Lessons from Hypernuclei

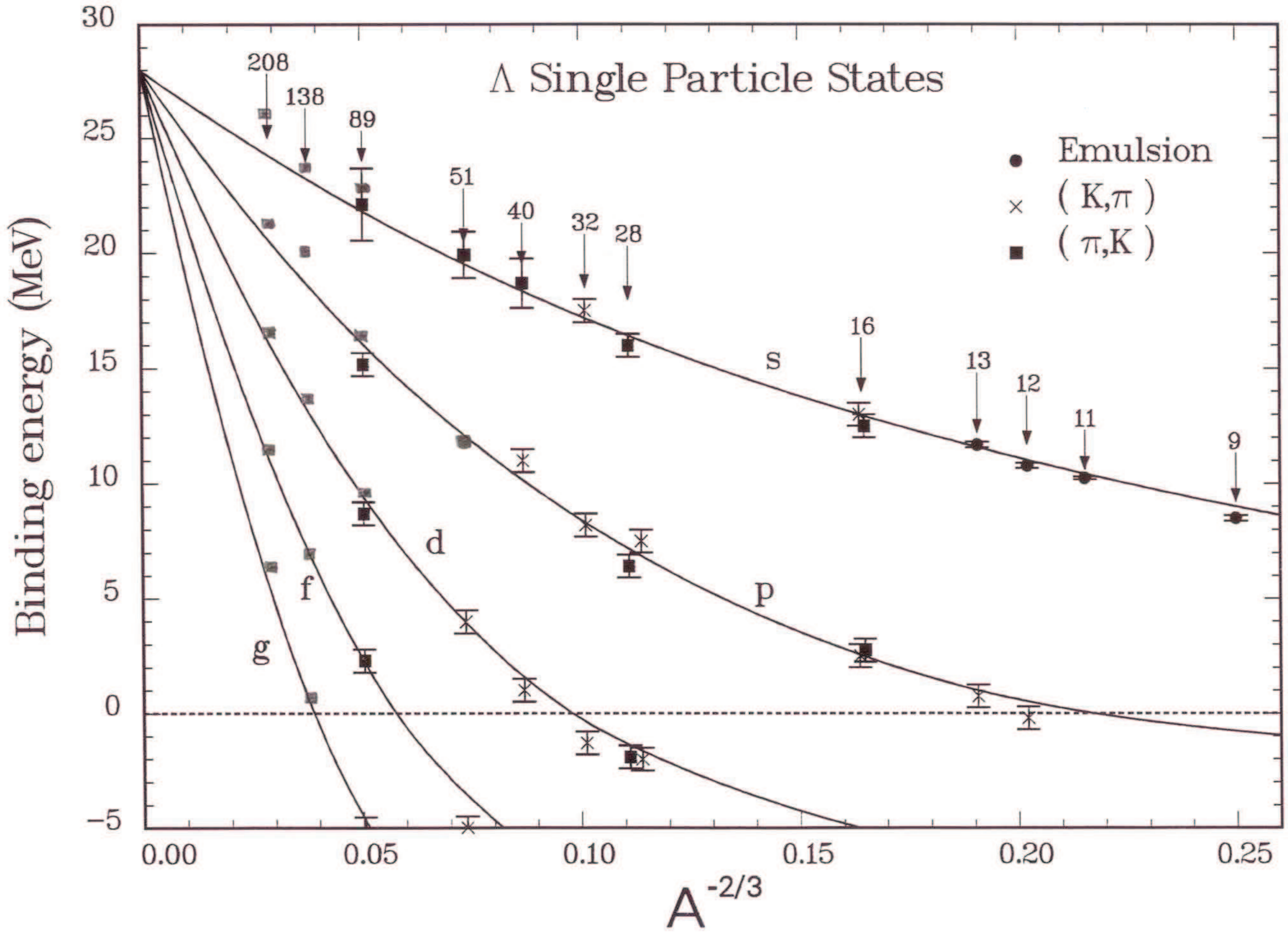
Avraham Gal, Hebrew University, Jerusalem

- Hypernuclear Spectroscopy and Structure
- Hyperons (Λ, Σ, Ξ) in Nuclear Matter and $S = -3, -4$
- Neutron Stars and Kaon Condensation
- NPA **804** (2008) 1-348, Eds. A. Gal, R.S. Hayano
- NPA **835** (2010) 1-469, Eds. B.F. Gibson, K. Imai, T. Motoba, T. Nagae, A. Ohnishi (Proc. HYP-X)
- PTPS **185** (2010) 1-343, Eds. E. Hiyama, T. Motoba, Y. Yamamoto; A. Gal, PTPS **186** (2010) 270-281
- NPA (2012), Eds. Gal-Hashimoto†-Pochodzalla

  † Deceased Feb. 3 2012, talk dedicated to his memory

Λ hypernuclei

spectroscopy, structure & decay



$B_\Lambda(\ell)$ curves produced by a density-dependent Λ-nuclear potential

Textbook example of shell model at work

D.J. Millener, C.B. Dover, A. Gal, Phys. Rev. C 38 (1988) 2700

Studies of Λ hypernuclei

- (K^-, π^-) – **emulsions, CERN, BNL, KEK, Frascati**
- (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; soon at MAMI.**
- ${}^{10}\mathrm{B}(\pi^-, K^+){}^{10}_{\Lambda}\mathrm{Li}$ **(KEK)** ${}^{6}\mathrm{Li}(K^-, \pi^+){}^{6}_{\Lambda}\mathrm{H}$, ${}^{6}_{\Lambda}\mathrm{H} \rightarrow {}^{6}\mathrm{He} + \pi^-$ **(FINUDA)**

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

- **E13: γ-ray spectroscopy of Λ hypernuclei**
- **E10: DCX studies of neutron-rich** ${}^{A}_{\Lambda}Z$

plus two experiments on weak interactions:

