Unresolved 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:

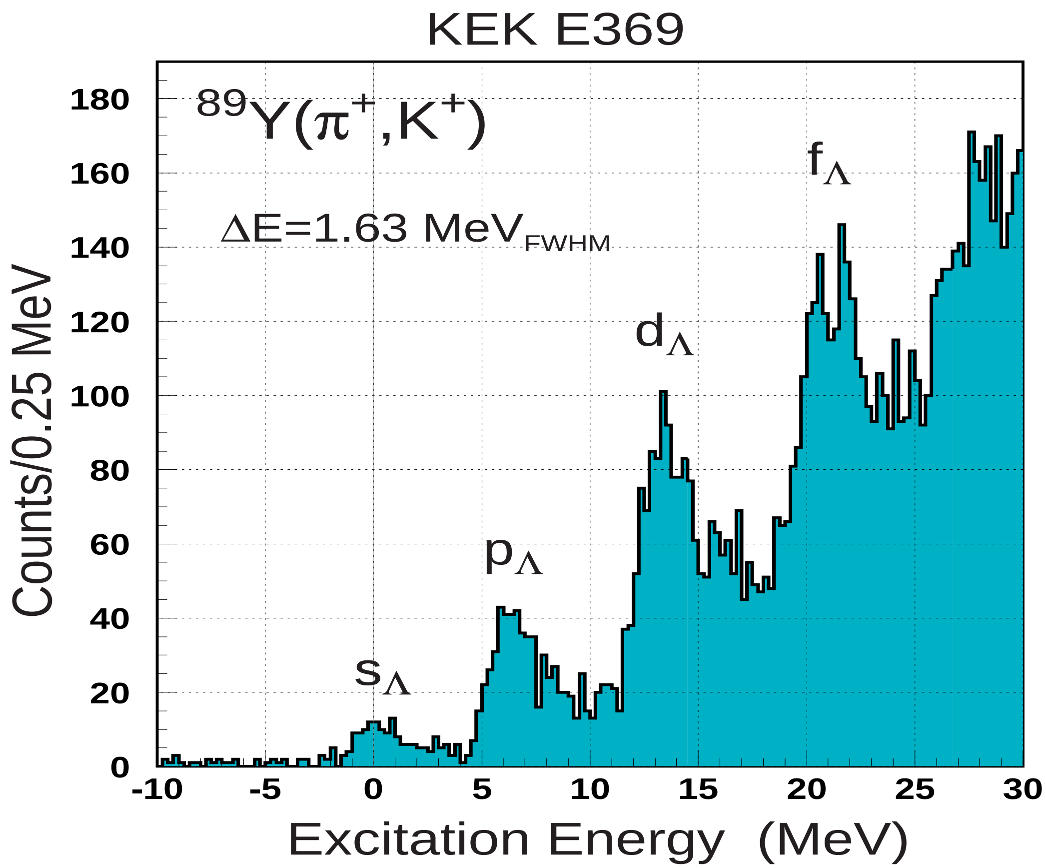
- E13: γ-ray spectroscopy of Λ hypernuclei
- E10: DCX studies of neutron-rich ${}^{A}_{\Lambda}Z$ (^{6}Li, ^{9}Be & ^{10}B targets)

plus two experiments on weak interactions:

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

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

Observation of Λ single-particle states

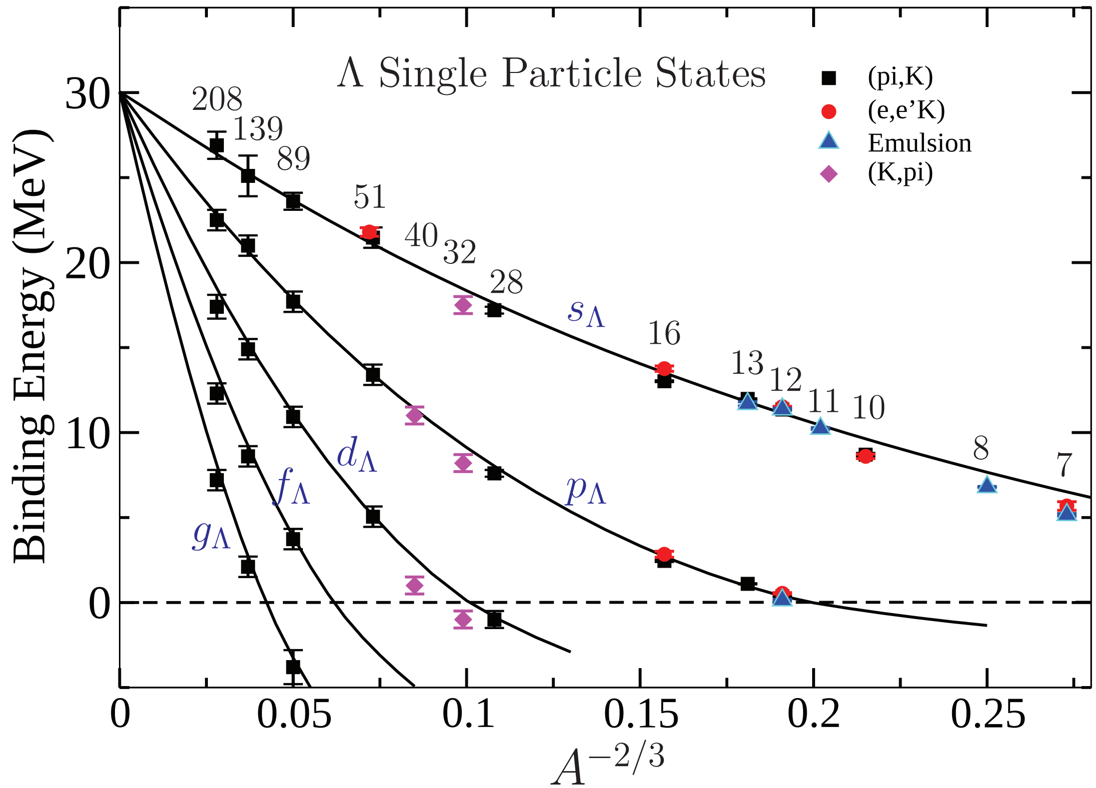


H. Hotchi et al., Phys. Rev. C 64 (2001) 044302 $B_\Lambda = 23.11 \pm 0.10$ MeV

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)

