Y-Nucleus potentials from Hypernuclei

EMMI Workshop, Bologna, Feb. 2023

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ΛNN vs. ΛN content of V_Λ

A $V_\Lambda^{\rm opt}$ applied to $1s_\Lambda$, $1p_\Lambda$ states, $12 \leq A \leq 208$,
suggests $\approx$14 MeV repulsive ΛNN component,
thereby constraining the 'hyperon puzzle'.
E. Friedman, A. Gal, PLB 837 (2023) 137669

V_Ξ from Ξ^- capture events

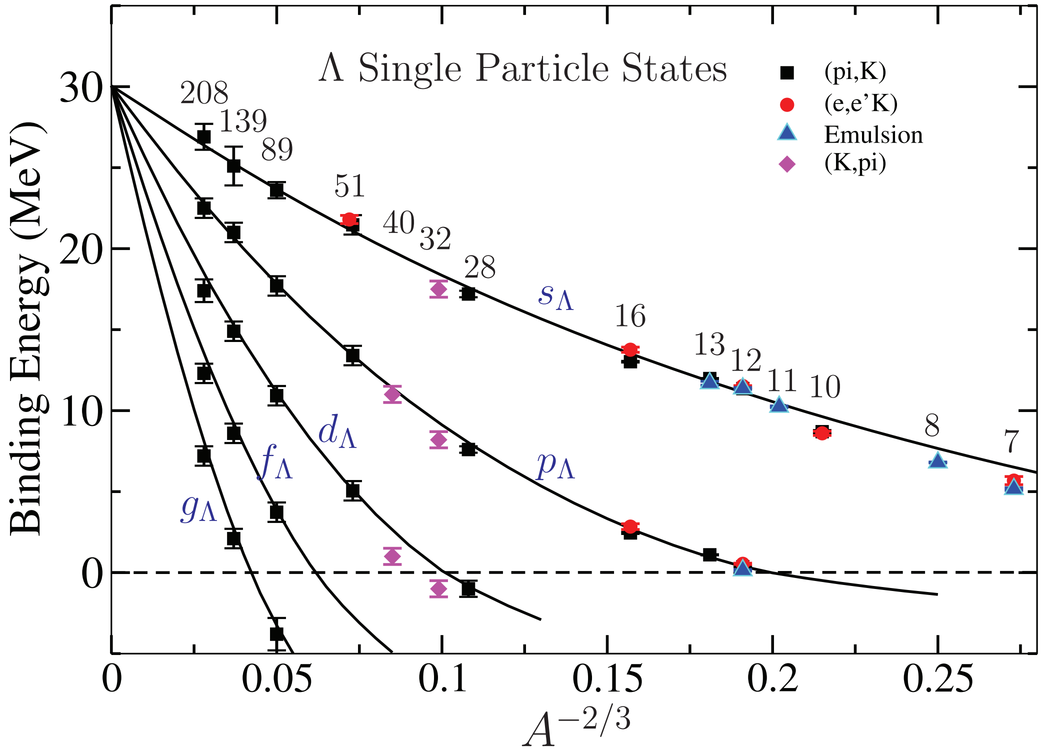
All five KEK & J-PARC $\Xi^- + {}^{A}$Z $\rightarrow$ ${}^{A'}_{\Lambda}$Z'+${}^{A''}_{\Lambda}$Z" capture
events in light-nuclei emulsion occur in $1p_{\Xi^-}$ nuclear states,
suggesting attractive $V_\Xi \geq$20 MeV.
E. Friedman, A. Gal, PLB 820 (2021) 136555

J-PARC E07 $1s_{\Xi^-}$ assignments in ^{14}N are questioned.
E. Friedman, A. Gal, PLB 837 (2023) 137640

ΛNN vs. ΛN content of $\mathbf{V}_{\Lambda}^{\rm opt}$

from Λ hypernuclei

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



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

B_Λ values in ${}^{7}_{\Lambda}$Li to ${}^{208}_{\Lambda}$Pb from experiment and as calculated from a 3-parameter WS potential, suggesting a Λ-nucleus potential depth $D_\Lambda \approx -30$ MeV.

Data: Table IV Gal-Hungerford-Millener, RMP 88 (2016) 035004.

D_Λ in ΛN-ΣN models

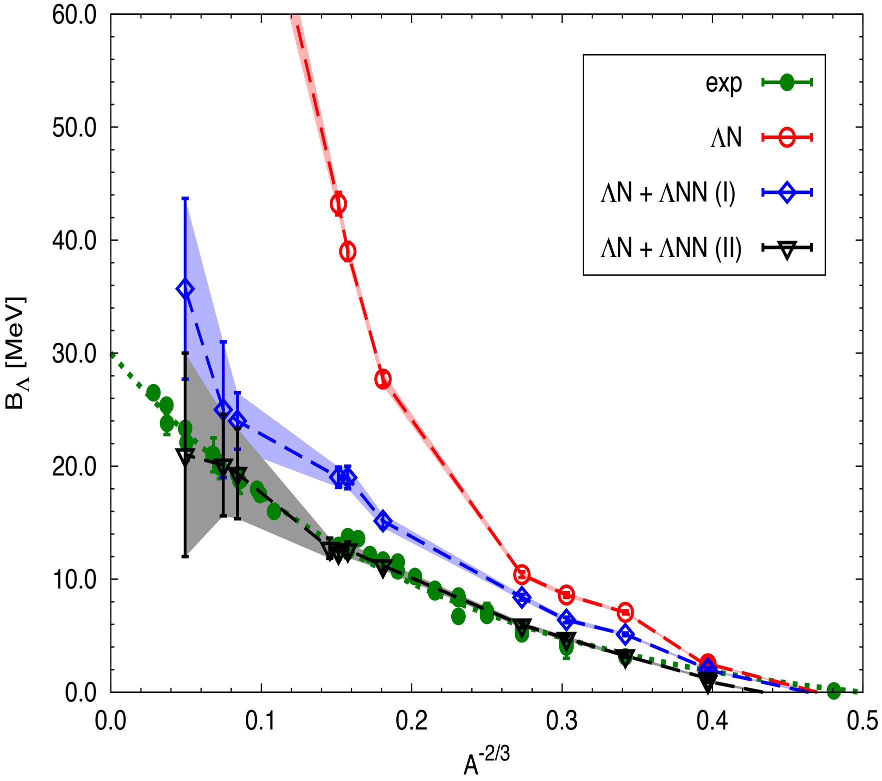
Most 2-body YN models overbind: $|D_\Lambda^{(2)}| > 30$ MeV.

