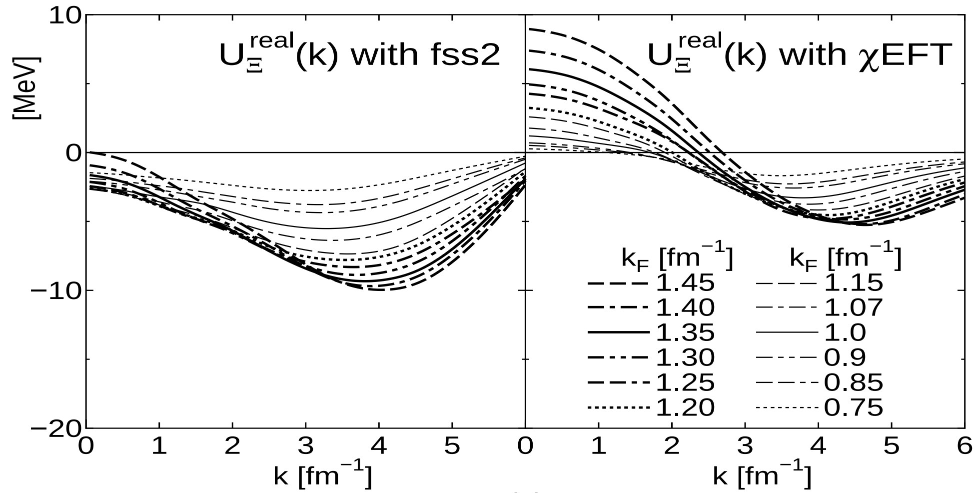
- **Experimental searches also rule out a bound H. J-PARC E42 will search for H in (K^-,K^+).**

Hyperons in nuclear matter

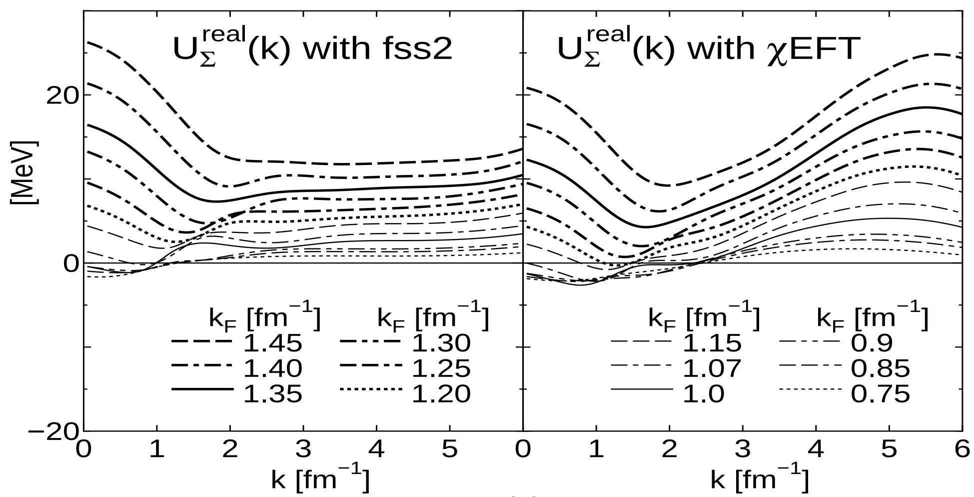
and $S = -3, -4$ systems



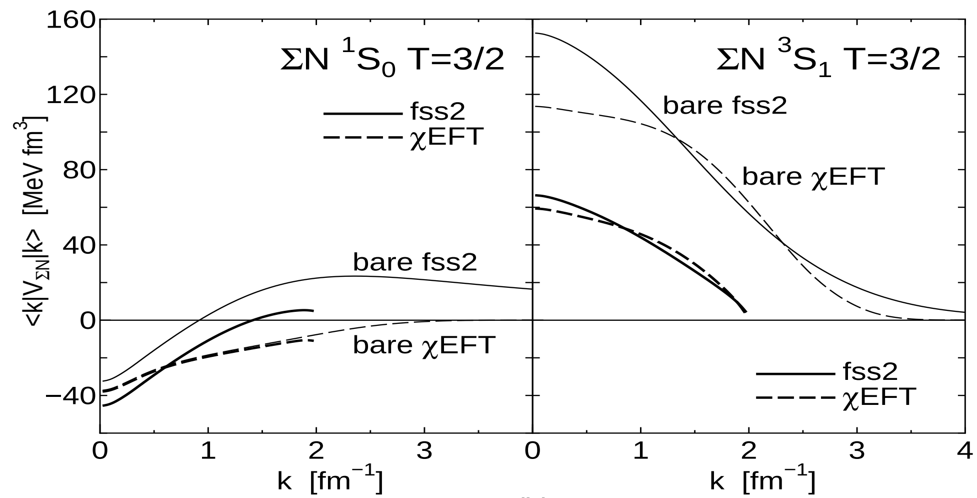
(a)