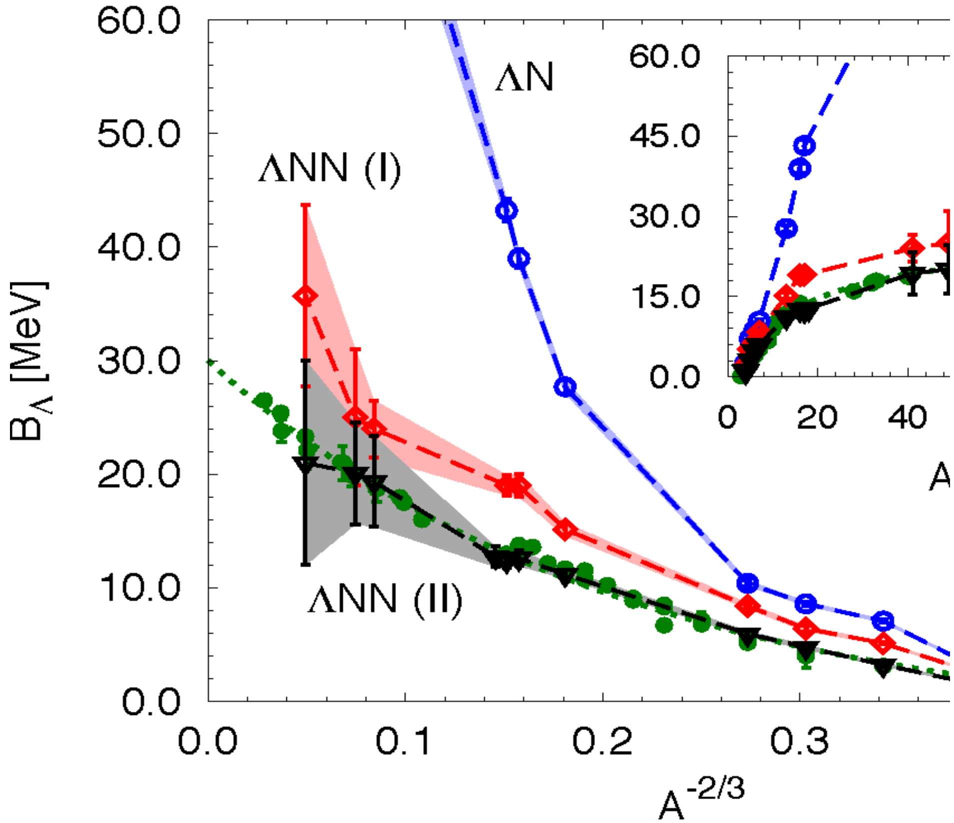


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

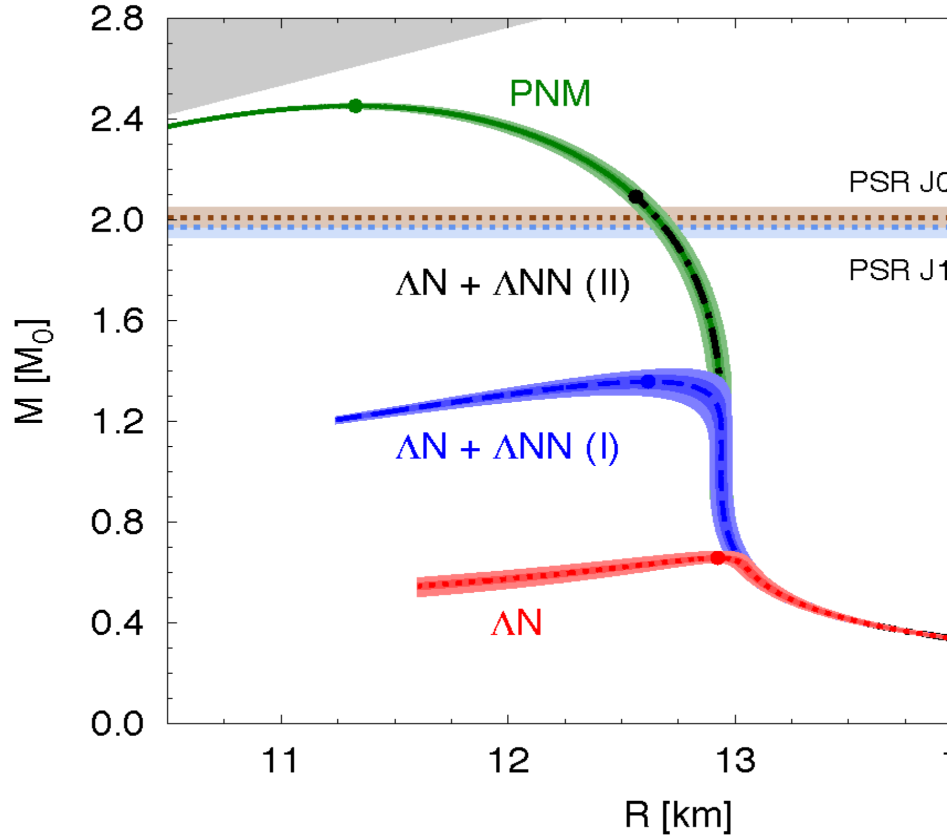
Textbook example of shell model at work.

SHF studies suggest ΛNN repulsion.

Hyperon puzzle: QMC calculations



Lonardoni et al, PRC 89 (2014) 014314



Lonardoni et al, arXiv:1407.4448

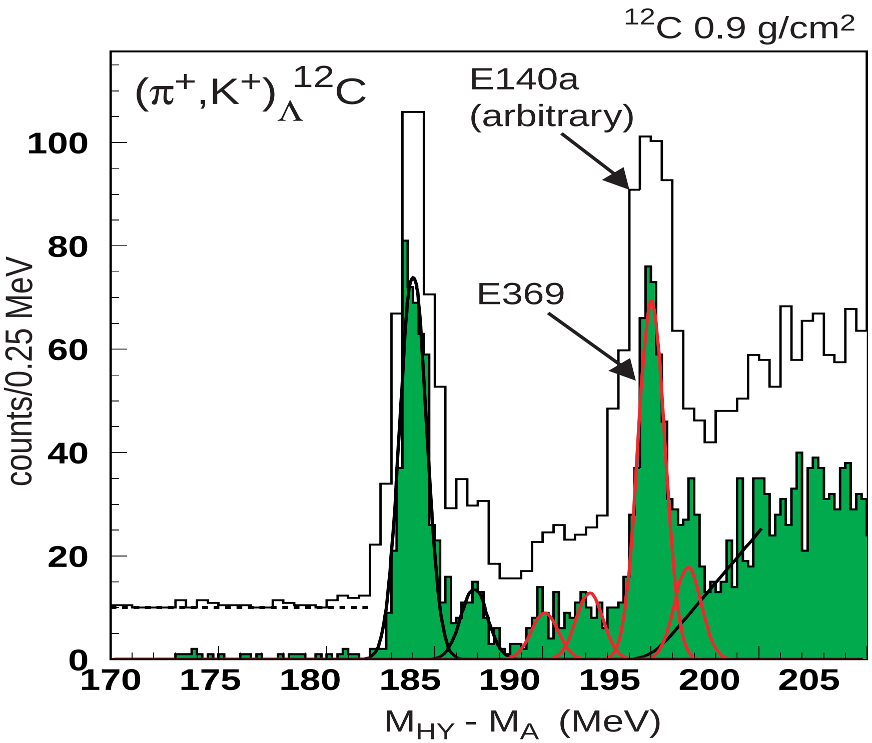
ΛNN effect on B_Λ(g.s.)

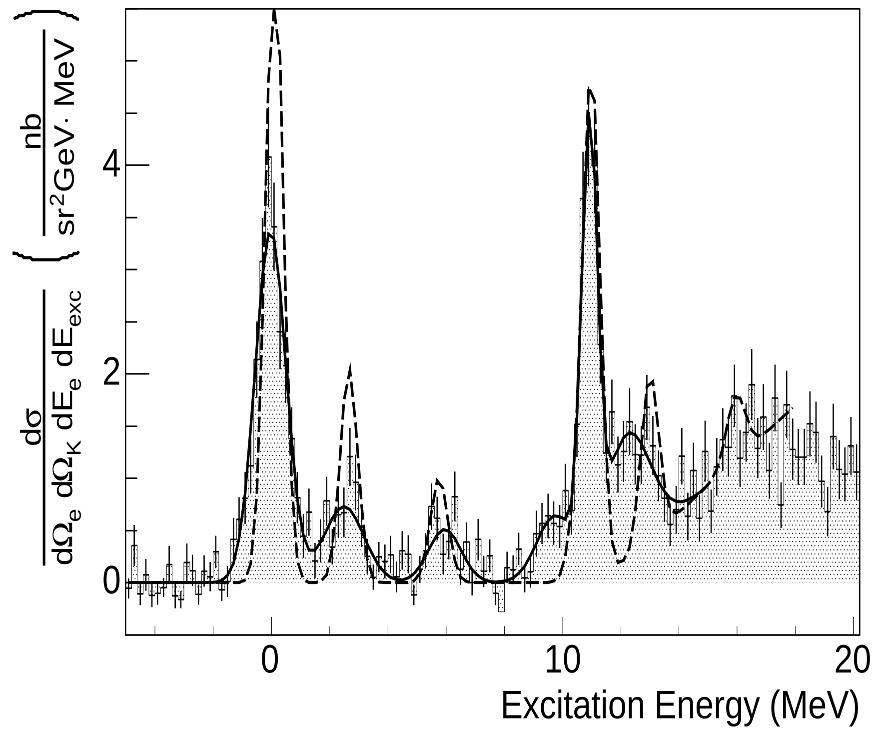
ΛNN effect on neutron stars

Adding ΛNN stiffens EOS of neutron stars.

Other hyperons besides Λ need to be considered too.