- NSC and ESC models overbind, with $D_\Lambda^{(2)} \sim -40$ MeV.
- χEFT(LO) overbinds, substantial cutoff dependence.
- χEFT(NLO): substantial model & cutoff dependence. NLO13 underbinds, but does best for repulsive $D_\Sigma^{(2)}$.
- χEFT(N^2LO) overbinds, $D_\Lambda^{(2)} \approx -(33\pm3)$ MeV.

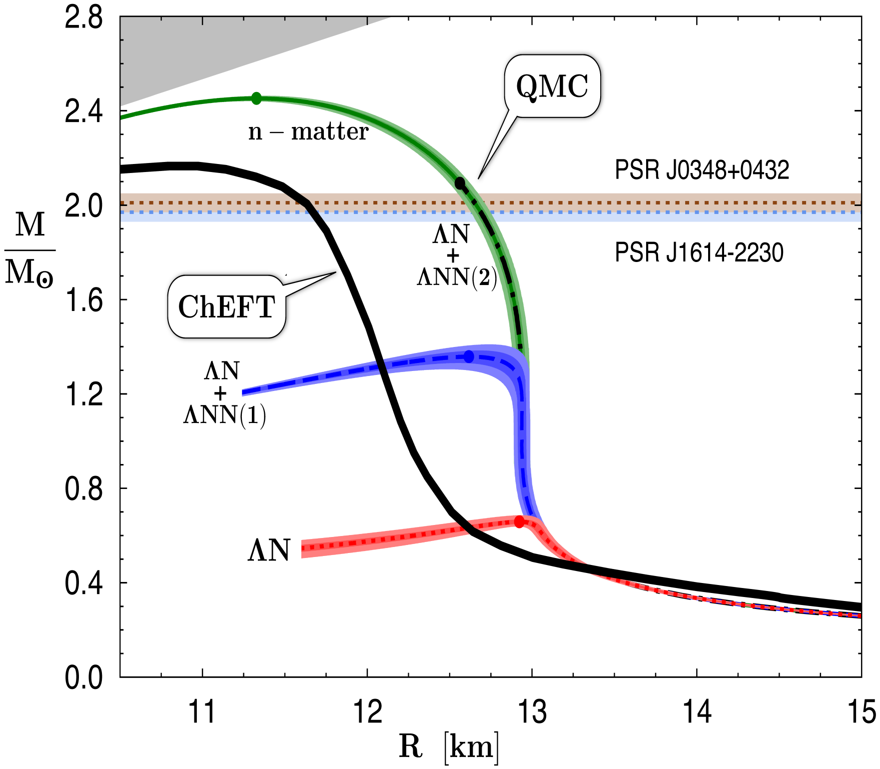
Underbinding would be disastrous for neutron-star matter considerations, implying attractive ΛNN contribution $D_\Lambda^{(3)}$ which will soften the EoS at sufficiently large density.

If repulsive, how large $D_\Lambda^{(3)}$ is?

Hyperon puzzle: AFDMC calculations



Lonardoni et al, PRC 89 (2014) 014314



PRL 114 (2015) 092301

- **ΛN overbinds; added ΛNN stiffens neutron-star EoS.**
- **However, problematic ${}^{5}_{\Lambda}$He & unlisted ${}^{17}_{\Lambda}$O B_Λ input.**
- **Produced nuclear radii are ≈20% too small.**

Critique of Skyrme-Hartree-Fock (SHF)

Millener-Dover-Gal, PRC 38 (1988) 2700
Schulze-Hiyama, PRC 90 (2014) 047301

$$V_\Lambda(\rho_N) = [\, V_\Lambda^{(2)}(\rho_N) = a_0\rho_N \,] + [\, V_\Lambda^{(3)}(\rho_N) = a_3\rho_N^2 \,]$$

is fitted to some $\mathrm{B}_\Lambda(\mathrm{A})$ data points $[\rho_0{=}0.17\ \mathrm{fm}^{-1}]$

Ref.	**Points**	$V_\Lambda^{(2)}(\rho_0)$	$V_\Lambda^{(3)}(\rho_0)$	$V_\Lambda(\rho_0)$ **(MeV)**
MDG88	**3**	**−57.8**	**31.4**	**−26.4**
SH14	**35**	**−55.4**	**20.4**	**−35.0** †
present (Q)	**2**	**−57.6**	**30.2**	**−27.4**

† **≈ −31 MeV adding $\mathrm{M_{eff}}(\Lambda)$ contribution.**

- **Introduce (WRW) Pauli correlations at $\rho^{4/3}$, affecting higher density powers, e.g., ρ^2.**
- **WRW: Waas-Rho-Weise, NPA 617 (1997) 449, practised since 2013 in K^- atoms analyses.**

WRW density dependence of V_Λ

$$\Lambda N \quad \Rightarrow \quad V_\Lambda^{(2)}(\rho) = -\frac{4\pi}{2\mu_\Lambda}\, b_0^{\mathrm{lab}}(\rho)\, \rho$$

$$b_0^{\mathrm{lab}}(\rho) = \frac{b_0^{\mathrm{lab}}}{1 + \frac{3k_F}{2\pi}\, b_0^{\mathrm{lab}}} \qquad b_0^{\mathrm{lab}} = (1 + \frac{A-1}{A}\frac{\mu_\Lambda}{m_N})\, b_0$$

for Pauli correlations, with $\mathbf{k}_F = (\mathbf{3}\pi^2\rho/\mathbf{2})^{1/3}$.