(a)



(a)



(b)

Kohno, PRC **81** (2010) 014003 Nuclear matter hyperon s.p. potentials

QM fss2 Fujiwara et al. (2007) χ EFT (LO) Polinder et al. (2007)

$\mathcal{S} = -2, -3, -4$ deuteron-like $L = 0$ dibaryon candidates

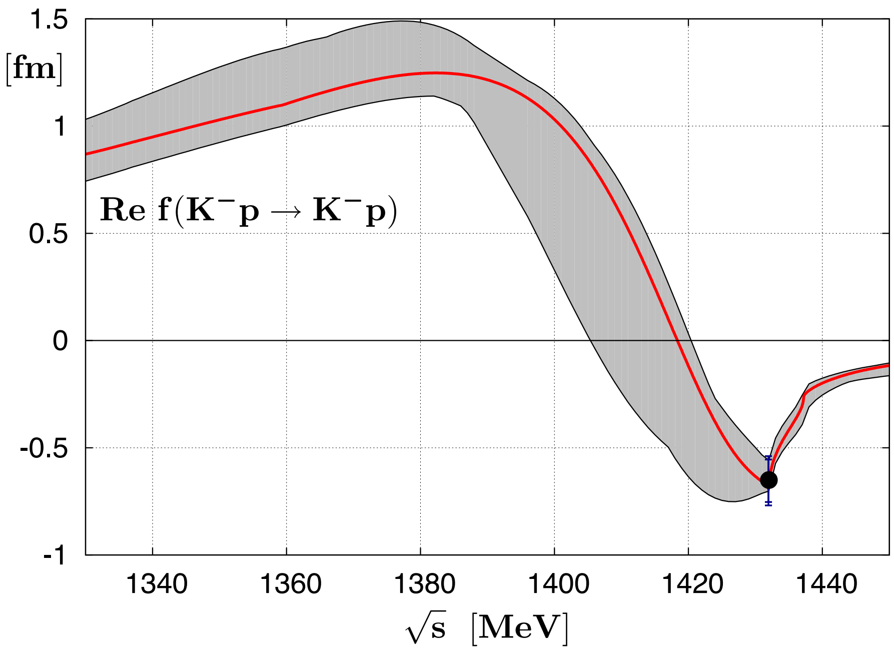
	$\Sigma\Sigma$ $(I = 2, {}^1S_0)$	$\Lambda\Xi$ $(I = \frac{1}{2}, {}^1S_0)$	$\Sigma\Xi$ $(I = \frac{3}{2}, {}^1S_0)$	$\Sigma\Xi$ $(I = \frac{3}{2}, {}^3S_1)$	$\Xi\Xi$ $(I = 1, {}^1S_0)$
NSC97	+	−	+	+	+
EFT (LO)	−	+	+	−	+
EFT (NLO)	−	−	−	−	−

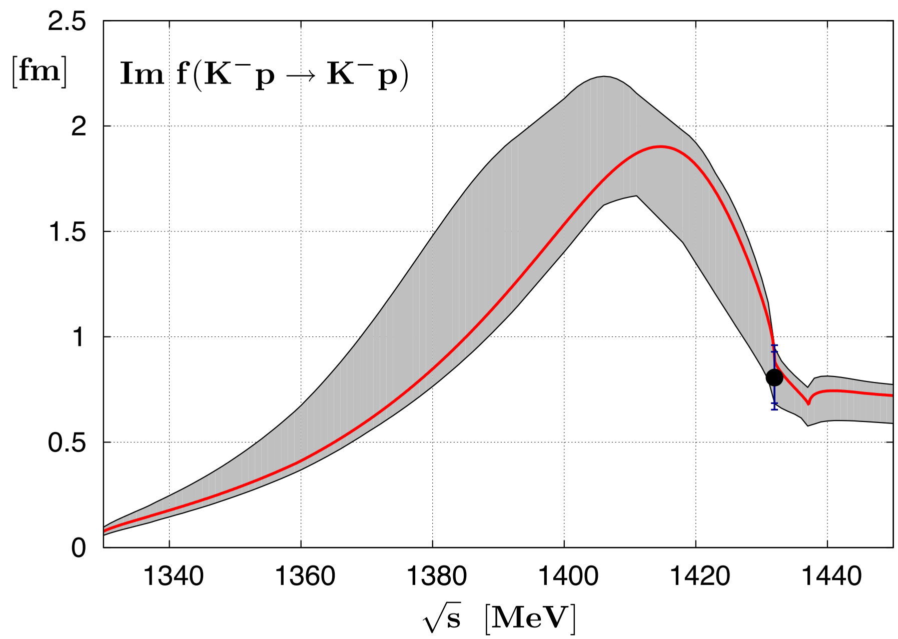
NSC97: V.G.J. Stoks, T.A. Rijken, Phys. Rev. C **59** (1999) 3009
EFT (LO): J. Haidenbauer, U.-G. Meißner, Phys. Lett. B **684** (2010) 275
EFT (NLO): JH, UGM, S. Petschauer, Eur. Phys. J. A **51** (2015) 17