Room for hypernuclear spectroscopy



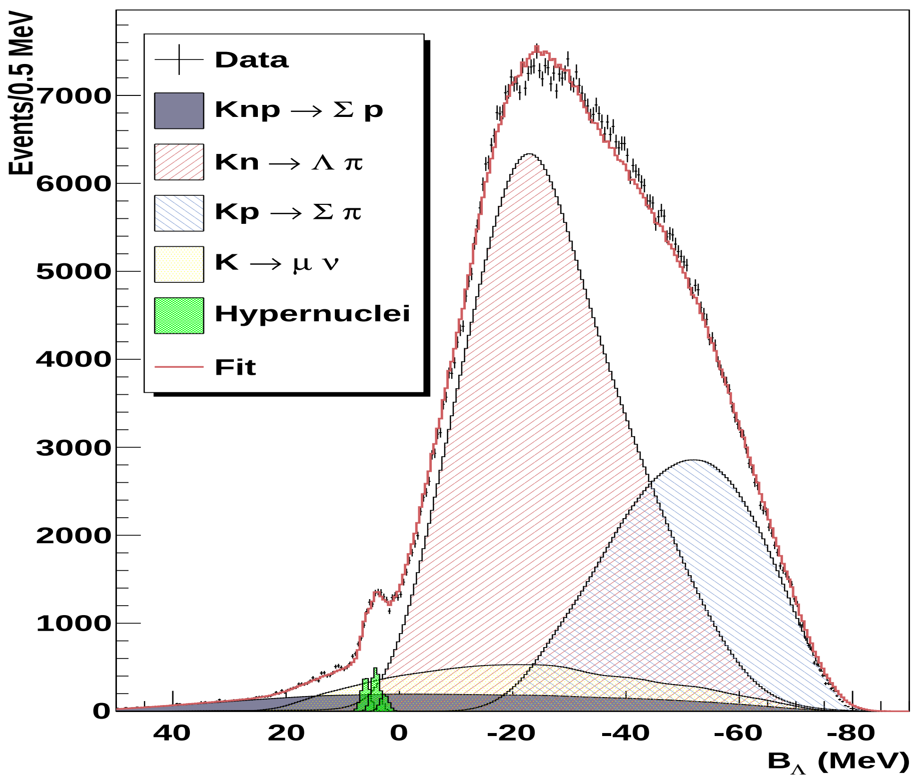


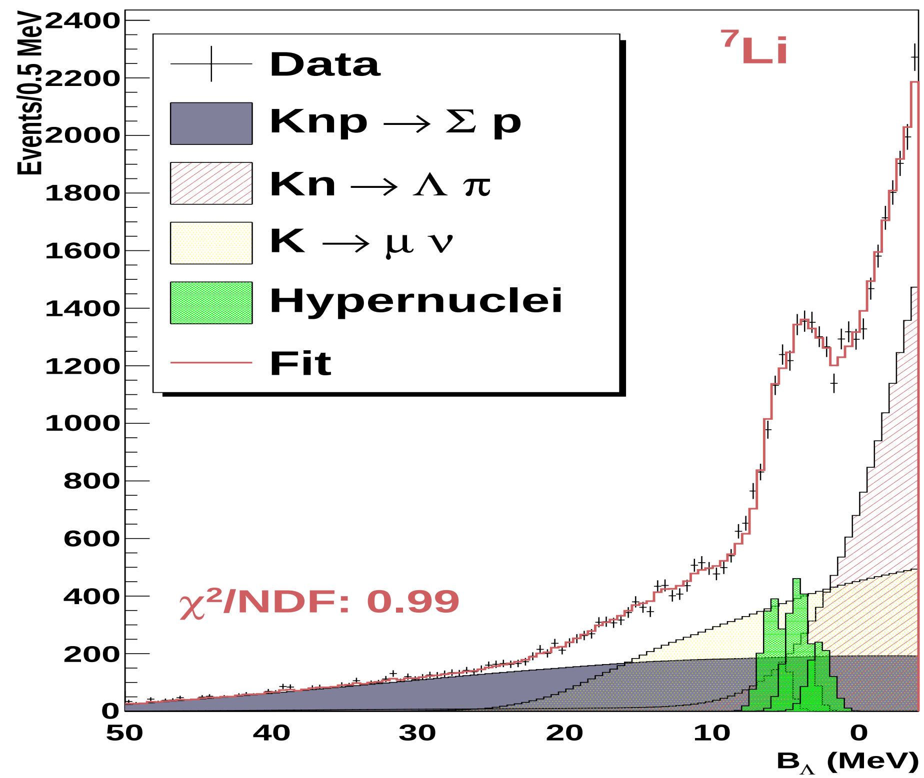
H. Hotchi et al., PRC 64 (2001) 044302 M. Iodice et al., PRL 99 (2007) 052501

$1s_\Lambda - 1p_\Lambda$ intermediate structure $^{12}_{\Lambda}$B in $(e, e'K^+)$, Jlab Hall A

energy resolution 1.6 MeV $\rightarrow$ **0.6 MeV [PRC 90 (2014) 034320]**

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





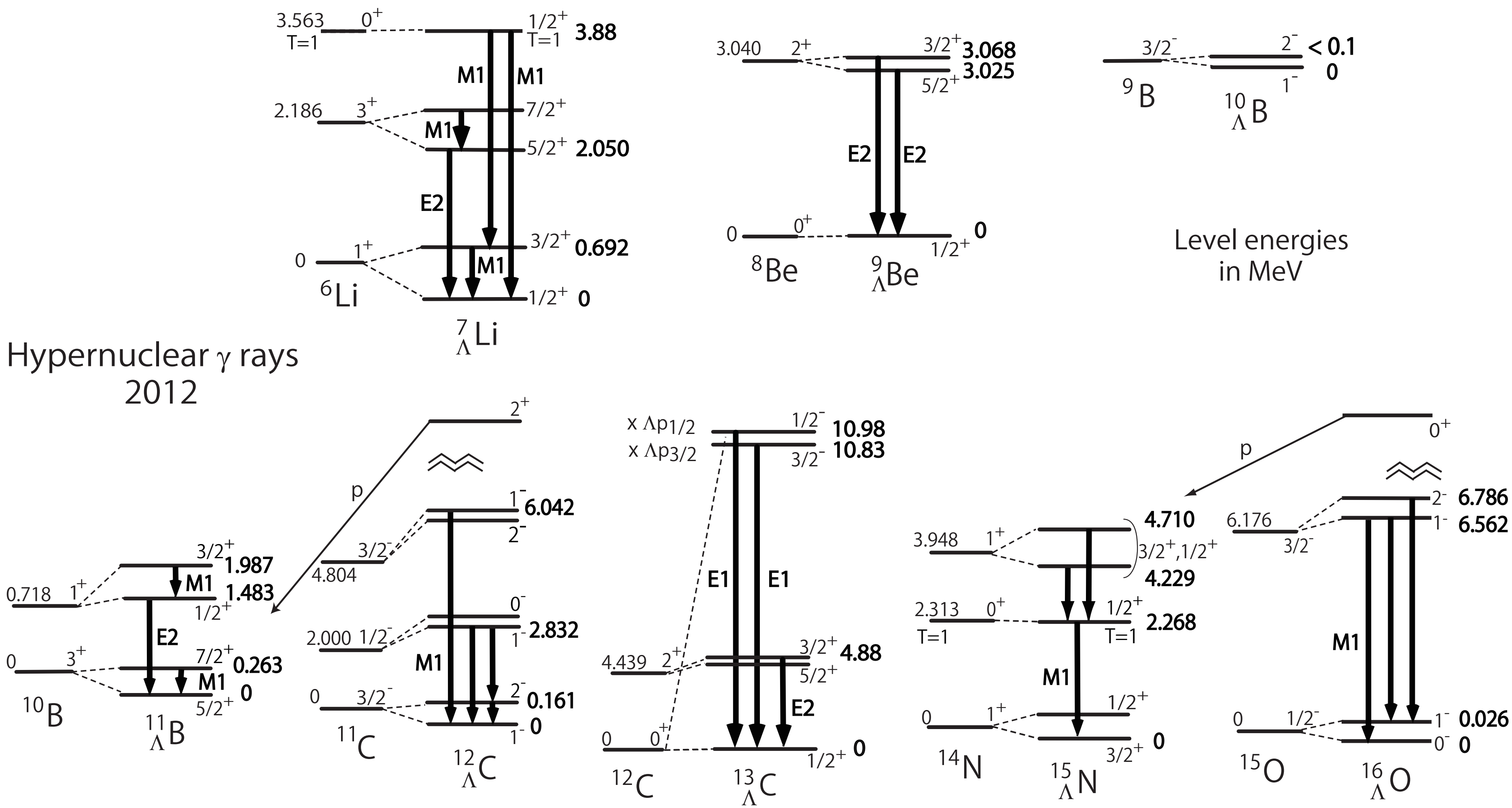
Production spectrum on ^{7}Li

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.