Short-range correlations negligible at $\rho \le \rho_0$.

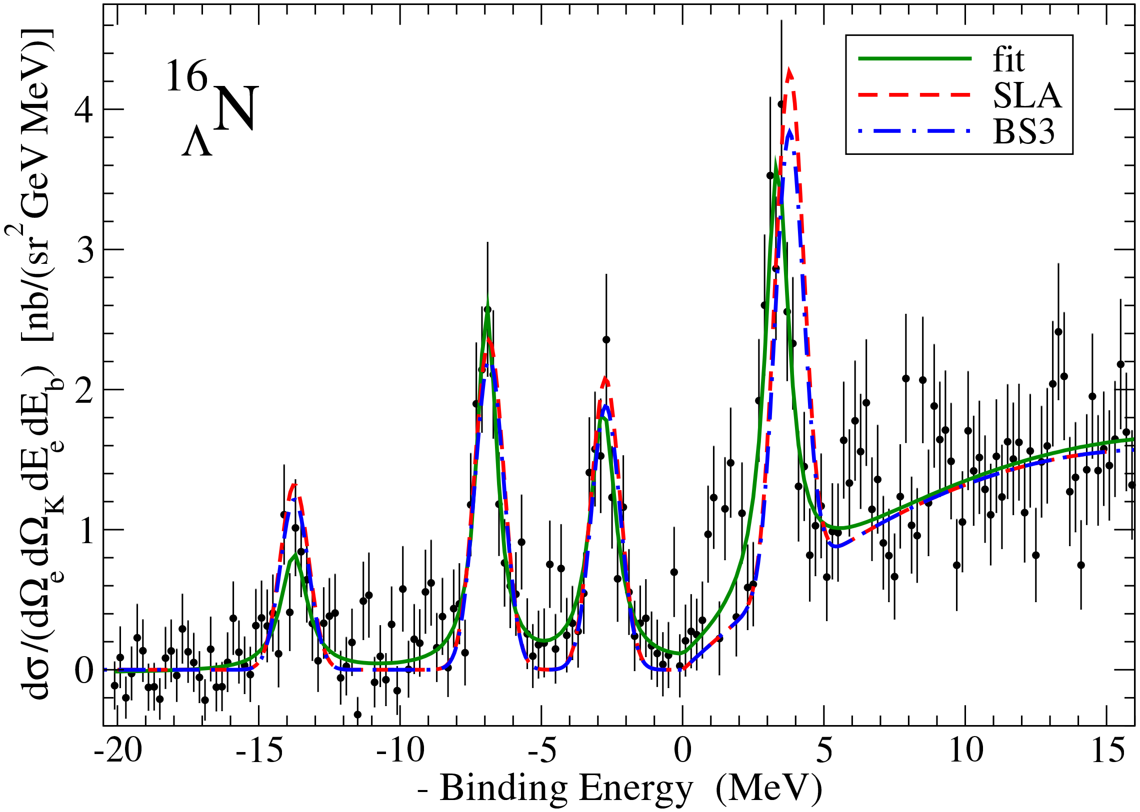
Pauli affects terms beyond $\rho^{4/3}$, e.g., ρ^2.

Low density limit: $b_0 = \Lambda$N scattering length.

$$\Lambda N N \quad \Rightarrow \quad V_\Lambda^{(3)}(\rho) = +\frac{4\pi}{2\mu_\Lambda}\, B_0^{\mathrm{lab}}\, \frac{\rho^2}{\rho_0}$$

Applying Pauli to $V_\Lambda^{(3)}(\rho)$ has a minor effect.

Fit b_0 and B_0^{lab} to $\mathbf{B}_\Lambda^{1s,1p}({}^{16}_{\Lambda}\mathbf{N})$.