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

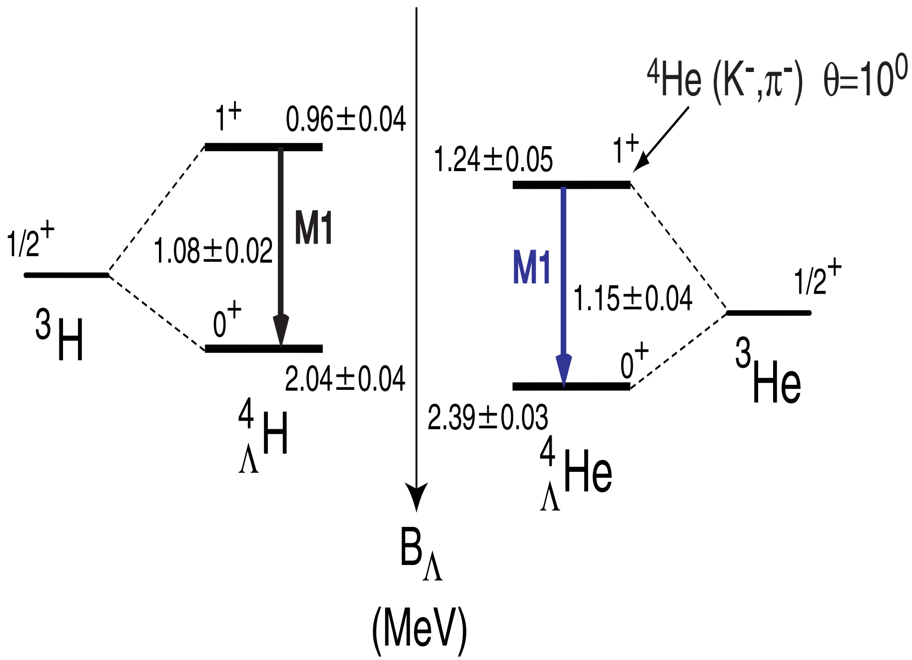


Figure 1: E13: $^{4}_{\Lambda}$He γ ray

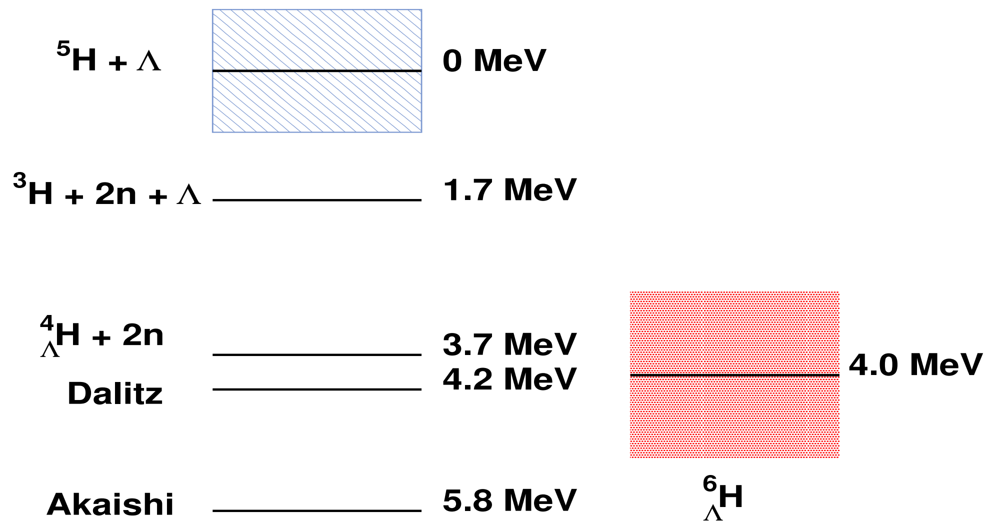


Figure 2: FINUDA's $^{6}_{\Lambda}$H spectrum

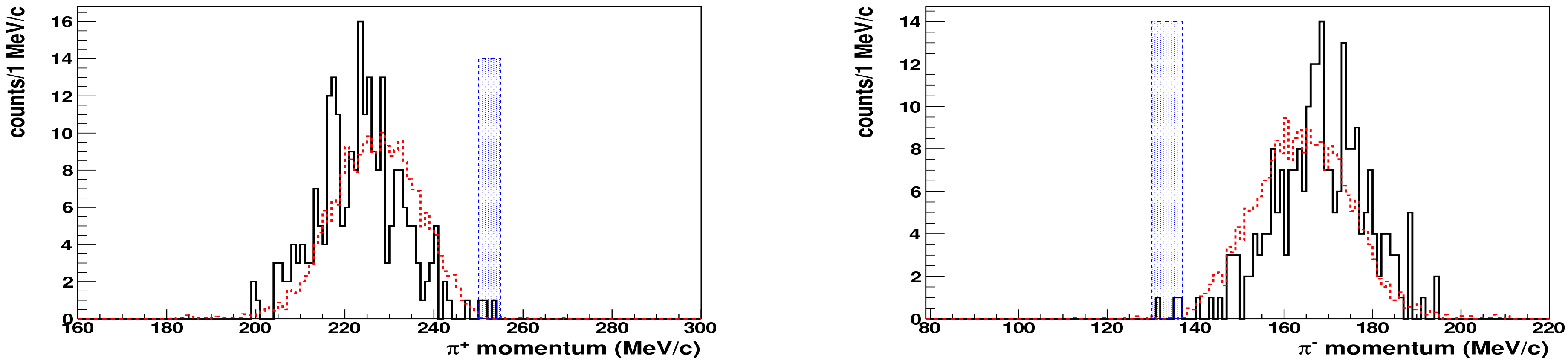
$^{6}_{\Lambda}$H: FINUDA Collaboration & A. Gal, PRL **108** (2012) 042501

$^{6}\mathrm{Li}(K^-,\pi^+)^{6}_{\Lambda}\mathrm{H}(1^+), \quad ^{6}_{\Lambda}\mathrm{H}(0^+) \to {}^{6}\mathrm{He} + \pi^-$

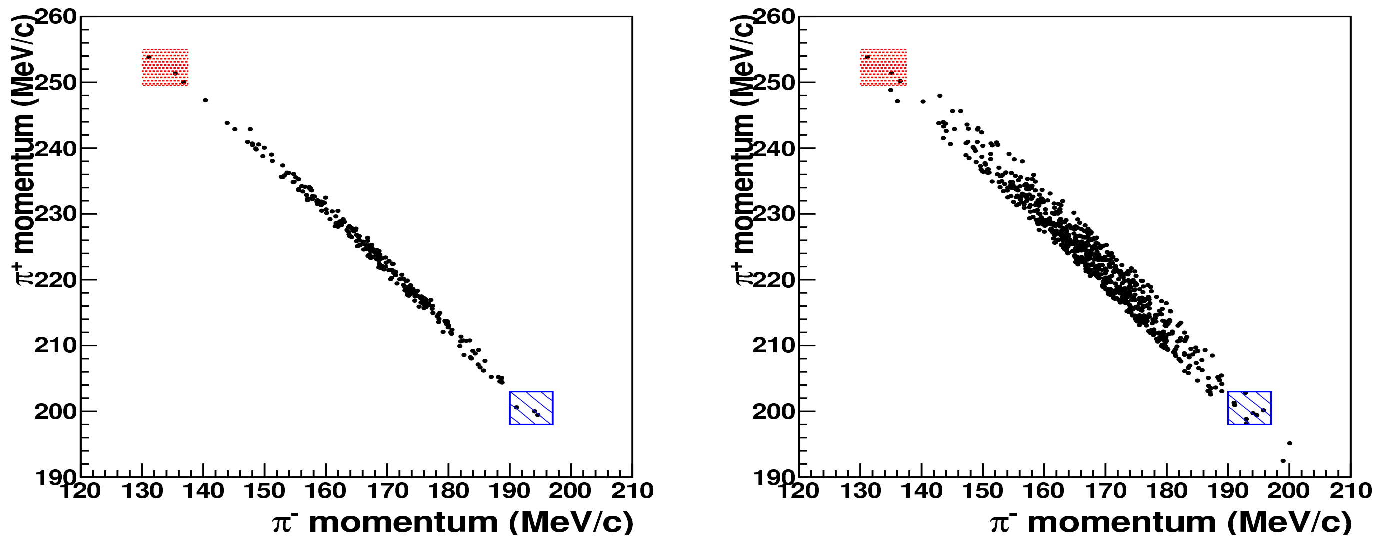
$\Delta E_{\mathrm{obs.}}(1^+ \to 0^+) = 0.98 \pm 0.74$ MeV