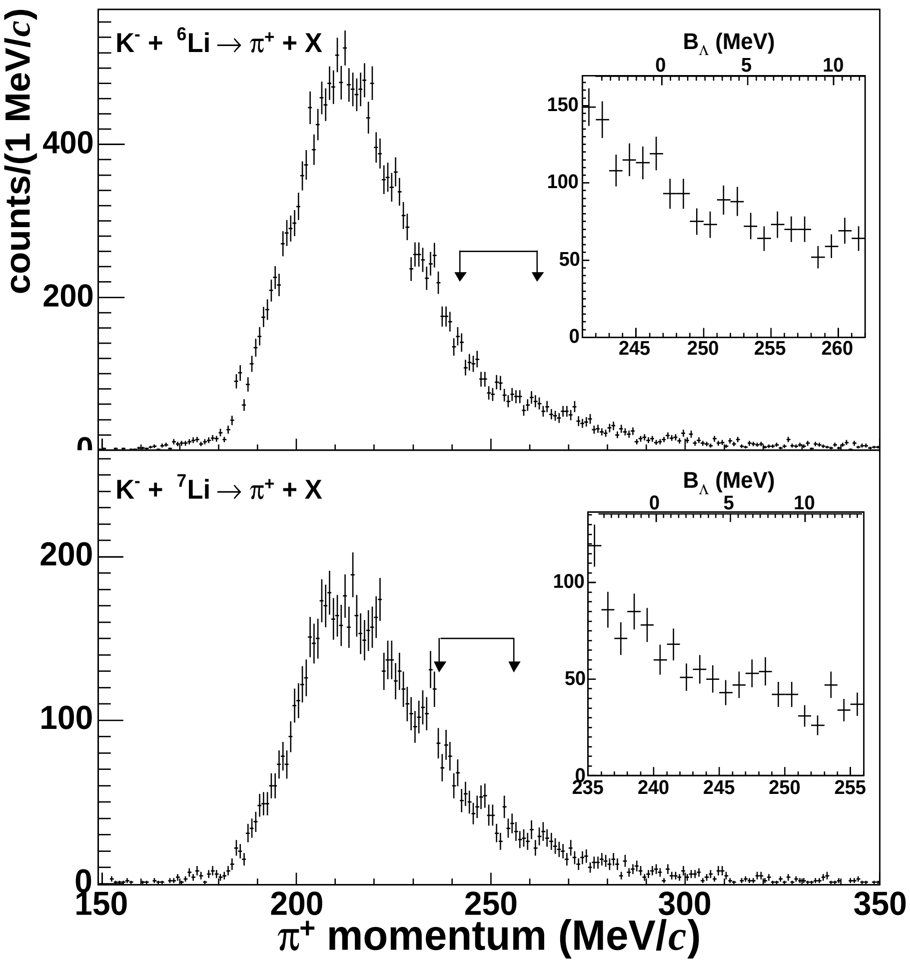


Hypernuclear level schemes from γ-ray measurements (BNL, KEK)

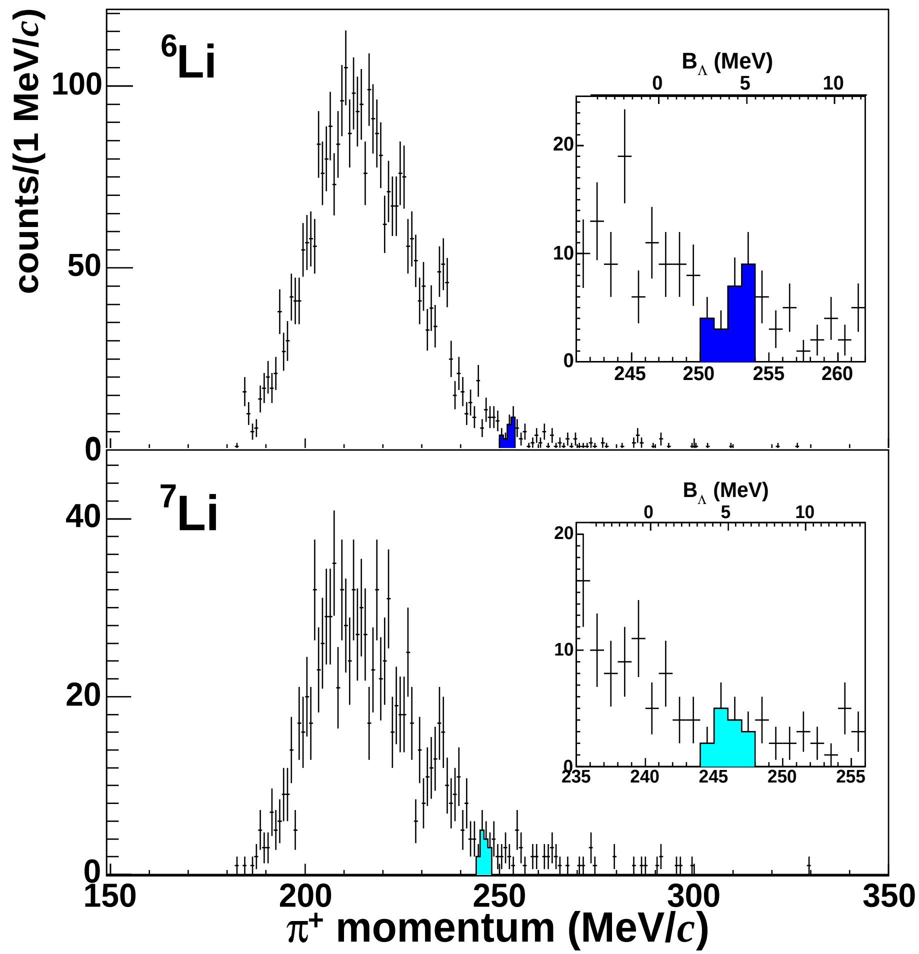
H. Tamura et al., Nucl. Phys. A 835 (2010) 3 [HYP09], updated at HYP12

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

FINUDA searches for ${}^{6,7}_{\Lambda}\mathrm{H}$ in $(K^-_{\rm stop}, \pi^+)$, PLB 640 (2006) 145



Raw $(K^-_{\rm stop}, \pi^+)$ spectra



Background subtracted spectra

$$R_{\pi^+}({}^{6}_{\Lambda}\mathrm{H}) < (2.5 \pm 0.4_{\rm stat}{}^{+0.4}_{-0.1\rm syst}) \cdot 10^{-5}/K^-_{\rm stop}$$

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

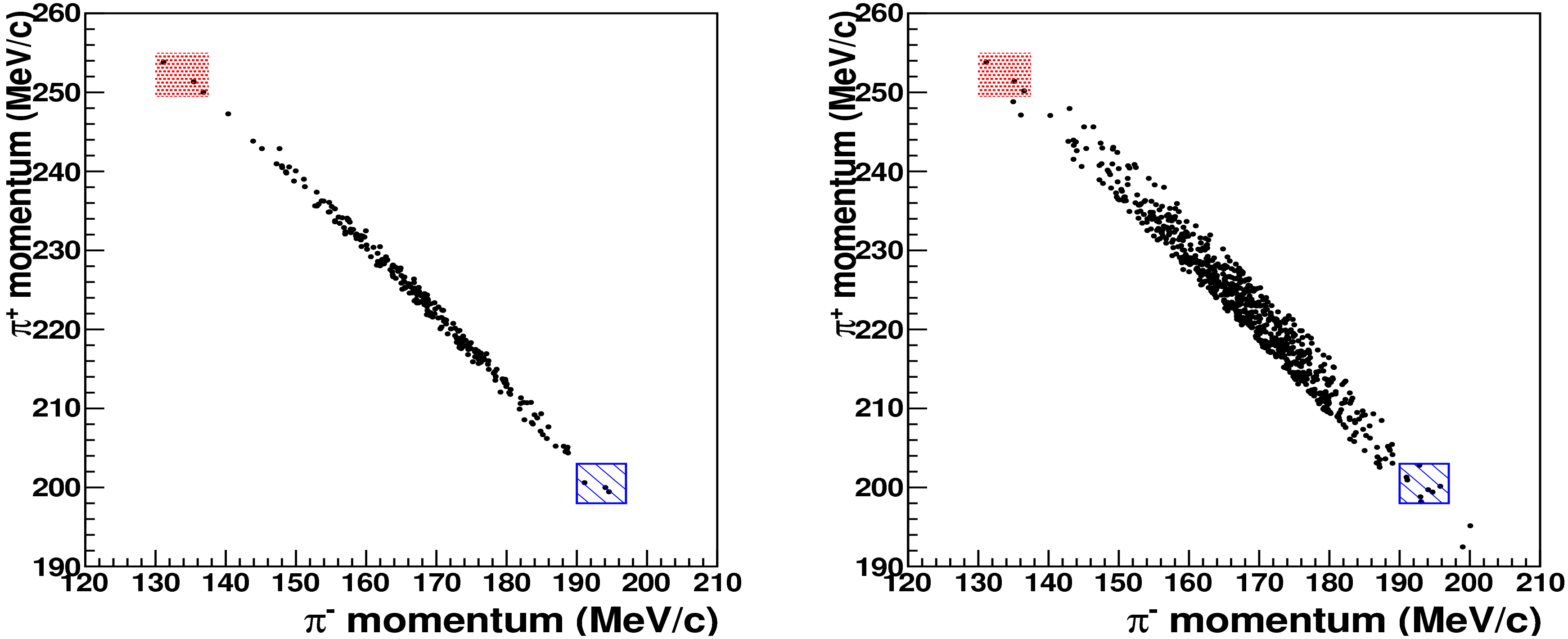
$$K^-_{\mathrm{stop}} + {}^6\mathrm{Li} \;\rightarrow\; {}^{6}_{\Lambda}\mathrm{H} + \pi^+ \quad (\sim 250 < p_{\pi^+} < 255\ \mathrm{MeV/c})$$

$$\hookrightarrow {}^6\mathrm{He} + \pi^- \quad (\sim 130 < p_{\pi^-} < 137\ \mathrm{MeV/c})$$