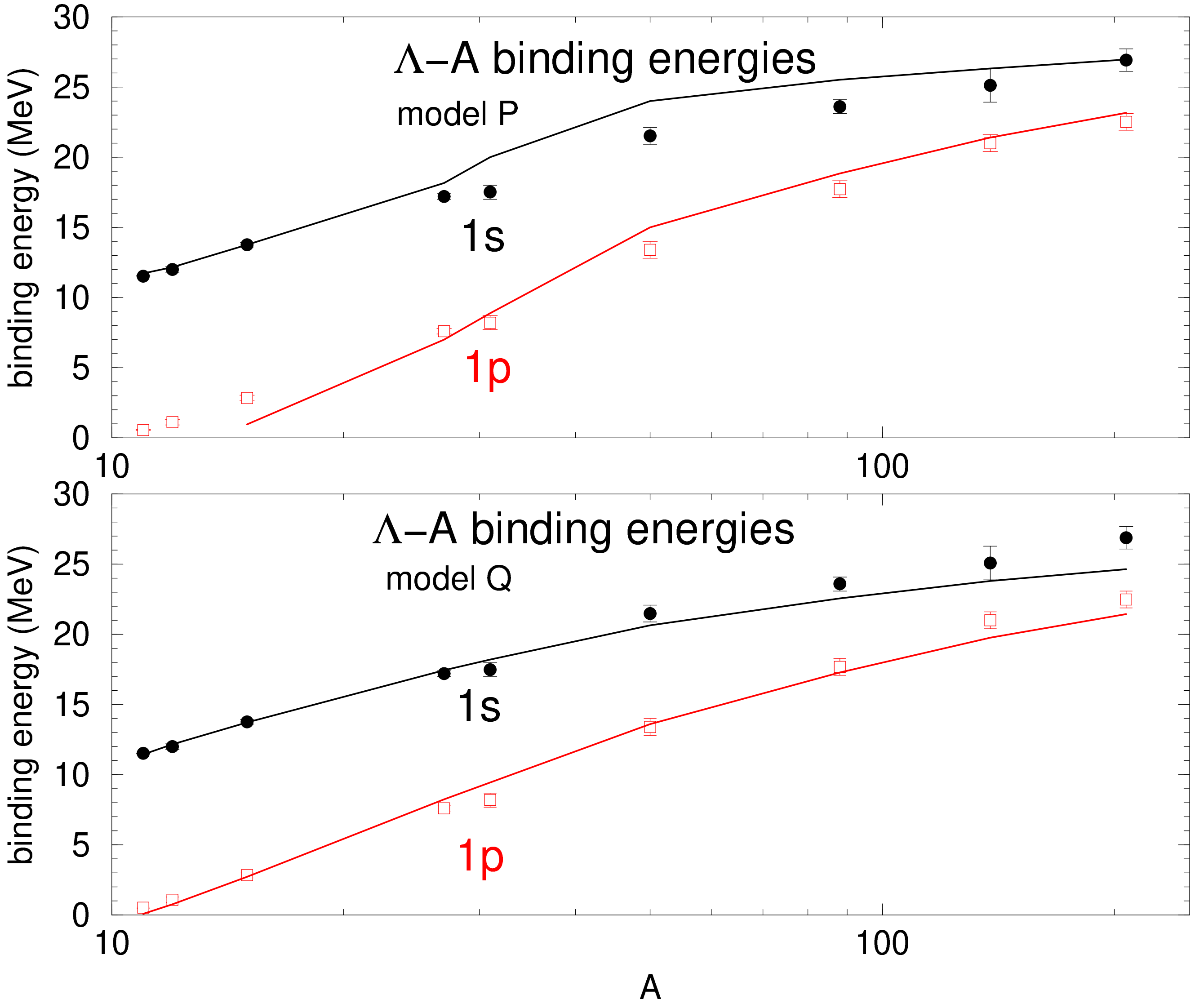


${}^{16}_{\Lambda}$N spectrum from JLab Hall A (e,e'K$^+$) experiment

PRL (2009) & PRC 99 (2019) 054309

Why ${}^{16}_{\Lambda}$N? – (i) very accurate data

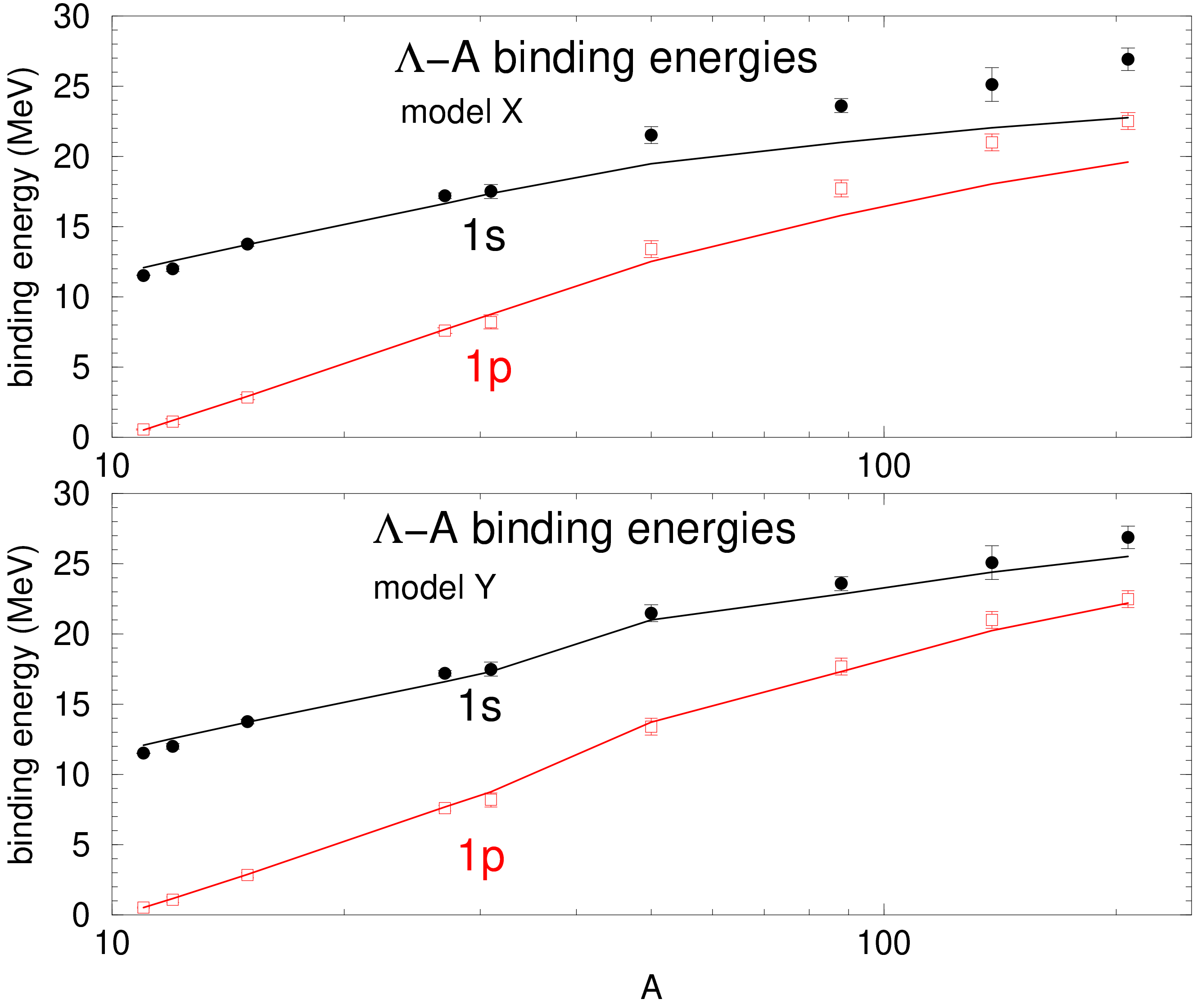
(ii) end of p-shell, very simple s.p. structure