Akaishi (1999): extra $2n \Rightarrow \Delta E_{\mathrm{pred.}}(1^+ \to 0^+) \approx 2.4$ MeV

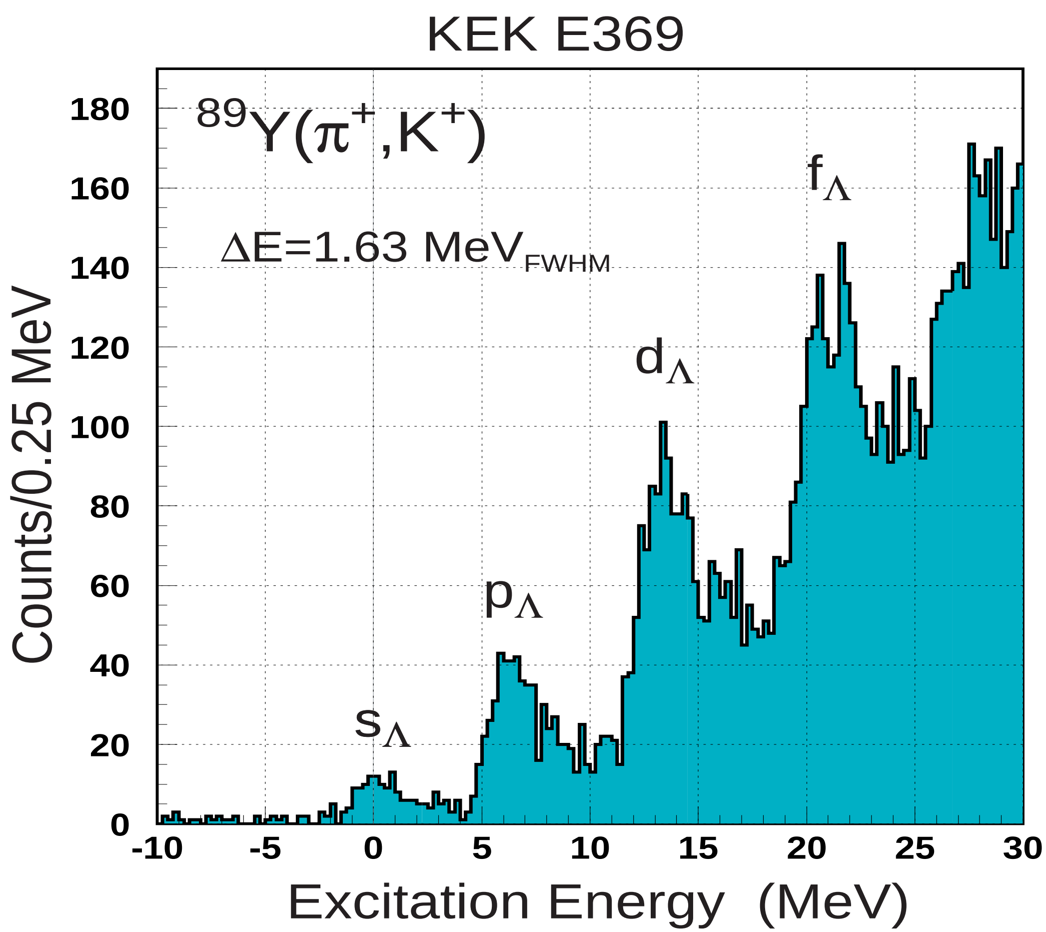
However, $B_\Lambda(^{7}_{\Lambda}\mathrm{He}) \approx 5.36$ MeV $\Rightarrow B_\Lambda(^{6}_{\Lambda}\mathrm{H}) \approx 4.28$ MeV



$\pi^\pm$ in coincidence (p_{π^+} left, p_{π^-} right), $T(\pi^+) + T(\pi^-) = 202 - 204$ MeV

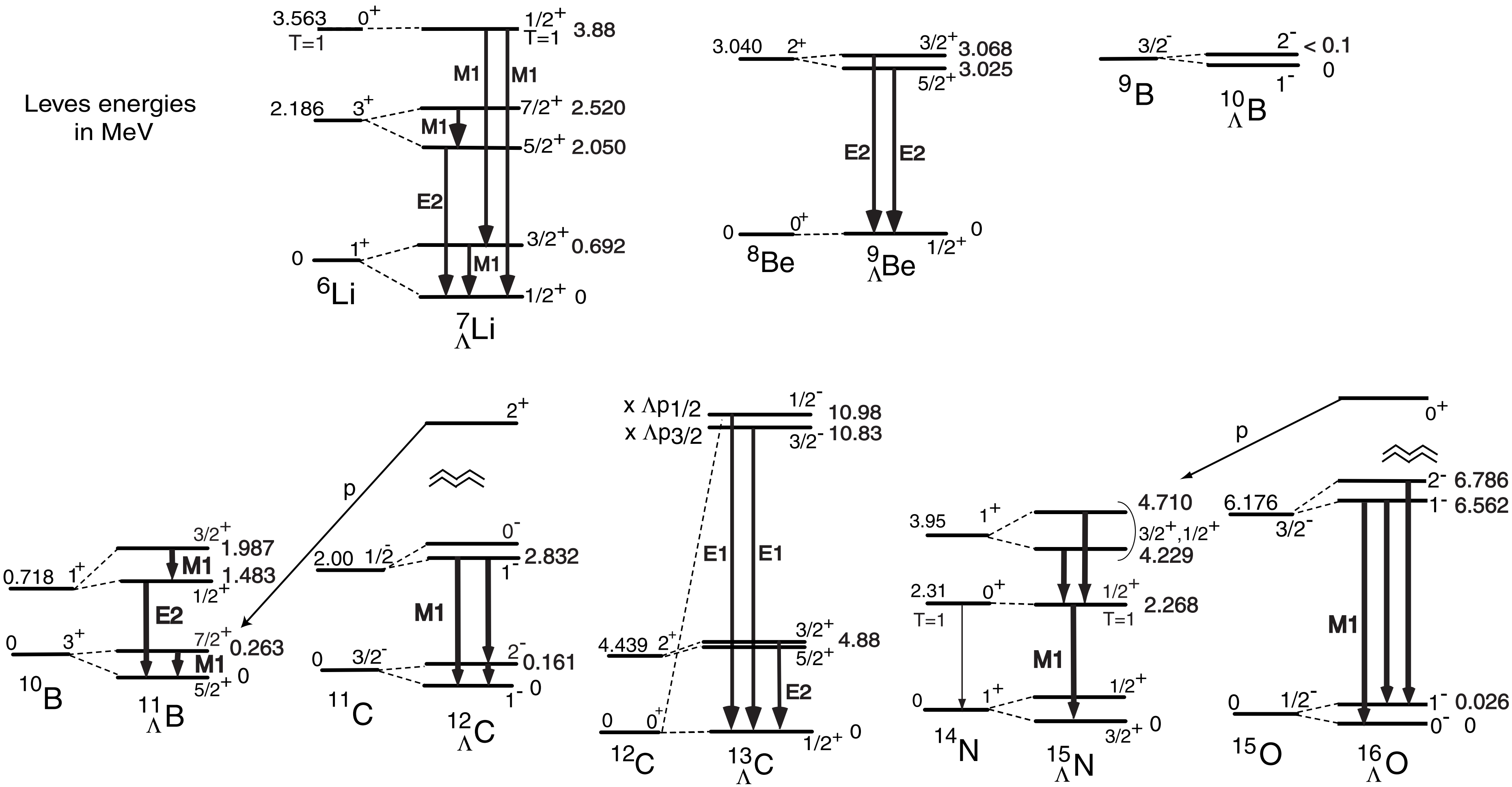


p_{π^+} vs. p_{π^-} for $T(\pi^+) + T(\pi^-) = 202 - 204,\ 200 - 206$ MeV (left, right)