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

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



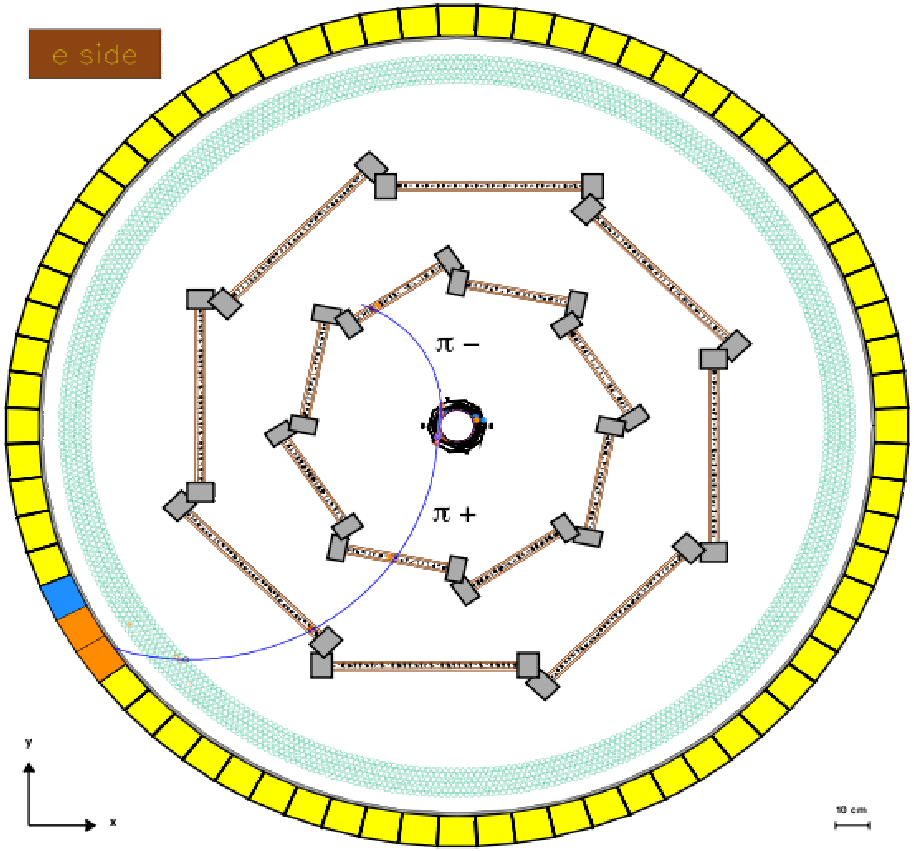
$T(\pi^+)$+$T(\pi^-)$=202–204 MeV (l.h.s.) 200–206 MeV (r.h.s.)

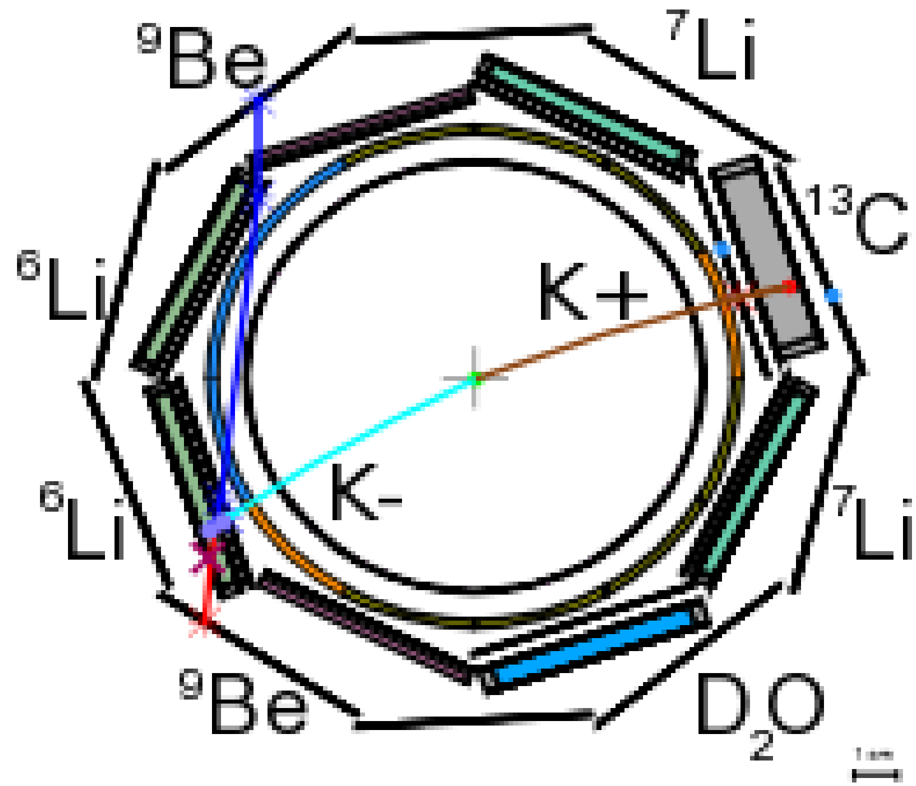
Red rectangles: p_{π^+}=250–255, p_{π^-}=130–137 MeV/c.

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

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

FINUDA's reconstructed ${}^{6}_{\Lambda}$H candidate event in ^{6}Li target

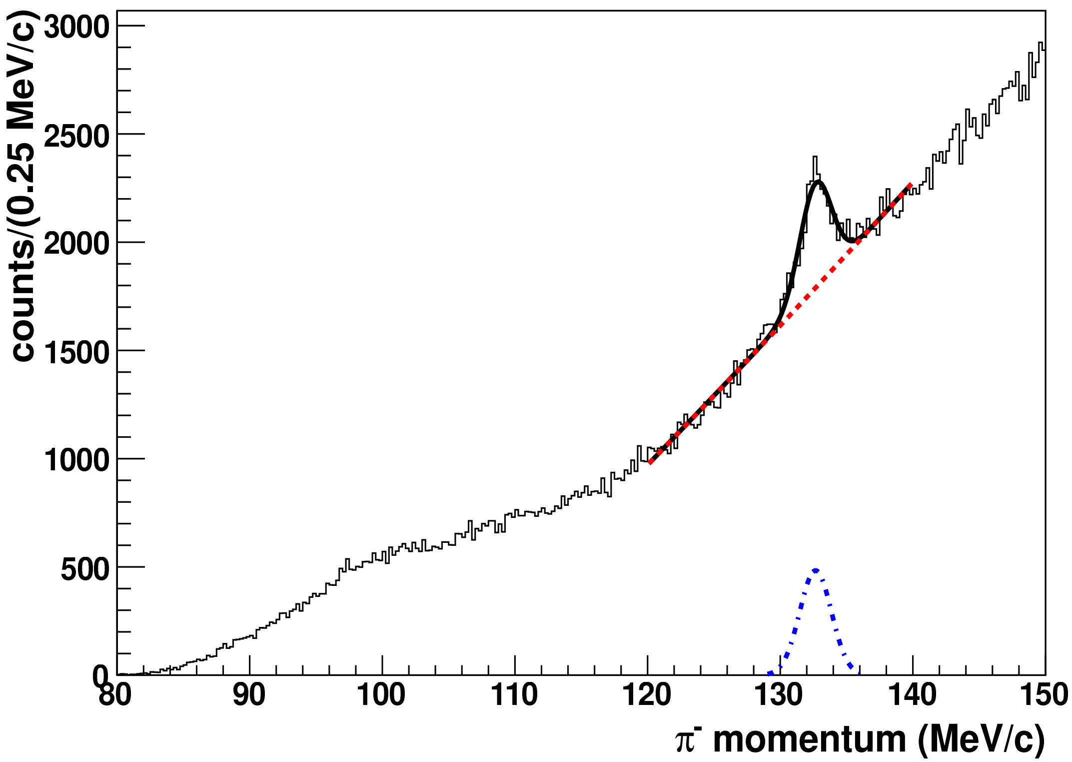




Left: a $\pi^{\pm}$ pair from ^{6}Li target crosses the spectrometer

Right: expanded view of a K^{-} track stopping in ^{6}Li target

FINUDA's distribution of low momentum π^- from ^{6}Li targets



120-140 MeV/c: QF $\Lambda \to p + \pi^-$ & $\Sigma^+ + \pi^-$ production plus

$^4_\Lambda\text{H} \to {}^4\text{He} + \pi^-$ $(p_{\pi^-} = 132.6 \pm 0.1,\ \sigma_{p(\pi^-)} = 1.2 \pm 0.1$ MeV/c)

Substantial $^4_\Lambda$H, and hence also $^4_\Lambda$He production.