- Systematics of EFT (LO): The $\mathcal{S} = -3, -4$ sectors require only the 5 LECs determined in the YN sector fit, independently of the 6th LEC required in the $\mathcal{S} = -2$ sector (this LEC is consistent with zero). Hence get PREDICTIONS.
- ${}^1S_0$ in $\mathrm{SU(3)_f}$ **27** (as nn), ${}^3S_1$ in $\mathrm{SU(3)_f}$ $\overline{\mathbf{10}}$ (as deuteron).
- Model dependence is assessed by varying a cutoff momentum in the range 550 – 700 MeV/c. **SU(3) breaking aborts binding at NLO.**
- **HALQCD Collab. predicts $N\Omega$ 2^+ bound state [NPA 928 (2014) 89].**

Kaons in nuclei

K^-p scattering amplitude from NLO chiral SU(3) dynamics





Y. Ikeda, T. Hyodo, W. Weise (IHW), PLB **706** (2011) 63; NPA **881** (2012) 98

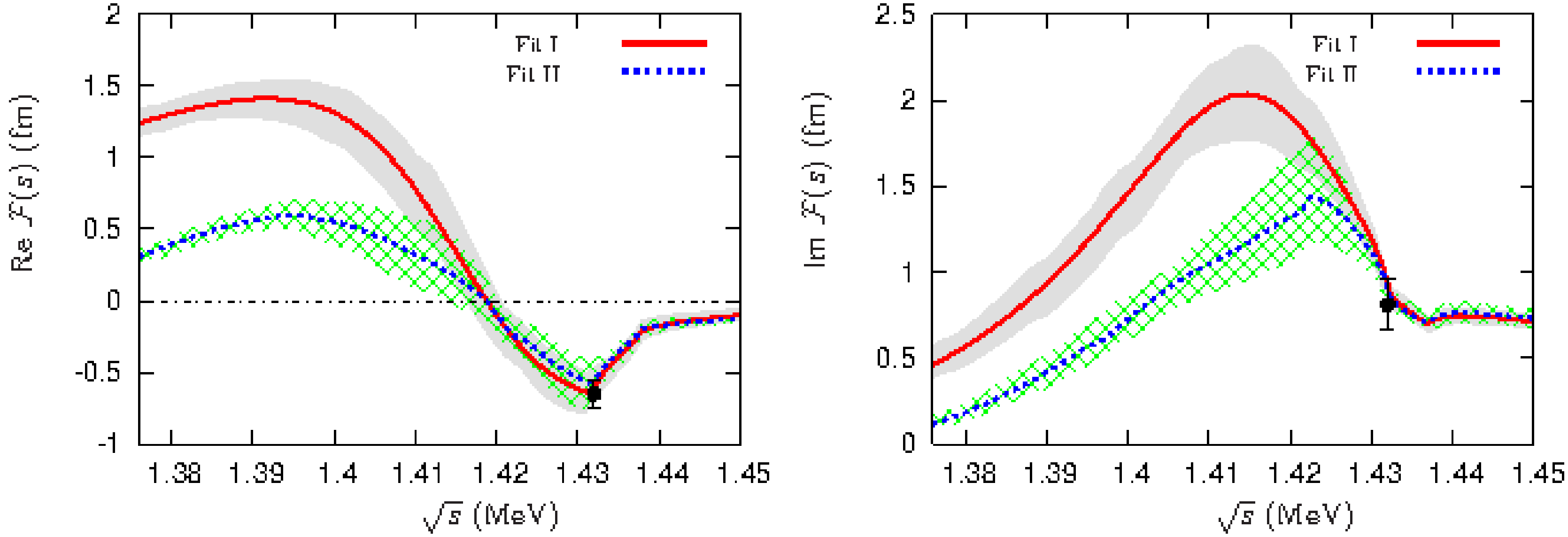
Threshold f(K^-p) given by SIDDHARTA K^-H experiment

PLB 704 (2011) 113, NPA 881 (2012) 88. Need f(K^-n)→ do K^-d.