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



Level schemes of Λ hypernuclei from recent γ-ray measurements

H. Tamura et al., Nucl. Phys. A 835 (2010) 3 [HYP-X]

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

(MeV)	$\bar{V}$	Δ	S_Λ	S_N	T
$N\Lambda$-$N\Lambda$ $\quad A = 7-$?	(-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)

	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 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.

$p_N s_\Lambda$ Λ-Σ coupling parameters from Nijmegen baryon-baryon potentials.

Source	Interaction	$\bar{V}'$	Δ'	S'_Λ	S'_N	T'
Akaishi (s-shell)	NSC97e/f	1.45	3.04	−0.09	−0.09	0.16
Yamamoto	NSC97f	0.96	3.62	−0.07	−0.07	0.31
Halderson	NSC97e	0.75	3.51	−0.45	−0.24	0.31
Halderson	NSC97f	1.10	3.73	−0.45	−0.23	0.30
Halderson	ESC08a	1.05	4.71	−0.07	0.02	0.32

D. Halderson, Phys. Rev. C 77, 034304 (2008).

- ${}^4_\Lambda$H/${}^4_\Lambda$He 0^+ $\bar{V}'_s + 3/4\ \Delta'_s$
- ${}^4_\Lambda$H/${}^4_\Lambda$He 1^+ $\bar{V}'_s - 1/4\ \Delta'_s$

YN interaction contributions to g.s. binding energies

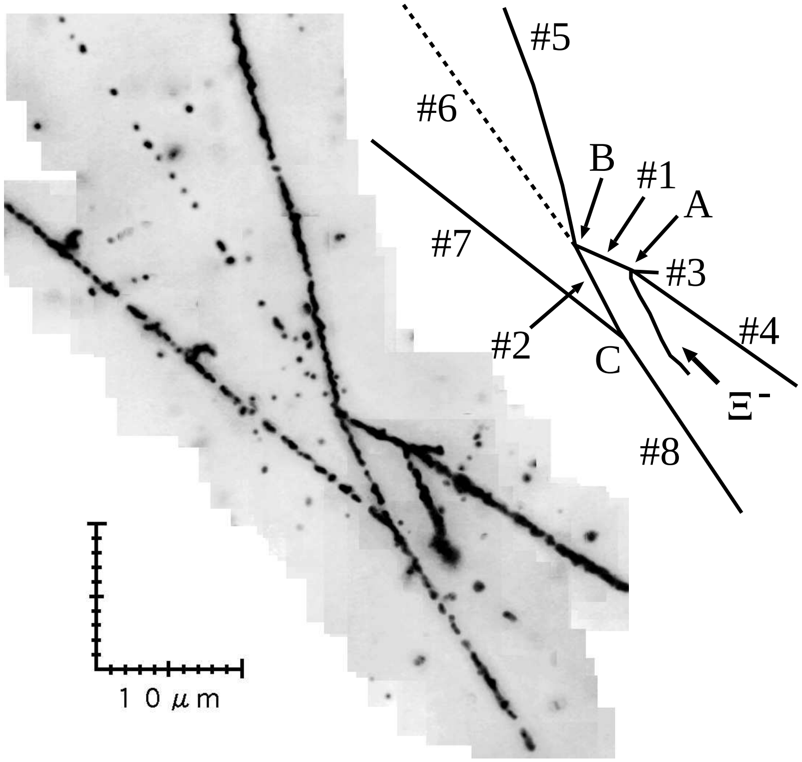
	${}^{7}_{\Lambda}$Li	${}^{8}_{\Lambda}$Li	${}^{9}_{\Lambda}$Li	${}^{10}_{\Lambda}$B	${}^{11}_{\Lambda}$B	${}^{11}_{\Lambda}$Be	${}^{12}_{\Lambda}$B	${}^{13}_{\Lambda}$C	${}^{15}_{\Lambda}$N	${}^{16}_{\Lambda}$N
keV	$1/2^+$	1^-	$3/2^+$	1^-	$5/2^+$	$1/2^+$	1^-	$1/2^+$	$3/2^+$	1^-
Λ-Σ	78	160	183	35	66	99	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

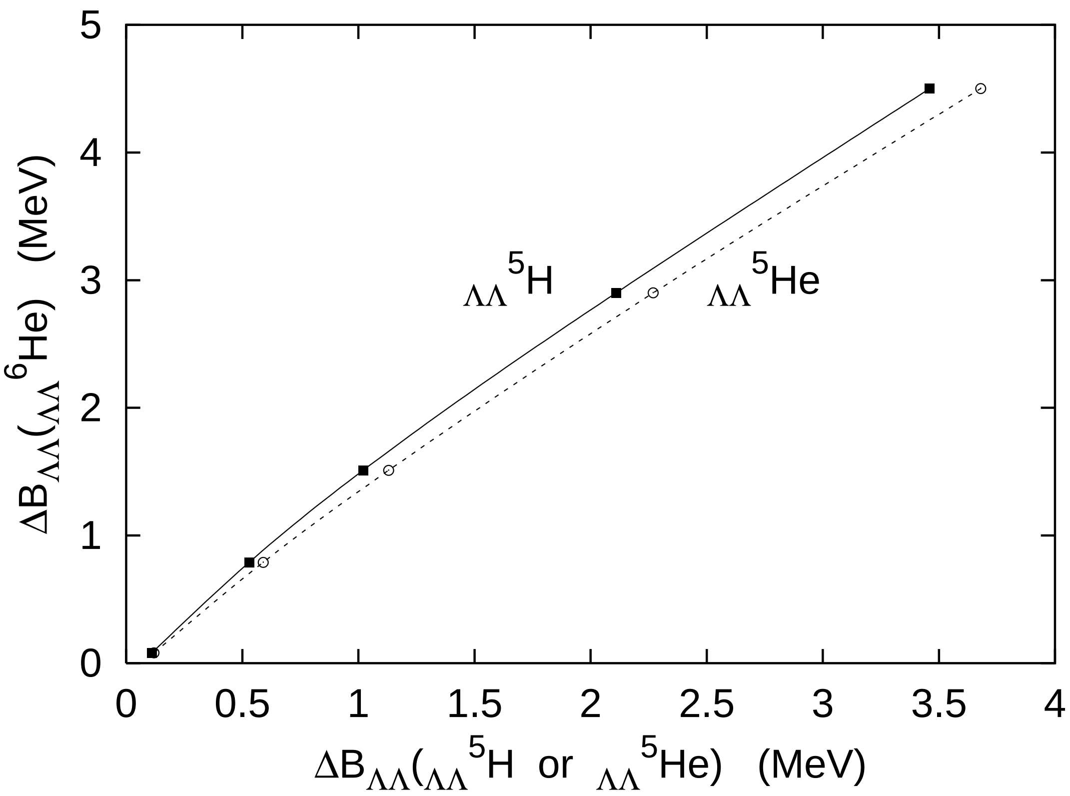
$\Lambda\Lambda$ hypernuclei



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 consistently and 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