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.**
- **$\Delta B_{\Lambda}({}^{4}_{\Lambda}$He–${}^{4}_{\Lambda}$H)=0.35(5) MeV: very large CSB.**

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

- **A. Nogga, NPA 914 (2013) 140**
  Faddeev & Fadeev-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 (2014) (arXiv:1403.3067)**
  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.**

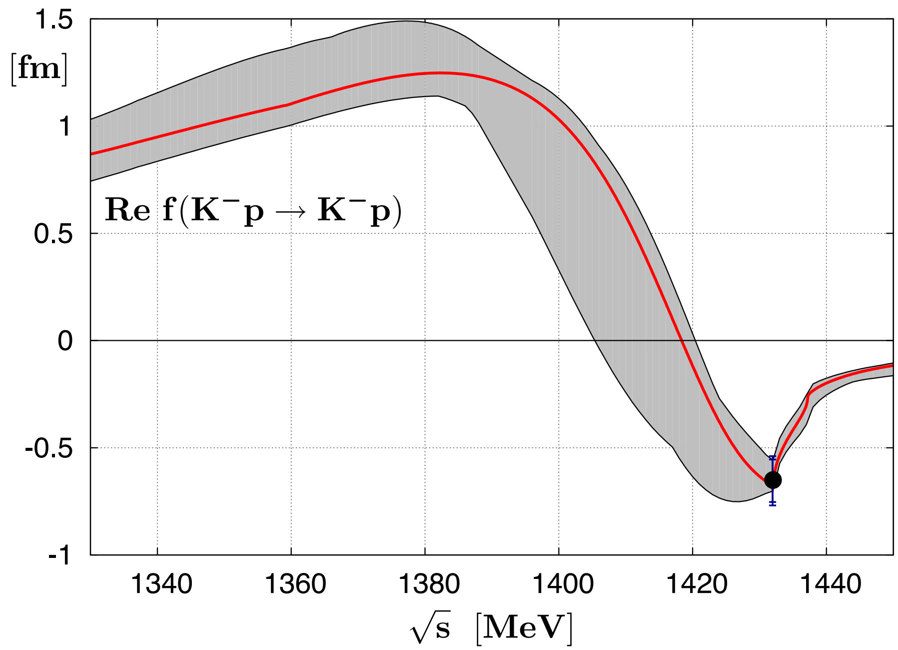
Studying the ${}^{4}_{\Lambda}$He–${}^{4}_{\Lambda}$H complex

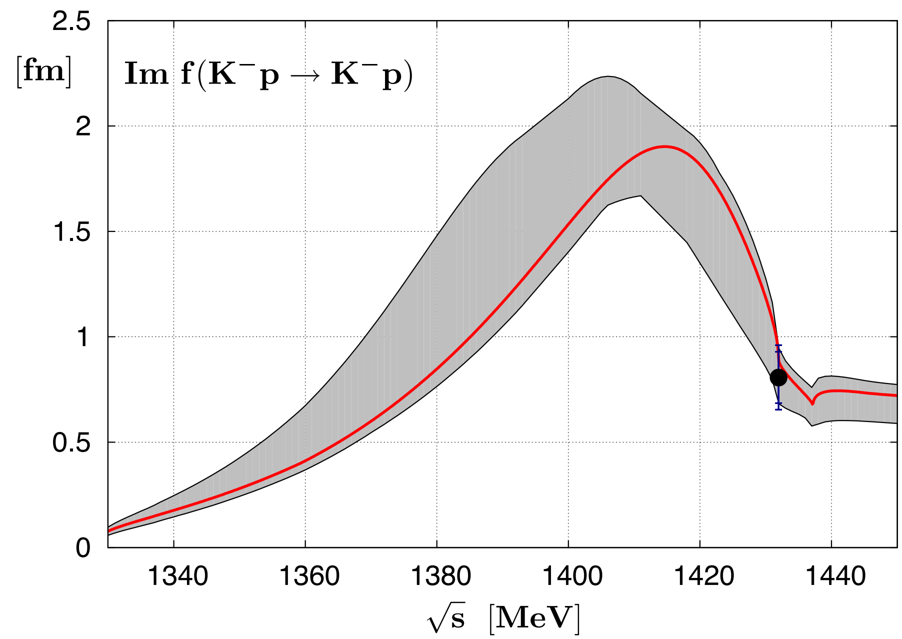
$$
\begin{aligned}
K^-_{\rm stop} + {}^6\mathrm{Li} \;&\rightarrow\; {}^{4}_{\Lambda}\mathrm{He} + d + \pi^- \\
&\qquad \hookrightarrow {}^4\mathrm{He} + \pi^0 \\
K^-_{\rm stop} + {}^6\mathrm{Li} \;&\rightarrow\; {}^{4}_{\Lambda}\mathrm{H} + d + \pi^0 \\
&\qquad \hookrightarrow {}^4\mathrm{He} + \pi^-
\end{aligned}
$$

- **^{7}Li target is also possible.**
- **$1^+_{\rm exc.}$ formation suppressed w.r.t. $0^+_{\rm g.s.}$.**
- **MAMI(preliminary): $B_\Lambda({}^{4}_{\Lambda}\mathrm{H})$=2.14±0.1 MeV, consistent with emulsion's 2.04±0.04 MeV.**
- **Measure $B_\Lambda({}^{4}_{\Lambda}\mathrm{He})$ to ±0.1 MeV from π^0 decay.**

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^-pp calculated binding energies & widths

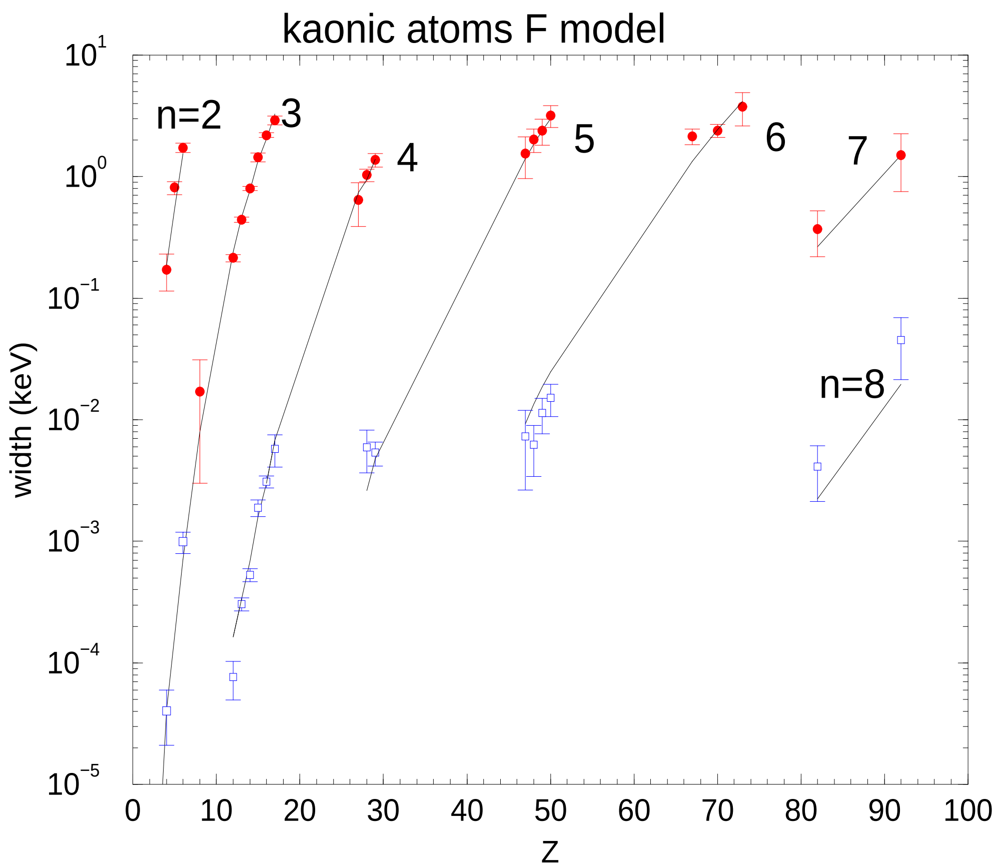
(MeV)	chiral, energy dep. calculations				non-chiral, static calculations			
	var. [1]	var. [2]	Fad. [3]	Fad. [4]	var. [5]	Fad. [6]	Fad. [7]	var. [8]
B	16	17–23	9–16	32	48	50–70	60–95	40–80
Γ	41	40–70	34–46	49	61	90–110	45–80	40–85