$B_{\Lambda}^{1s,1p}$(A) in Models P,Q fitted to ${}^{16}_{\Lambda}$N. No Pauli

Model P: $b_0 \neq 0$, $B_0 = 0$ Model Q: $b_0 \neq 0$, $B_0 \neq 0$

Model Q results close to SHF results



$B_{\Lambda}^{1s,1p}(A)$ **in Models X,Y fitted to** $^{16}_{\Lambda}N$. **Pauli added to** $b_0 \neq 0$ **&** $B_0 \neq 0$. **In Model Y, neutron excess is decoupled from sym. nucl. matter:** $\rho^2 = (\rho_{\rm sym} + \rho_{\rm exc})^2 \rightarrow (\rho_{\rm sym}^2 + \rho_{\rm exc}^2)$.

ΛN & ΛNN contributions to D_Λ

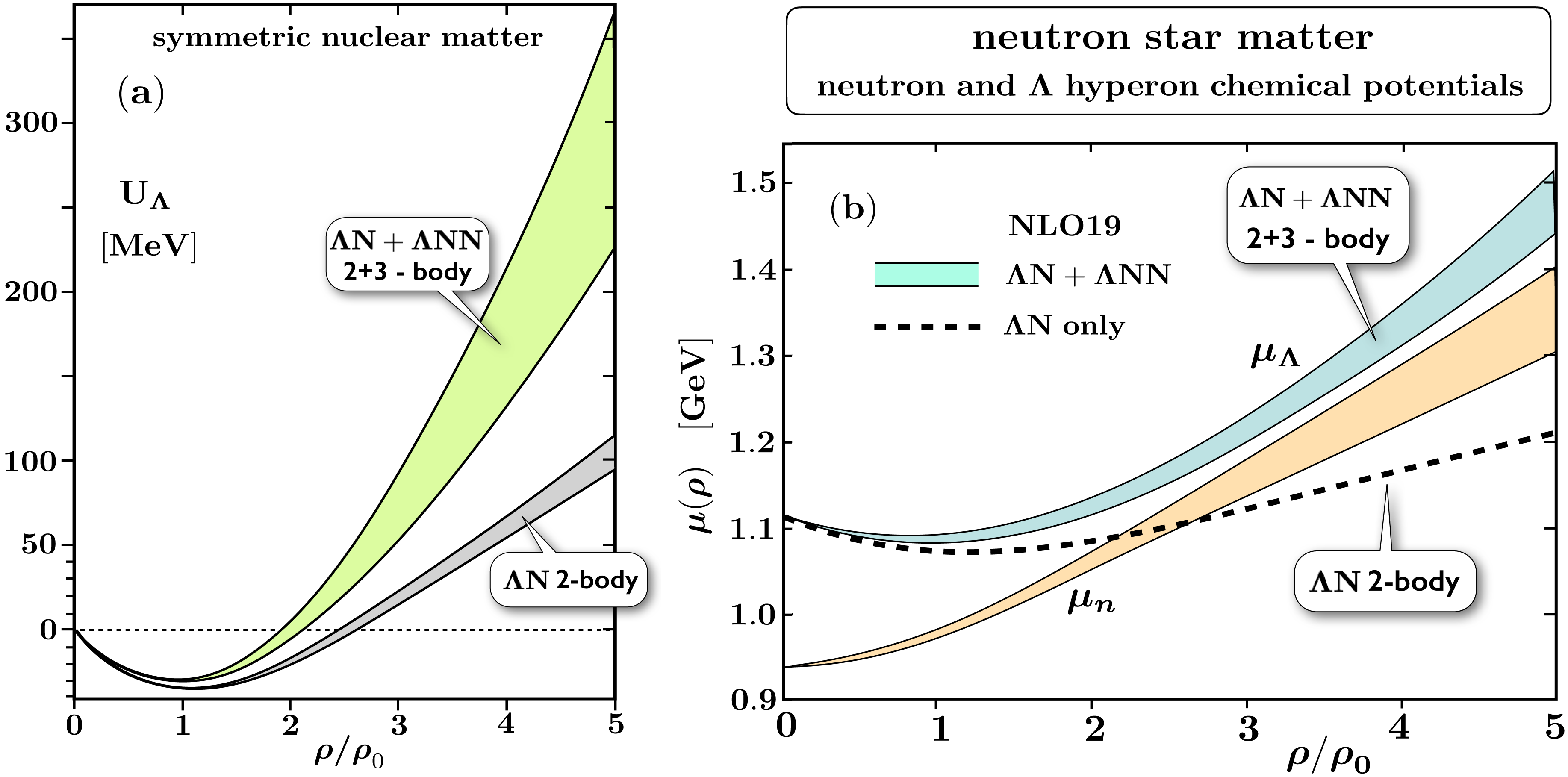
Model	Pauli	$D_\Lambda^{(2)}$	$D_\Lambda^{(3)}$	D_Λ (MeV)
P	No	−34.1	–	−34.1
P’	Yes	−31.3	–	−31.3
MDG88	No	−57.8	31.4	−26.4
Q	No	−57.6	30.2	−27.4
X,Y	Yes	−39.9	13.9	−26.0

- **Final depth values, including uncertainties:** $D_\Lambda^{(2)}=-40.4\pm0.6$ MeV, $D_\Lambda^{(3)}=13.9\pm1.4$ MeV $D_\Lambda=-26.5\pm1.5$ MeV.

- **AFDMC depths: scale $\rho_0=0.17$ fm^{-3} by r_N^{-3}.** $D_\Lambda^{(2)}=-78.9\pm1.2$ MeV, $D_\Lambda^{(3)}=53.0\pm5.3$ MeV $D_\Lambda=-26.5\pm1.5$ MeV.