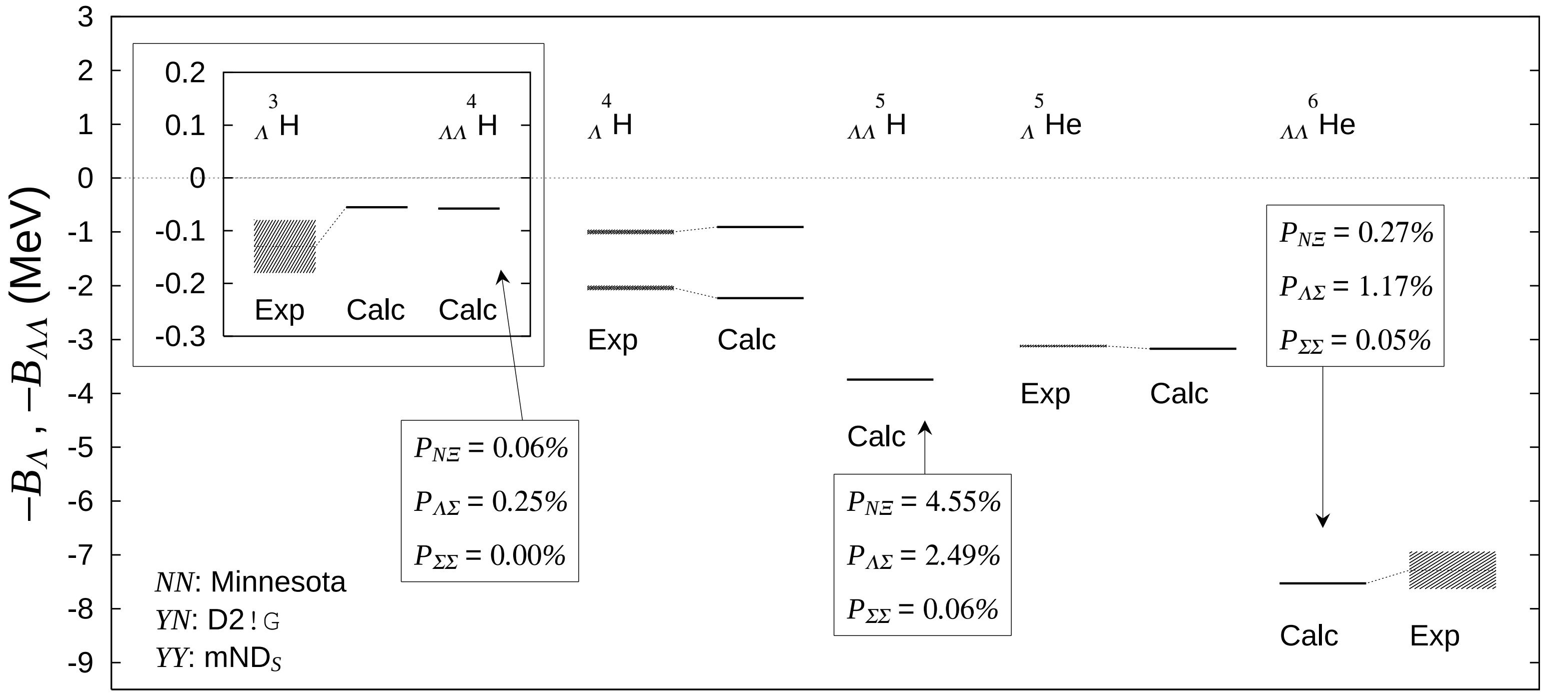
I.N. Filikhin, A. Gal, Nucl. Phys. A **707** (2002) 491

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

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

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

${}_{\Lambda\Lambda}^{5}\mathrm{H}$ & ${}_{\Lambda\Lambda}^{5}\mathrm{He}$ 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]

Ambiguities in identifying $\Lambda\Lambda$ emulsion events

- $\Lambda\Lambda$ hypernuclei often formed in, or decay to, excited states. Unseen γ energy should be added or subtracted accordingly.
- Demachiyanagi (KEK-E373): $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{10}_{\Lambda\Lambda}\mathrm{Be}^*(2^+) + t$.
  From production: $B_{\Lambda\Lambda} = 11.90 \pm 0.13 \rightarrow 14.94 \pm 0.13$ MeV.
- Danysz et al. (1963): ${}^{10}_{\Lambda\Lambda}\mathrm{Be} \rightarrow {}^{9}_{\Lambda}\mathrm{Be}^*(5/2^+, 3/2^+) + p + \pi^-$.
  From decay: $B_{\Lambda\Lambda} = 17.7 \pm 0.4 \rightarrow 14.7 \pm 0.4$ MeV.
- KEK-E176: $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{13}_{\Lambda\Lambda}\mathrm{B} + p + n$, followed by ${}^{13}_{\Lambda\Lambda}\mathrm{B} \rightarrow {}^{13}_{\Lambda}\mathrm{C}^*(5/2^+, 3/2^+) + \pi^-$, with $E_{\mathrm{x}} \approx 4.8$ MeV.
  Both production & decay consistent with $B_{\Lambda\Lambda} = 23.4 \pm 0.7$ MeV.
  Other, less likely interpretations are not ruled out,
  S. Aoki et al., NPA 828 (2009) 191.

Shell-model approach

- Account for the Λ-nuclear interactions of each Λ using $\overline{B}_\Lambda({}^{A-1}_{\ \ \Lambda}Z)$, the $(2J+1)$-averaged B_Λ in the ${}^{A-1}_{\ \ \Lambda}Z$ g.s. doublet, as appropriate to $(1s_\Lambda)^2_{J=0}$ in ${}_{\Lambda\Lambda}^{\ \ A}Z$.