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)

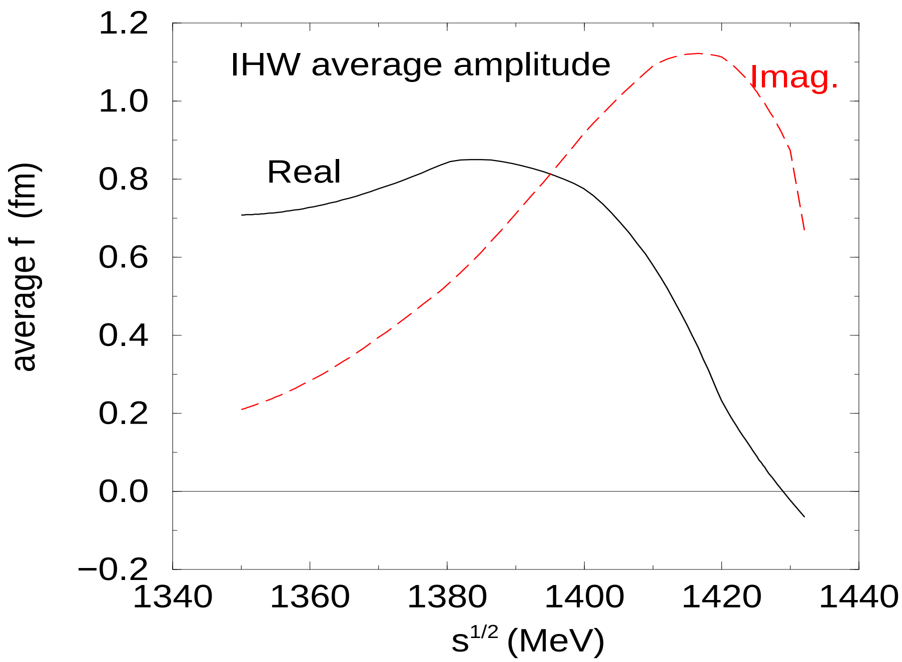
What do K^- atoms tell us?

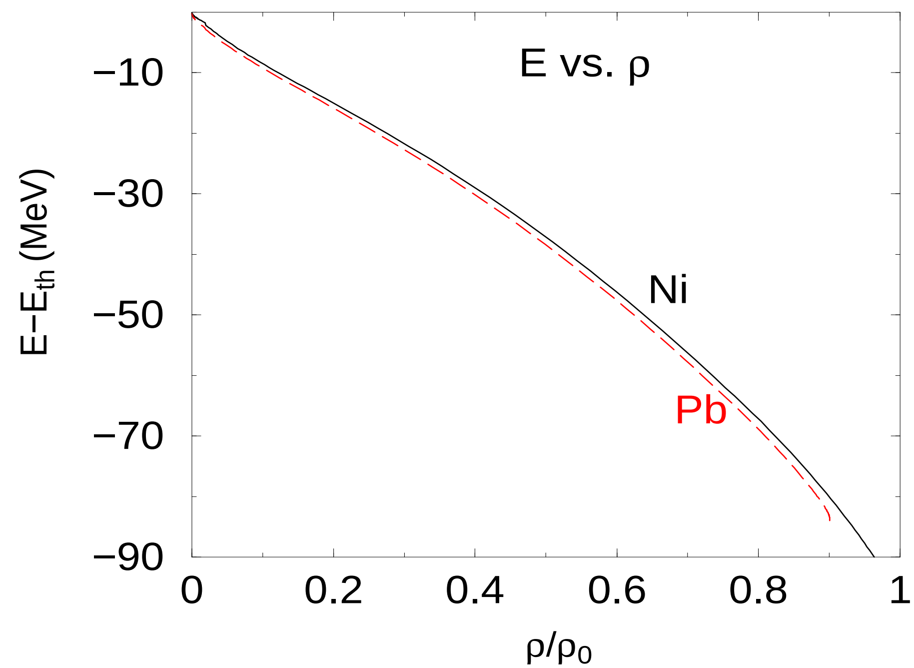


$K^-_{\rm atom}$ widths across the periodic table in model F (deep pot.)

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

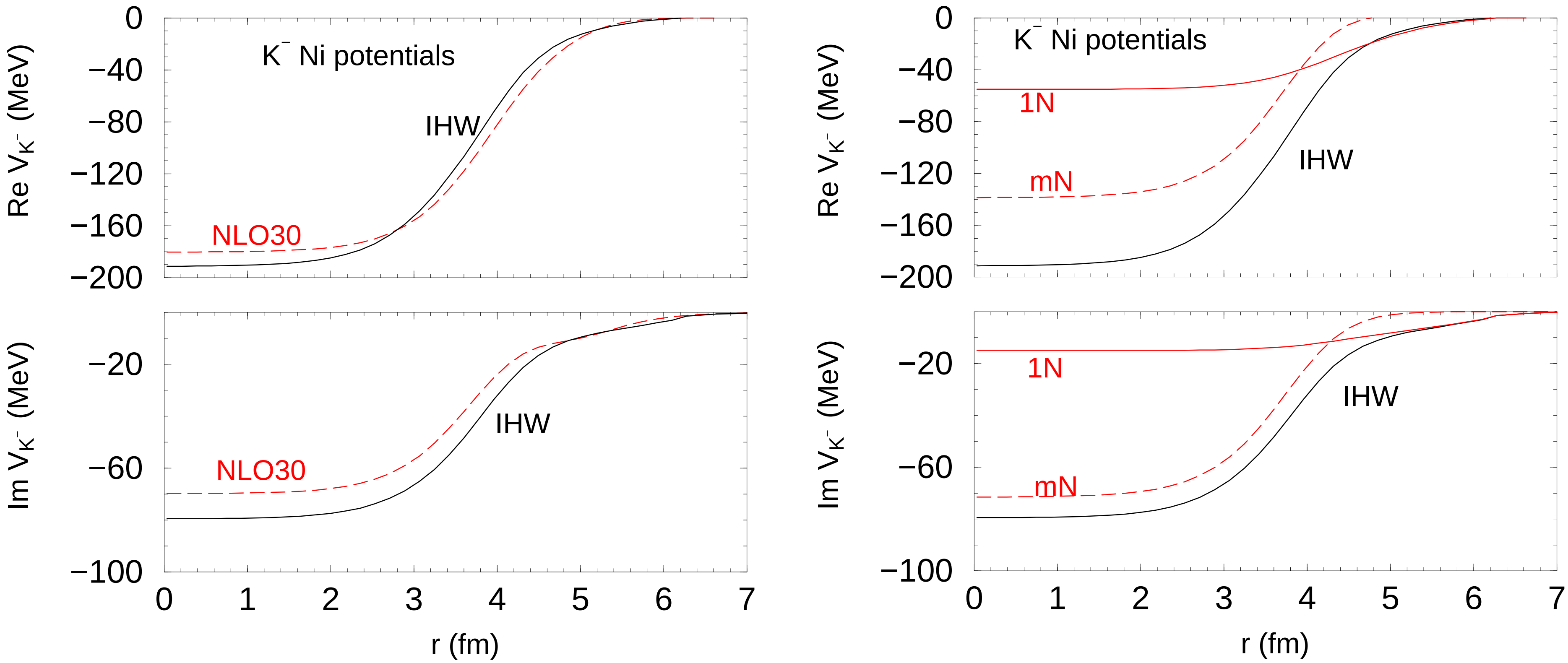
E. Friedman, A. Gal, Phys. Rep. 452 (2007) 89.