Strong subthreshold K^-p attraction; $\Lambda(1405)$ physics;

consequences for kaonic atoms & nuclear clusters.

K^-p subthreshold ambiguity



Two NLO chiral-model fits by Guo-Oller, PRC 87 (2013) 035202

- **Fit I: meson-independent $f = 125.7 \pm 1.1$ MeV.**
- **Fit II: physical values for f_π, f_K, f_η.**
  Will create problems when confronted with K^--atom data.
- **Amplitudes constrained at threshold by SIDDHARTA.**
  $\bar{K}N$ pole robust, $\pi\Sigma$ pole correlated with fit.

K^-pp calculated binding energies & widths

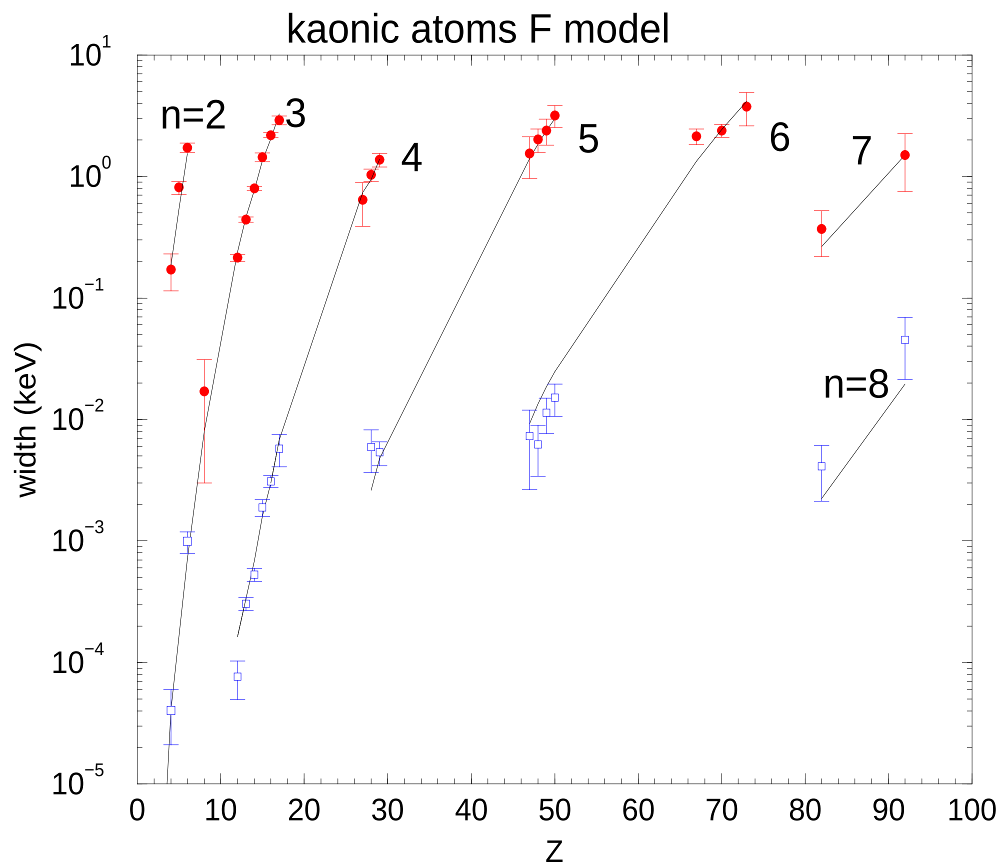
(MeV)	chiral, energy dep. calculations				non-chiral, static calculations			
	var. [1]	var. [2]	Fad. [3]	Fad. [4]	var. [5]	Fad. [6]	Fad. [7]	var. [8]
B	16	17–23	9–16	32	48	50–70	60–95	40–80
Γ	41	40–70	34–46	49	61	90–110	45–80	40–85

Robust binding & large widths; chiral models give weak binding.

Searches at Frascati, GSI, J-PARC are inconclusive.

1. N. Barnea, A. Gal, E.Z. Liverts, PLB **712** (2012)
2. A. Doté, T. Hyodo, W. Weise, NPA **804** (2008) 197, PRC **79** (2009) 014003
3. Y. Ikeda, H. Kamano, T. Sato, PTP **124** (2010) 533
4. J Revai, N.V. Shevchenko, PRC **90** (2014) 034004
5. T. Yamazaki, Y. Akaishi, PLB **535** (2002) 70
6. N.V. Shevchenko, A. Gal, J. Mareš, PRL **98** (2007) 082301
7. Y. Ikeda, T. Sato, PRC **76** (2007) 035203, PRC **79** (2009) 035201
8. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including p waves)