- Identify $< V_{\Lambda\Lambda} >_{\rm SM}$ with
  $B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\ \ 6}{\rm He}) - 2B_\Lambda({}^5_\Lambda{\rm He}) = 0.67 \pm 0.17$ MeV.
  Note $< V_{\Lambda\Lambda} >_{\rm CM} = B_{\Lambda\Lambda}(V_{\Lambda\Lambda} \neq 0) - B_{\Lambda\Lambda}(V_{\Lambda\Lambda} = 0)$,
  $\Rightarrow$ 0.54 (${}_{\Lambda\Lambda}^{\ \ 6}{\rm He}$), 0.53 (${}_{\Lambda\Lambda}^{\ 10}{\rm Be}$), 0.56 (${}_{\Lambda\Lambda}^{\ 11}{\rm Be}$) MeV,
  from E. Hiyama et al. PRL **104** (2010) 212502

- Use $B^{\rm SM}_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\ \ A}Z) = 2\overline{B}_\Lambda({}^{A-1}_{\ \ \Lambda}Z) + < V_{\Lambda\Lambda} >_{\rm SM}$

- Input $\overline{B}_\Lambda({}^{A-1}_{\ \ \Lambda}Z)$ requires spin dependence analysis

- Modify where nuclear core is unbound (^{8}Be)

Binding energy consistency of $\Lambda\Lambda$ 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 production in ${}^{10}_{\Lambda\Lambda}$Be 1st excited state 2^{+}(3.04 MeV)

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

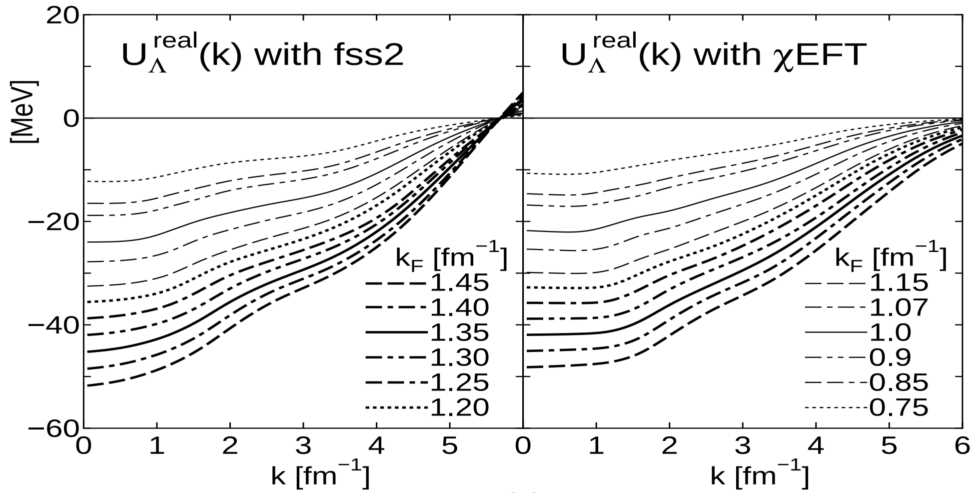
- Hida-event [PTPS **185** (2010) 335] offers no clue
- $B^{\rm SM}_{\Lambda\Lambda} \approx B^{\rm CM}_{\Lambda\Lambda}$, but SM spans a wider A range

$\Lambda\Lambda$ conclusions

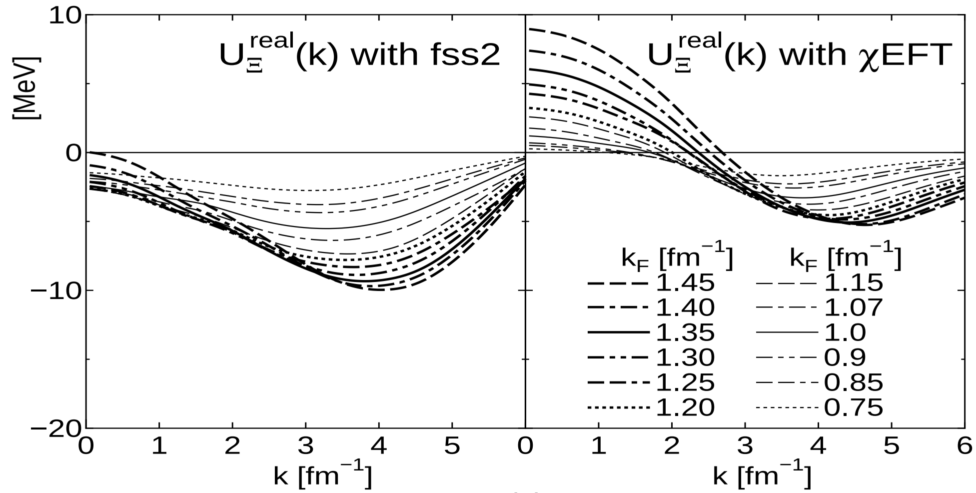
- Relatively weak $\Lambda\Lambda$ interaction
  $< V_{\Lambda\Lambda} > \approx 0.6$ MeV, $|a_{\Lambda\Lambda}| < 1$ fm
- Onset of $\Lambda\Lambda$ binding likely with ${}_{\Lambda\Lambda}^{5}$H & ${}_{\Lambda\Lambda}^{5}$He
- Shell model works well beyond ${}_{\Lambda\Lambda}^{6}$He
- No sound SM or 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
- FAIR (PANDA): slowing down Ξ^- from $\bar{p}p \rightarrow \Xi^-\bar{\Xi}^+$

Hyperons in Nuclear Matter

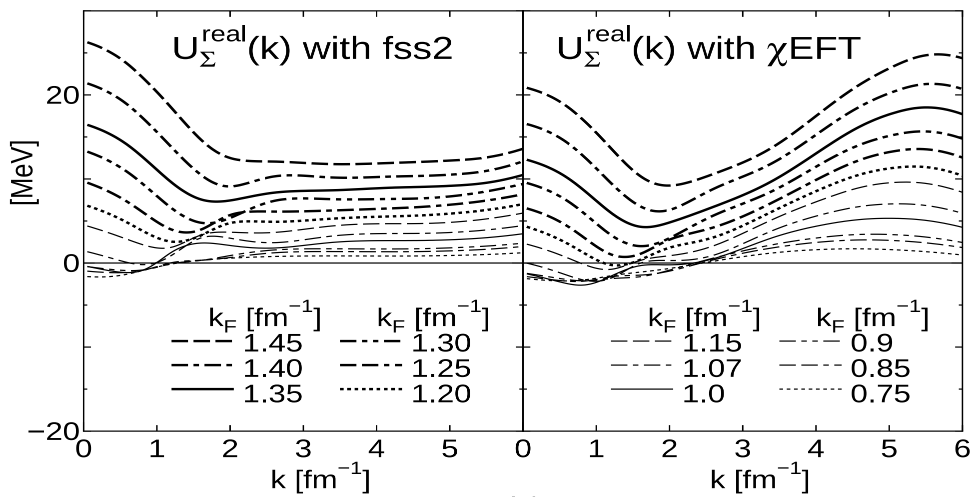
and $S = -3, -4$ Systems



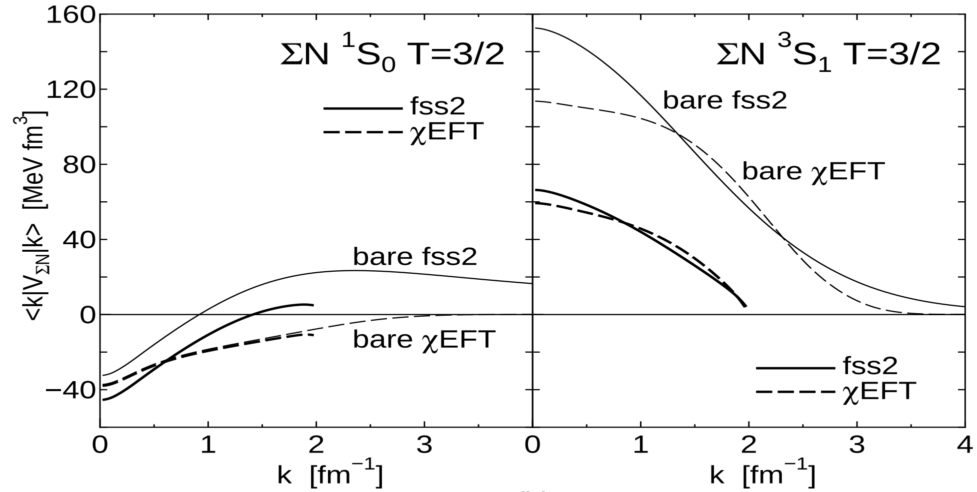
(a)