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 $\chi^2/N_{\rm data}^{\rm atom}$=118/65**   **Friedman-Gal, NPA 899 (2013) 60.**



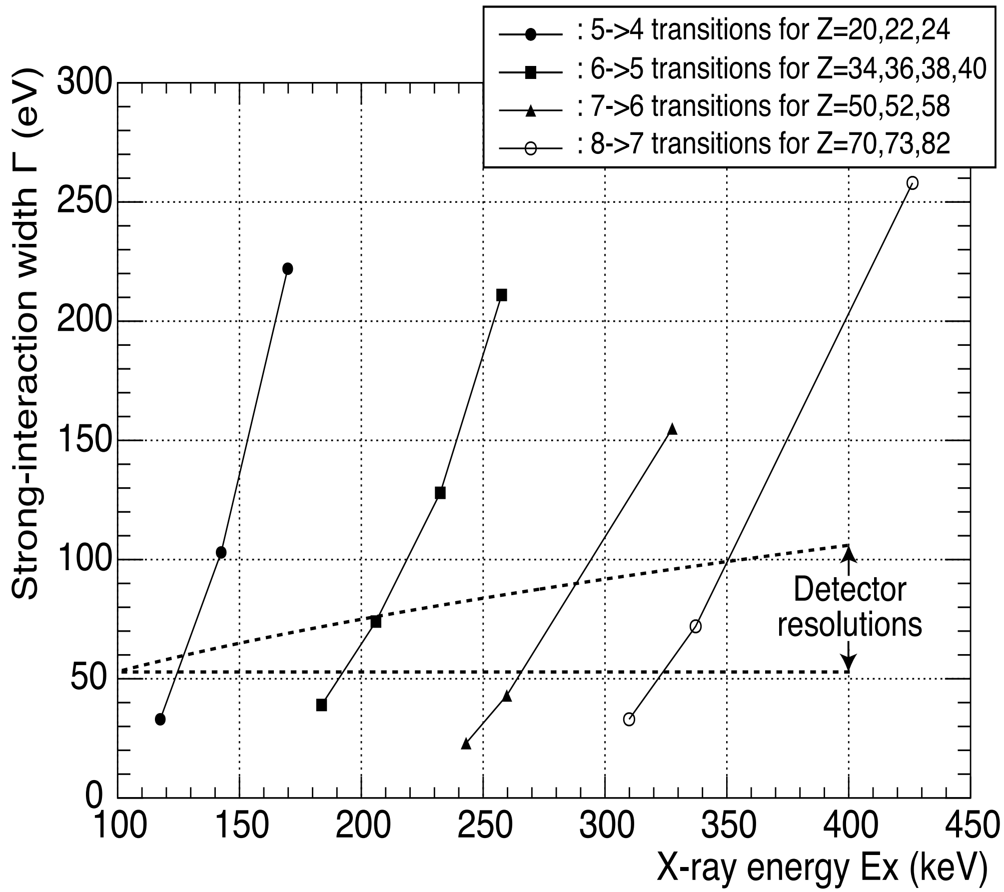
NLO30: A. Cieply, J. Smejkal, NPA **881** (2012) 115 (in-medium).

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

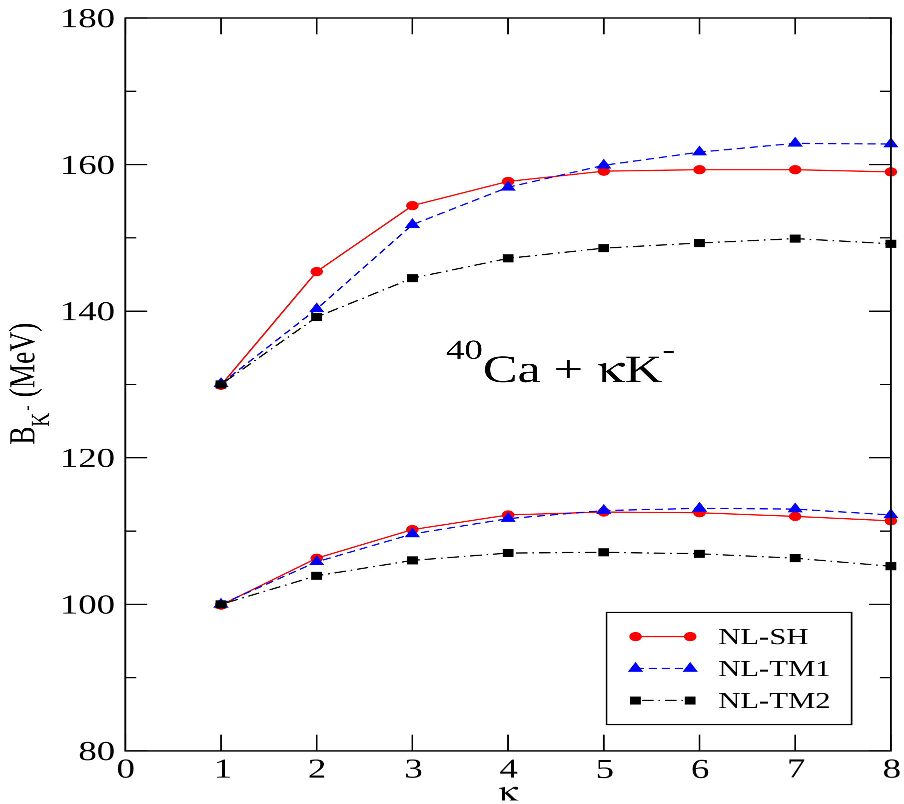
Kaonic-atom best-fit V_{K^-} for Ni & its non-additive breakdown into in-medium 1N and phenomenological m(any)N contributions.

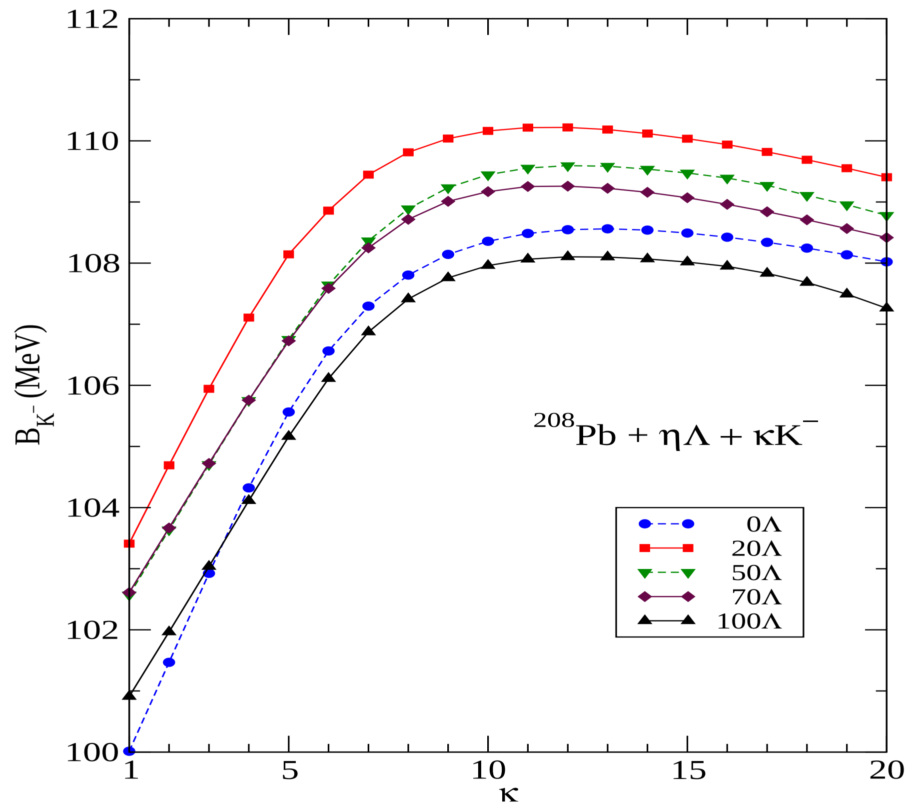
Upper level sensitive to 1N & lower level to mN terms. Measure both selectively [Friedman-Okada, NPA 915 (2013) 170].

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 (Okada's talk).





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 & LNF assignments

- 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.
- 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.
- Do K^-d (SIDDHARTA-2) to constrain K^-n.
- Establish experimental program for precise K^- atom selective measurements.