ΛNN summary & outlook

- $\mathrm{V}_\Lambda^{\mathrm{opt}}$ applied to Λ single-particle states across the periodic table.
- Pauli corrected ΛN term, plus ΛNN term.
- Implicit isospin dependence in ΛNN term: neutron-excess density decoupled from symmetric nuclear-matter density.
- Final depth values, including uncertainties: $\mathrm{D}_\Lambda^{(2)}=-40.4\pm0.6$ MeV with $\mathrm{b}_0 \approx 1.7$ fm, $\mathrm{D}_\Lambda^{(3)}=13.9\pm1.4$ MeV, $\mathrm{D}_\Lambda=-26.5\pm1.5$ MeV.
- $\mathrm{D}_\Lambda^{(3)} \approx 14$ MeV excludes in EFT Λ hyperons from dense neutron-star matter, $\mu_\Lambda > \mu_n$, see Gerstung-Kaiser-Weise, EPJA 56 (2020) 175.



W. Weise, EPJ Web Conf. 271 (2022) 06003

Following Gerstung-Kaiser-Weise, EPJA 56 (2020) 175

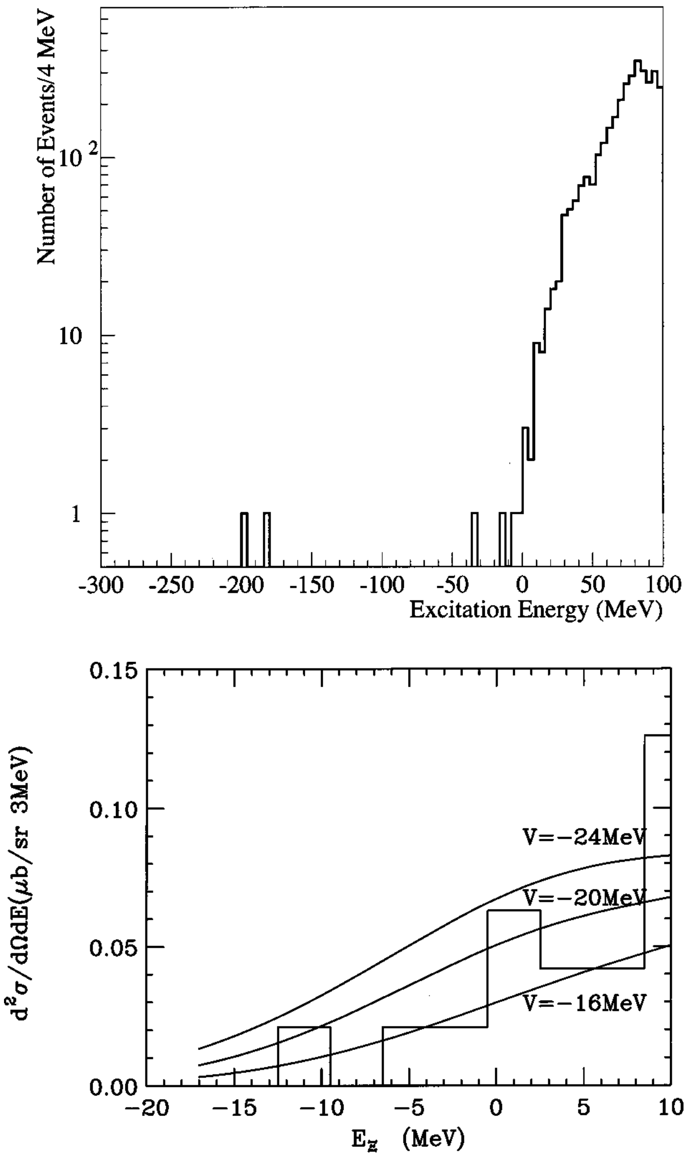
Ξ^- nuclear physics

from counter experiments,

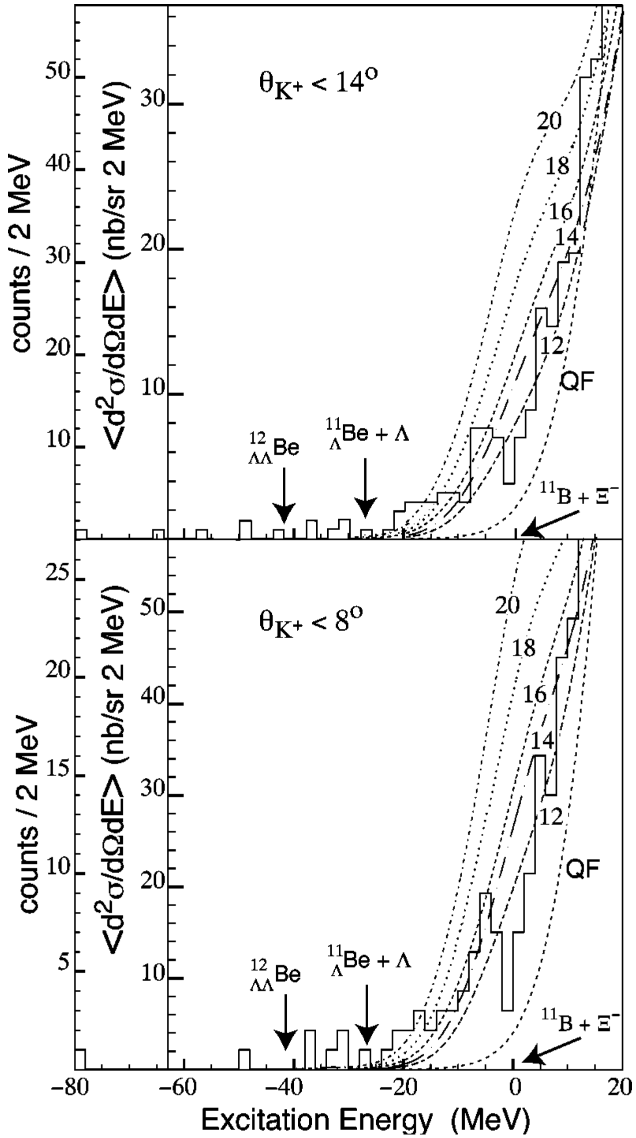
from theory and femtoscopy,

& from capture in emulsion nuclei

E224 (KEK)