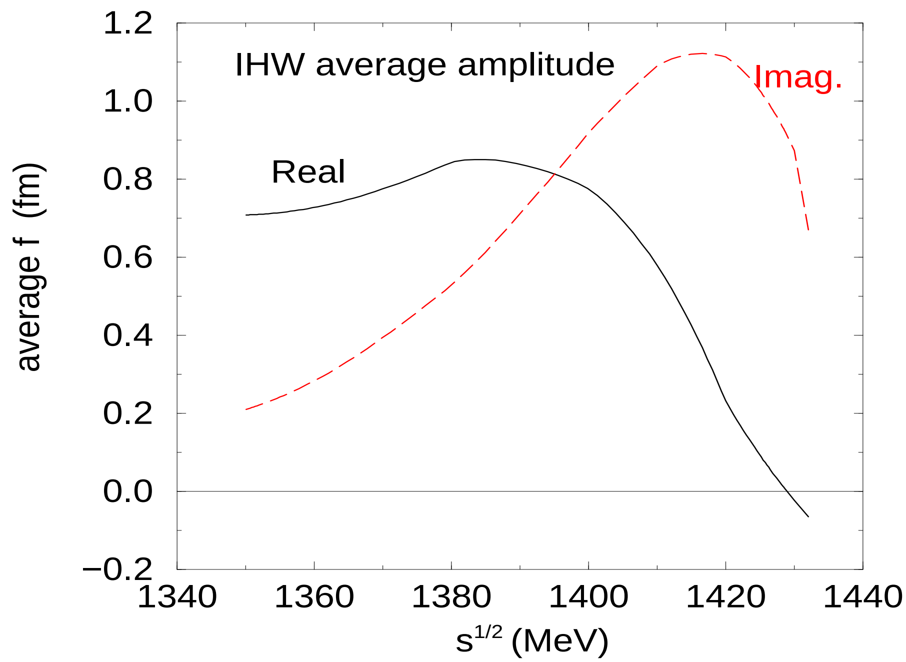
What do K^- atoms tell us?

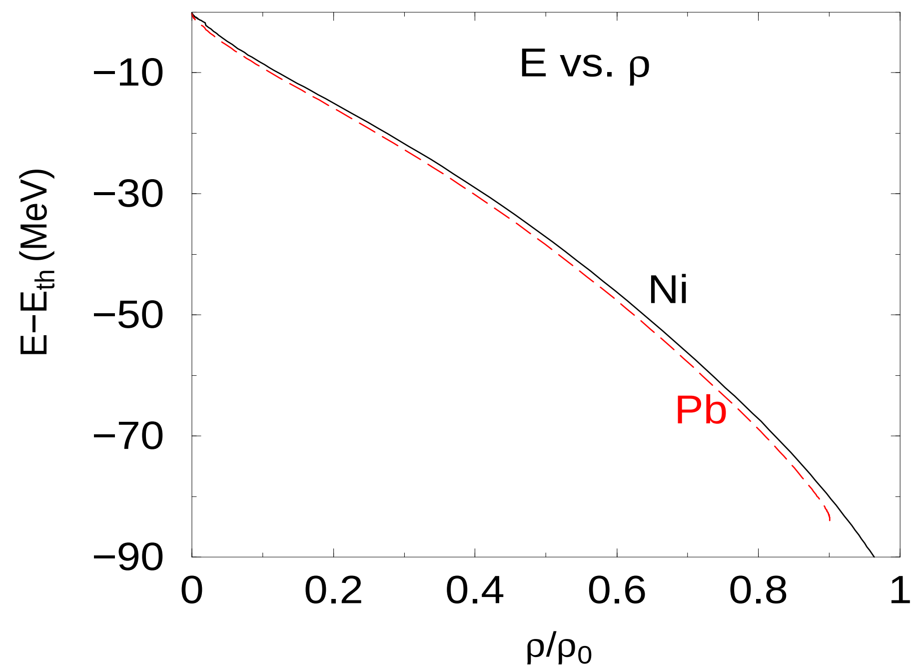


$K^-_{\rm atom}$ widths across the periodic table in model F (deep pot.)