(a)



(a)



(b)

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

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

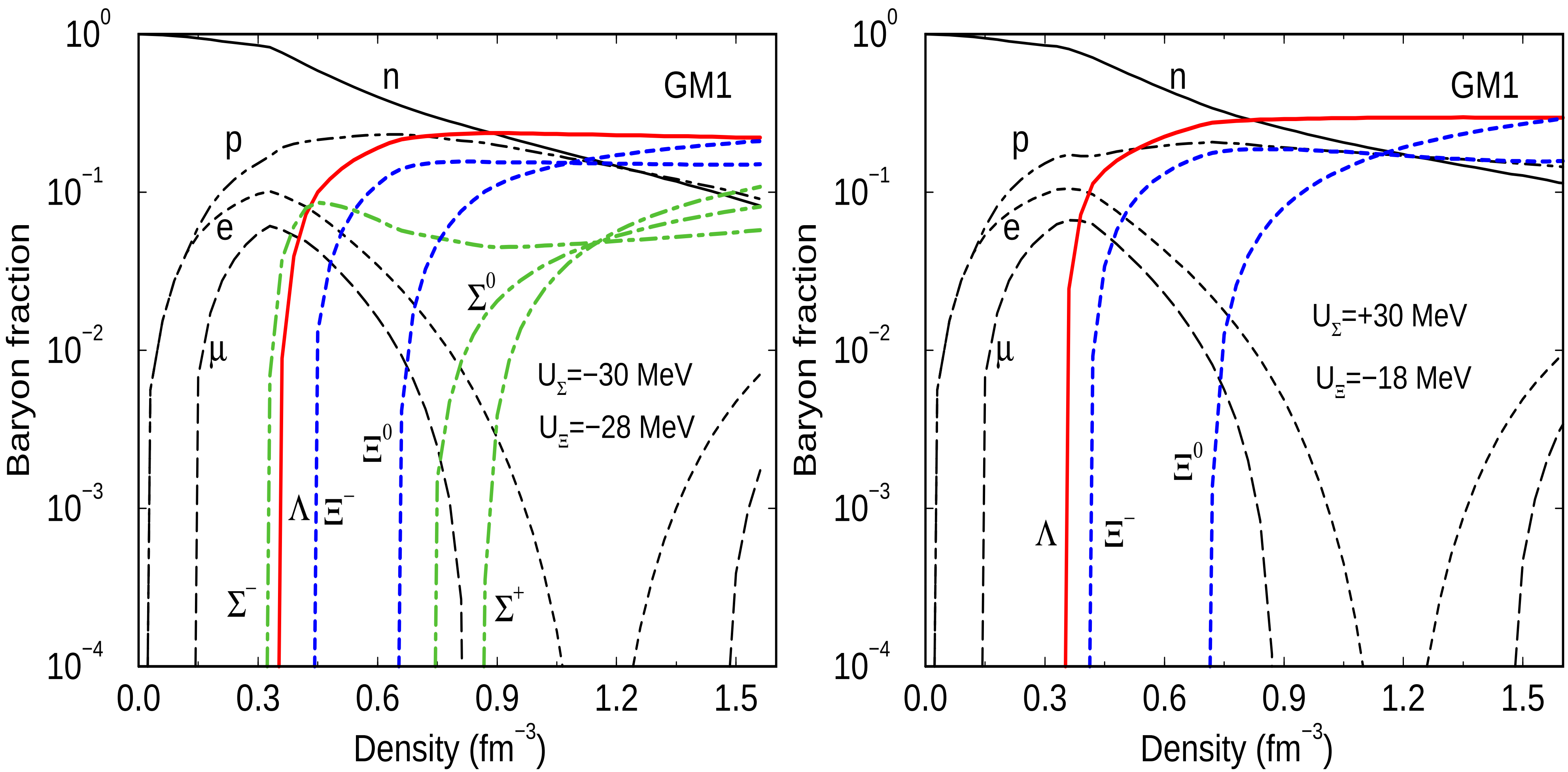
$\mathcal{S} = -2, -3, -4$ deuteron-like $L = 0$ dibaryon candidates

	$\Sigma\Sigma$ $(I=2, {}^1S_0)$	$\Lambda\Xi$ $(I=\frac{1}{2}, {}^1S_0)$	$\Sigma\Xi$ $(I=\frac{3}{2}, {}^1S_0)$	$\Sigma\Xi$ $(I=\frac{3}{2}, {}^3S_1)$	$\Xi\Xi$ $(I=1, {}^1S_0)$
fss2	–	–	–	–	–
NSC97	+	–	+	+	+
EFT (LO)	–	+	+	–	+

fss2: Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog. Part. Nucl. Phys. **58** (2007) 439
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

- 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 $SU(3)_f$ **27** (as nn), ${}^3S_1$ in $SU(3)_f$ $\overline{\mathbf{10}}$ (as deuteron).
- Model dependence is assessed by varying a cutoff momentum in the range $550 - 700$ MeV/c.