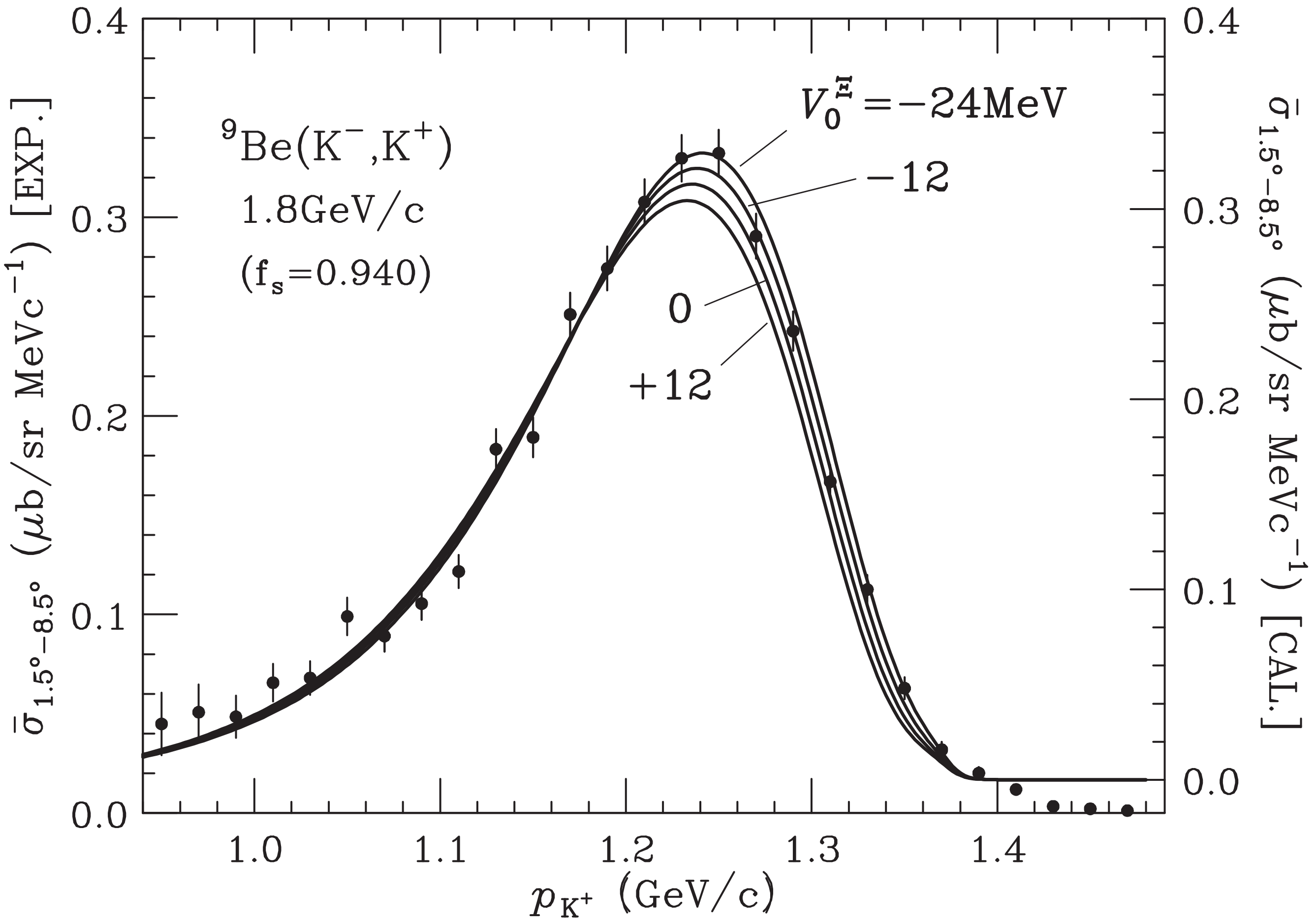


E885 (BNL)



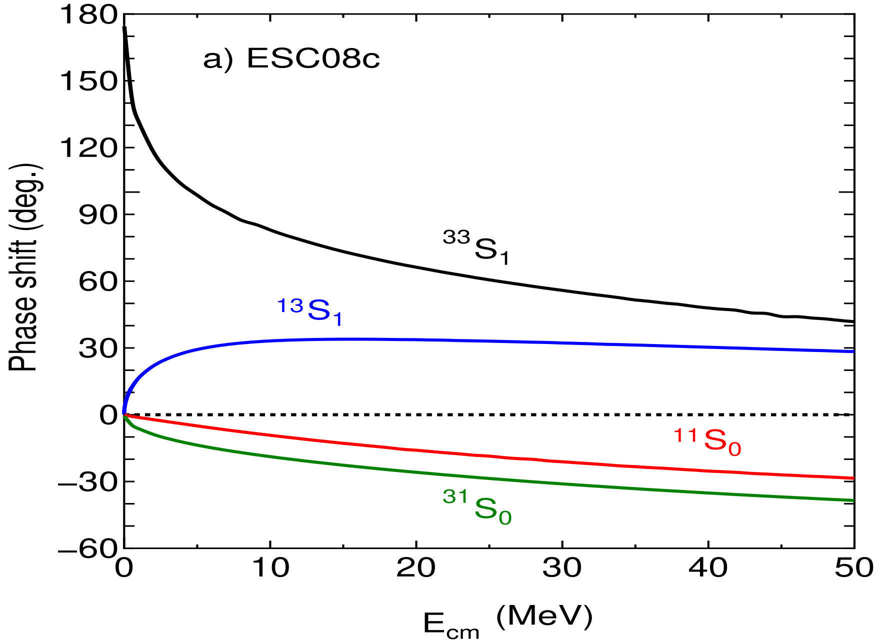
^{12}C(K^{-},K^{+}) counter experiments, end of 1990s.