Lowest χ^2 phenom. model, $\chi^2 = 84$ per 65 data points,

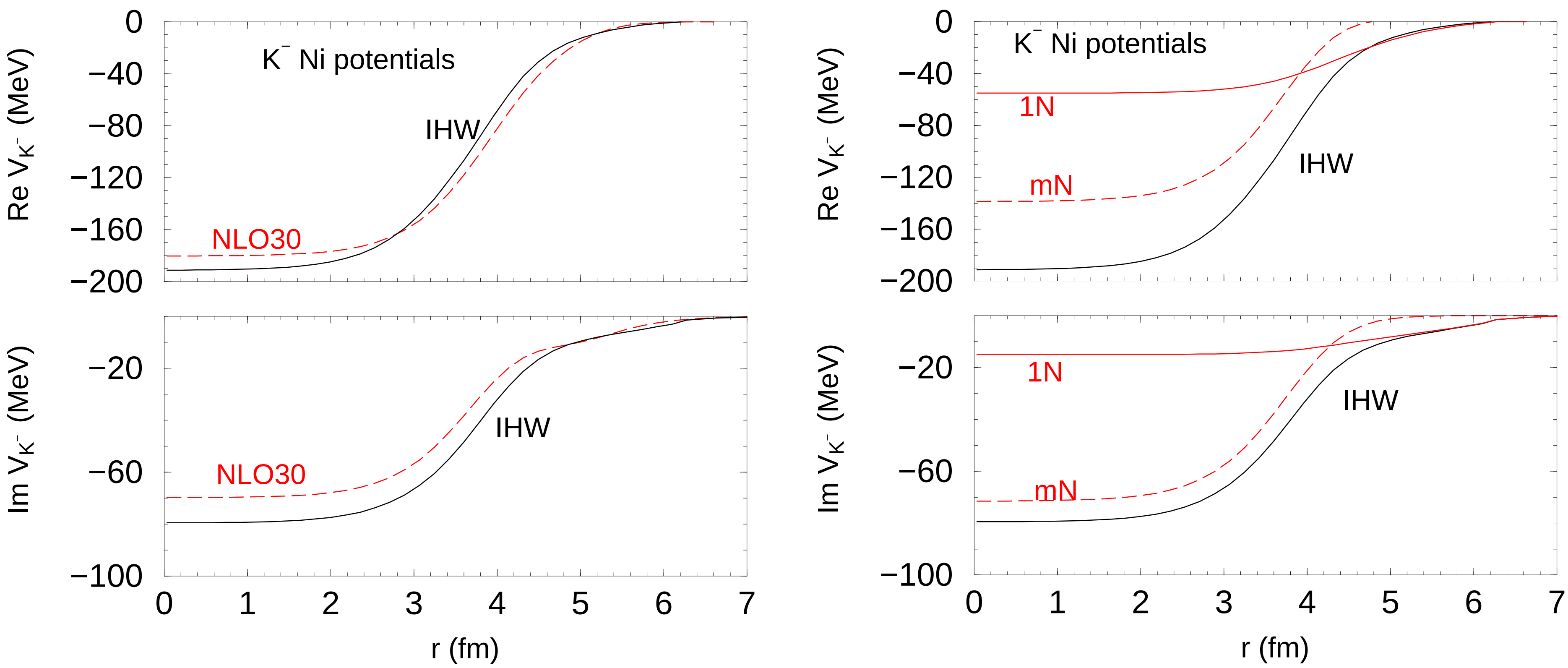
E. Friedman, A. Gal, Phys. Rep. 452 (2007) 89.





Left: IHW f_{K^-N} input   Right: $(E - E_{\rm th})$ *vs* nuclear density output

- Subthreshold energy shift applied self consistently to in-medium 1N IHW amplitude plus (2+...)N phenomenological amplitude.
- Multiple-scattering inclusion of in-medium correlations.
- **Best-fit $\chi^2/\mathrm{N}^{\rm atom}_{\rm data}$=118/65**   **Friedman-Gal, NPA 899 (2013) 60.**