Neutron Stars and Kaon Condensation

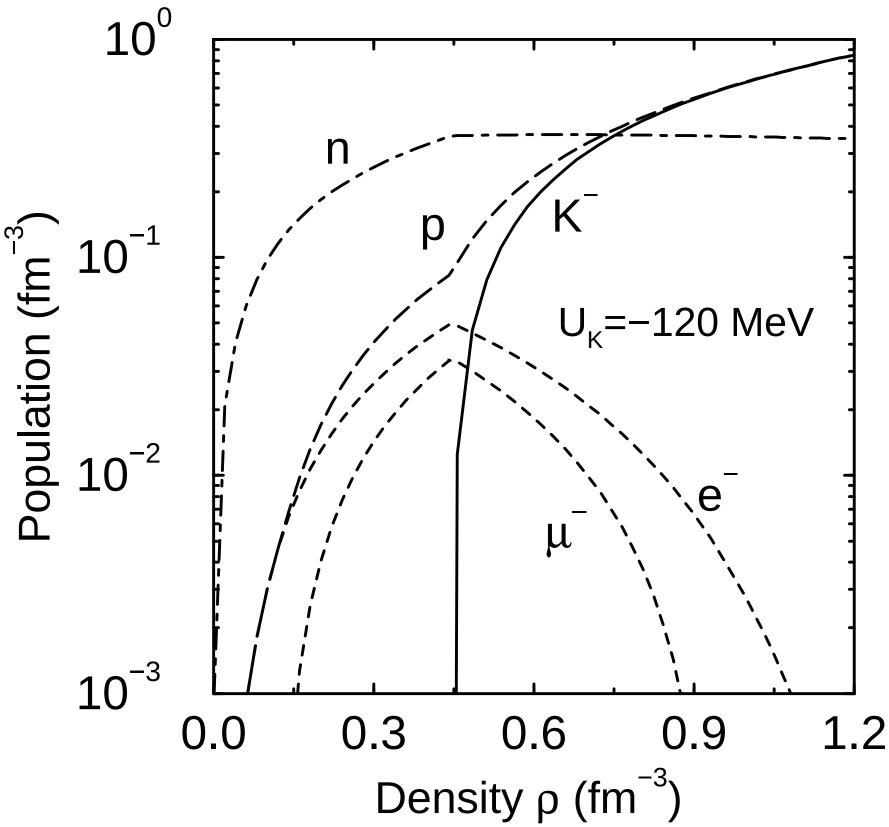


J. Schaffner-Bielich, NPA **804** (2008) 309, **835** (2010) 279

RMF calculation of baryon & lepton fractions in neutron star matter

Hyperons join at $\rho \geq 2.5\rho_0$. $\quad M_{\max} \approx (1.6 - 1.7) M_\odot$

Why not $\Lambda \to p + K^-$?

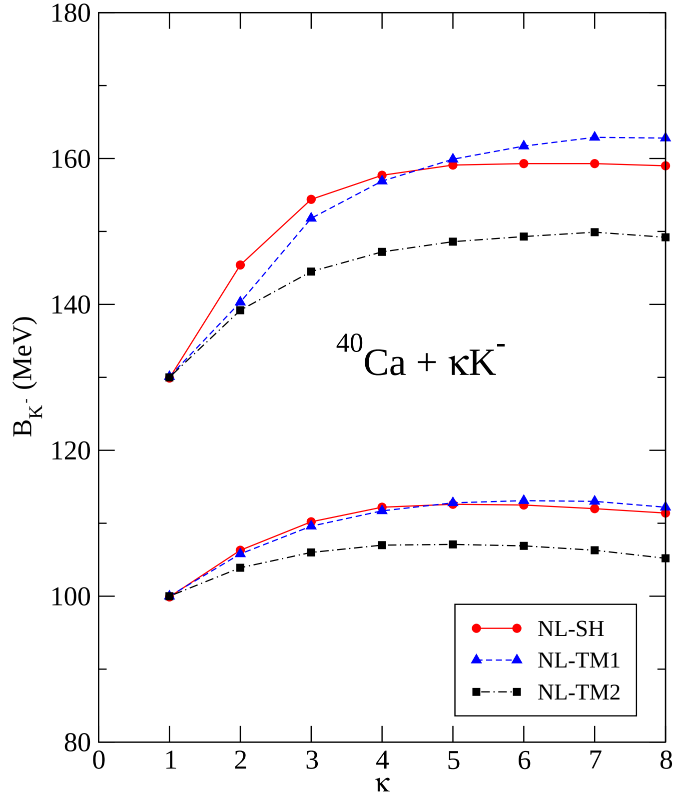


N.K. Glendenning, J. Schaffner-Bielich, PRC 60 (1999) 025803

Population of nuclear star matter under kaon condensation

$\ell^- \to K^- + \nu_\ell$: lepton depletion occurs for $\rho \geq 3\rho_0$

However, hyperons delay kaon condensation or even void it.

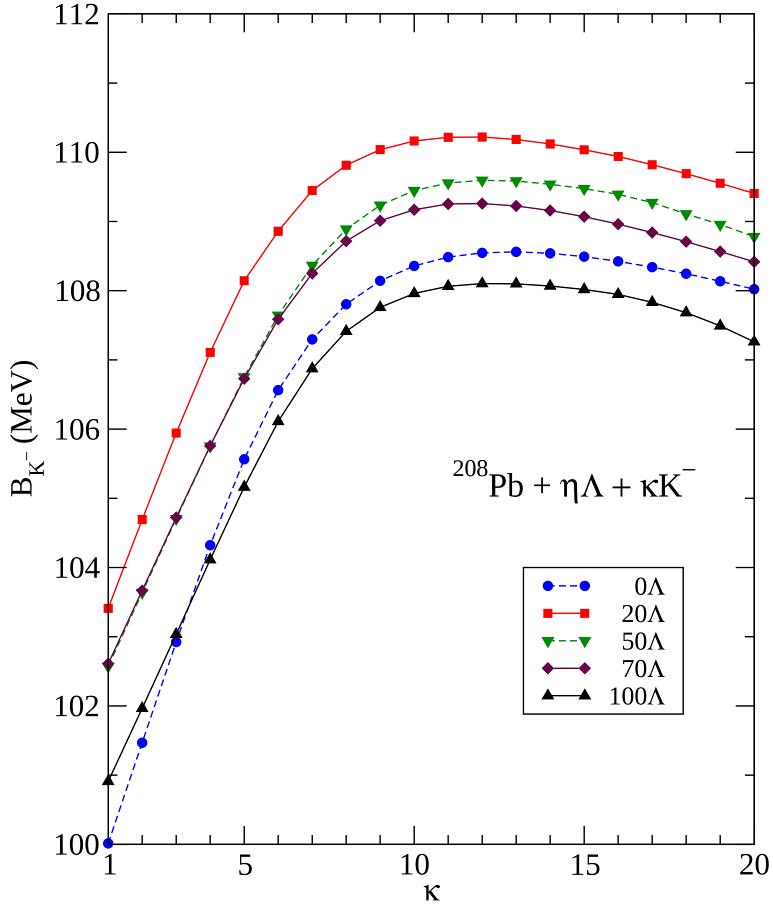


D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

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

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

$\bar{K}$ mesons do not replace hyperons in stable self-bound strange matter



D. Gazda, E. Friedman, A. Gal, J. Mareš, Phys. Rev C 80 (2009) 035205

Adding hyperons in RMF

Saturation of $B_{\bar{K}}(\kappa)$ in $^{208}\mathrm{Pb} + \eta\Lambda + \kappa K^-$, far from $\bar{K}$ condensation

Summary

- ΛN hypernuclear spin dependence deciphered
- How small is Λ spin-orbit splitting and why?
- Role of 3-body ΛNN interactions?
- Repulsive Σ-nuclear interaction; how repulsive?
- Onset of $\Lambda\Lambda$ binding: ${}^{4}_{\Lambda\Lambda}$H or ${}^{5}_{\Lambda\Lambda}$H & ${}^{5}_{\Lambda\Lambda}$He?
- Ξ hyperons bound by ~ 15 MeV in nuclear matter?
  No quasibound Ξ observed yet $\Rightarrow$ J-PARC E05
- Onset of Ξ stability: ${}^{6}_{\Lambda\Xi}$He or ${}^{7}_{\Lambda\Lambda\Xi}$He?
- Is Strange Hadronic Matter $\{N, \Lambda, \Xi\}$ ground state of self-bound strange matter?
  No $\bar{K}$ condensation in self-bound stable matter

J-PARC SNP Exps. 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**