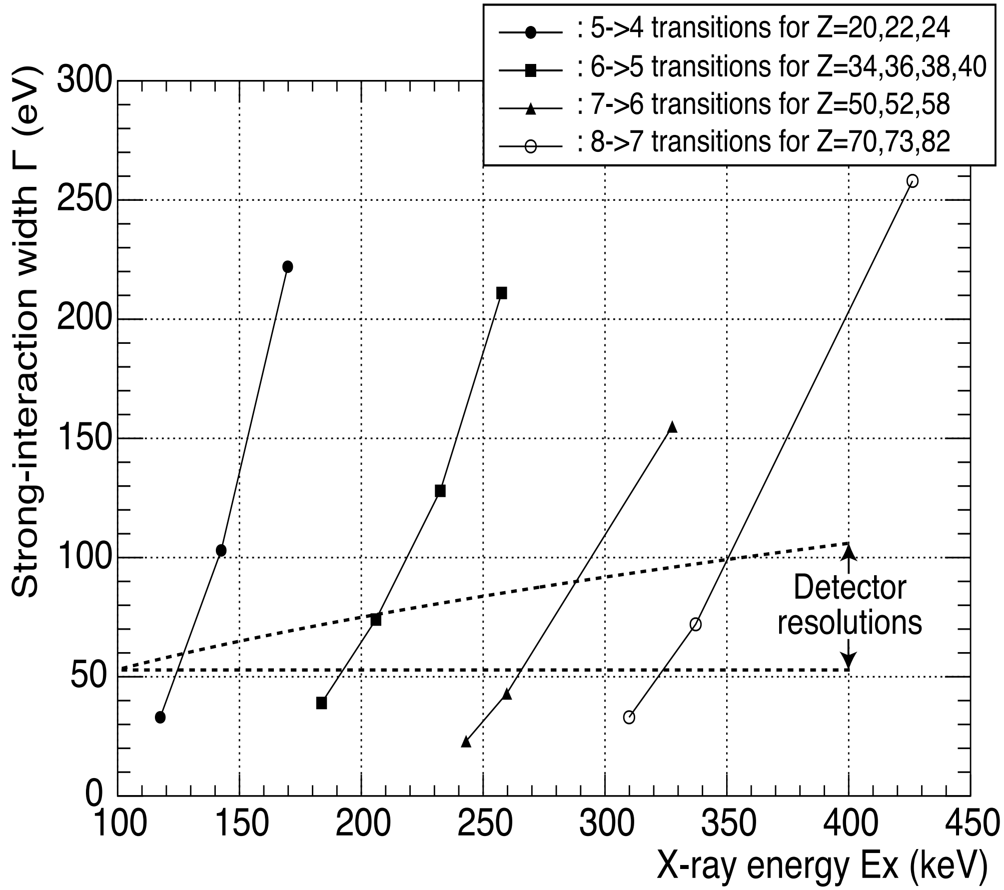
NLO30: A. Cieply, J. Smejkal, NPA **881** (2012) 115 (in-medium).

IHW: Y. Ikeda, T. Hyodo, W. Weise, NPA **881** (2012) 98.

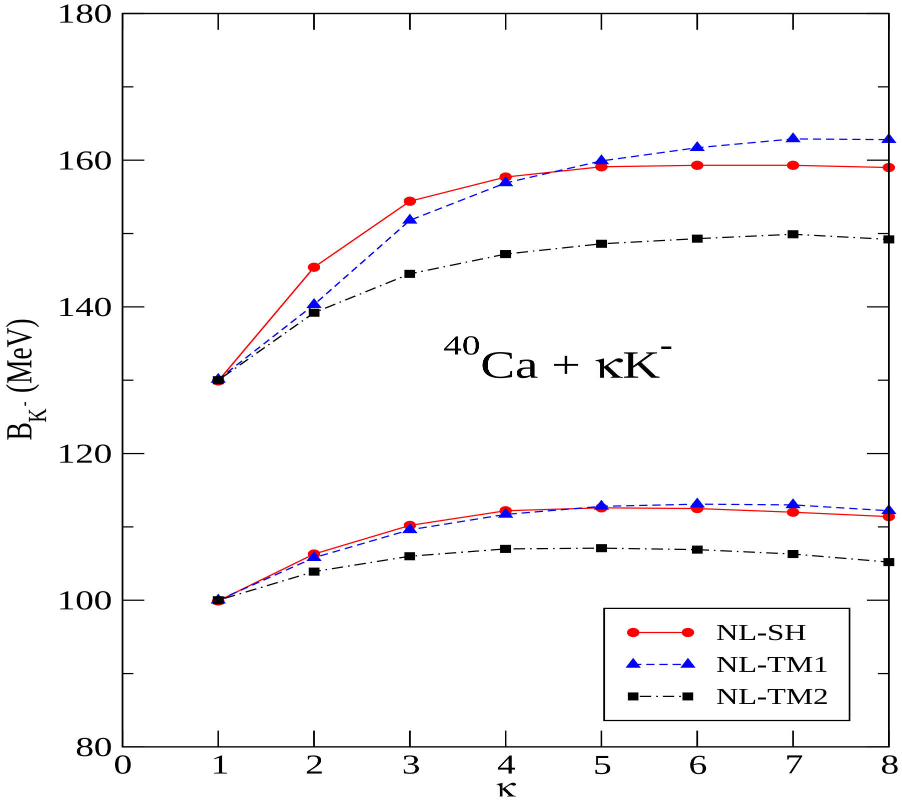
Kaonic-atom best-fit V_{K^-} for Ni & its non-additive breakdown into in-medium 1N and phenomenological m(any)N contributions.

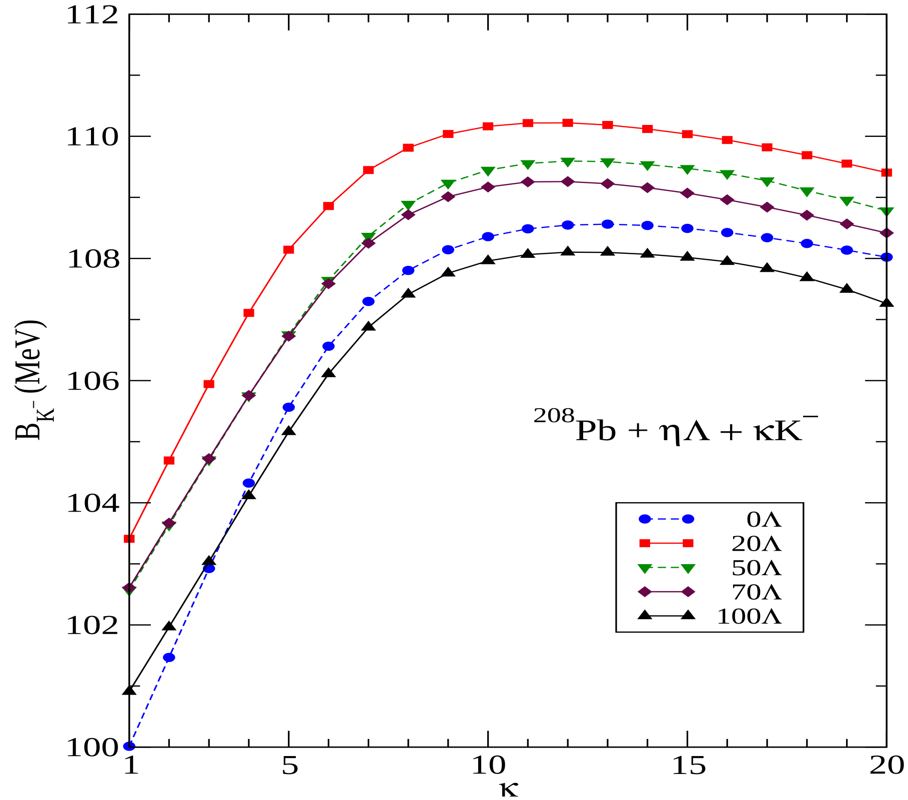
Upper level sensitive to 1N & lower level to mN terms. Measure both selectively [Friedman-Okada, NPA 915 (2013) 170].

Targets for K^- atom measurements



For these targets, both upper-level and lower-level can be studied simultaneously owing to a ≈50 eV resolution of new microcalorimeter detectors.





Gazda-Friedman-Gal-Mareš: PRC **77** (2008) 045206, **80** (2009) 035205

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for multi-K^- nuclei & hypernuclei.

Vector-meson repulsion among $\bar{K}$ mesons. $\bar{K}$ **mesons do not replace hyperons in self-bound strange matter.**

Summary & Outlook

- ΛN hypernuclear spin dependence deciphered.
- How small is Λ spin-orbit splitting and why?
- Role of 3-body ΛNN interactions?
- Confirm ${}^{6}_{\Lambda}$H & search for other n-rich ${}^{A}_{\Lambda}$Z.
- Re-measure the ${}^{4}_{\Lambda}$H–${}^{4}_{\Lambda}$He complex.
- Repulsive Σ-nuclear interaction; how repulsive?
- Onset of $\Lambda\Lambda$ binding: ${}_{\Lambda\Lambda}{}^{4}\mathrm{H}$ or ${}_{\Lambda\Lambda}{}^{5}\mathrm{H}$ & ${}_{\Lambda\Lambda}{}^{5}\mathrm{He}$?
- Do Ξ hyperons quasi-bind in nuclei ($\Xi N \to \Lambda\Lambda$)?
  No quasibound Ξ firmly established yet.
- Onset of Ξ stability: ${}_{\Lambda\Xi}{}^{6}\mathrm{He}$ or ${}_{\Lambda\Lambda\Xi}{}^{7}\mathrm{He}$?

- **Search for K^-pp $[\Lambda^* N(I = \frac{1}{2}, J^\pi = 0^-)]$.**
- **Is there $\Sigma^* N(I = \frac{3}{2}, J^\pi = 2^+)$ strange dibaryon?**
- **No $\bar{K}$ condensation in self-bound matter.**
  $\{N, \Lambda, \Xi\}$ provides Strange-Hadronic-Matter g.s.
- **Do K^-d (SIDDHARTA-2) to constrain K^-n.**
- **Establish experimental program for precise K^- atom selective measurements.**

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

- **E03: X rays from Ξ^- atoms**
- **E05: $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$**
- **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 $^3\mathrm{He}(K^-, n)$**
- **E17: kaonic $^3\mathrm{He}\ 3d \to 2p$ X rays**
- **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**