Unresolved bound states, if any, V_{Ξ} of order 15 MeV

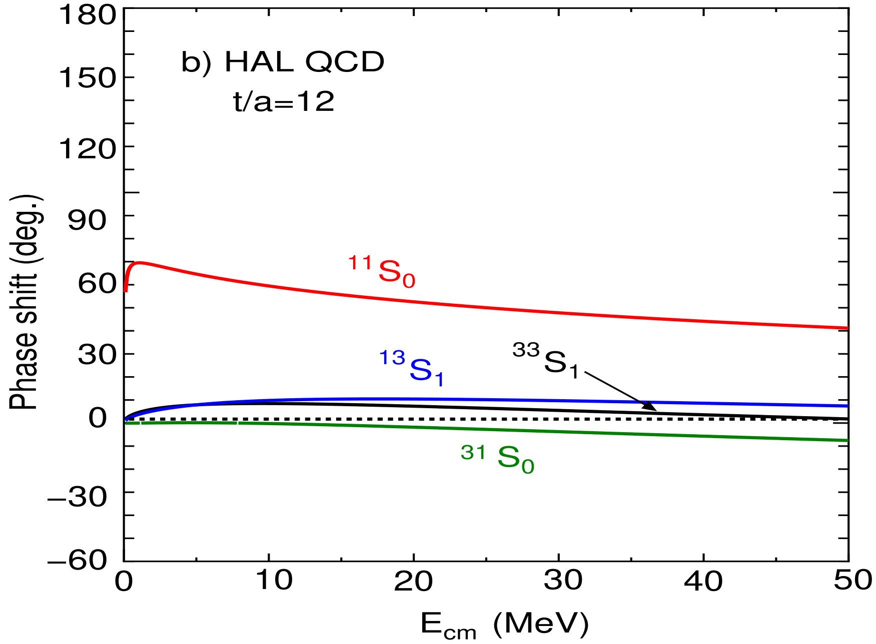


BNL AGS-906 on ^{9}Be. A QF calculation by Harada & Hirabayashi, PRC 103 (2021) 024605 concludes V_Ξ=17±6 MeV. Yet, no Ξ^- bound-state smoking gun from (K^-, K^+) experiments. Await J-PARC final E05 & future E70 results.

ΞN s-wave model interactions



Nijmegen ESC08c version



HAL-QCD version

Hiyama et al. PRL 124 (2020) 092501: A$\leq$4 Ξ hypernuclei

Substantial model dependence

HAL-QCD: LQCD calculation at $m_{\pi(K)}$=146(525) MeV

Sasaki et al. NPA 998 (2020) 121737

Inoue et al. AIPCP 2130 (2019) 020002: $V_{\Xi}^{\rm LQCD}$=4±2 MeV

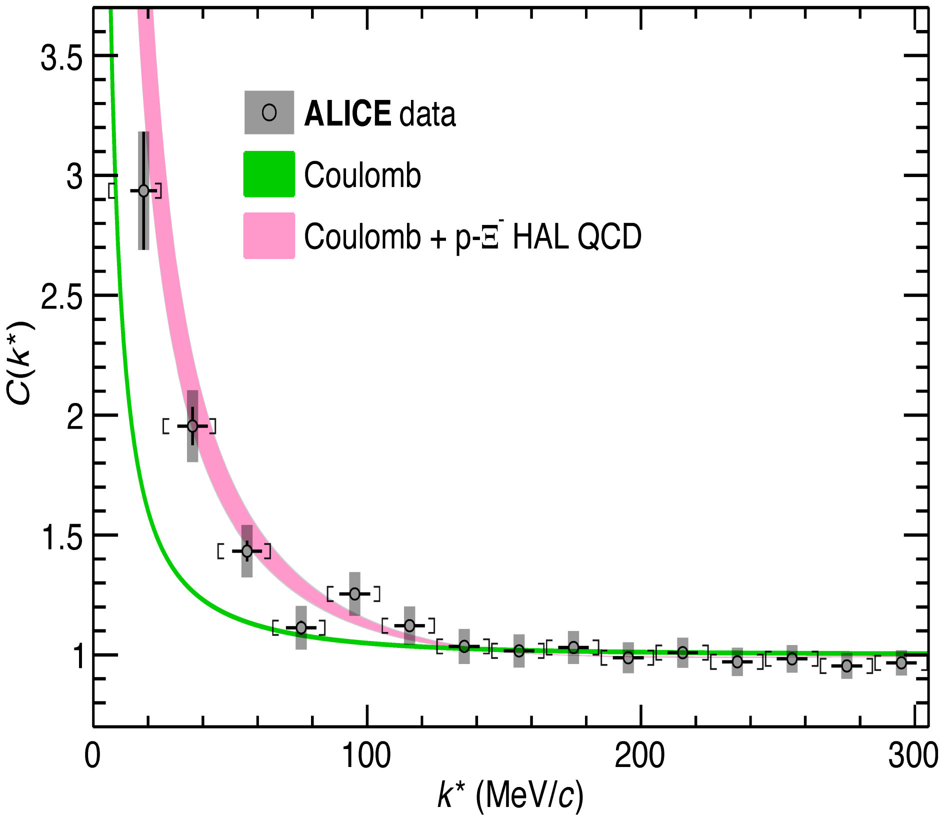
Kohno, PRC 100 (2019) 024313: $V_{\Xi}^{\rm EFT} \approx 10$ MeV

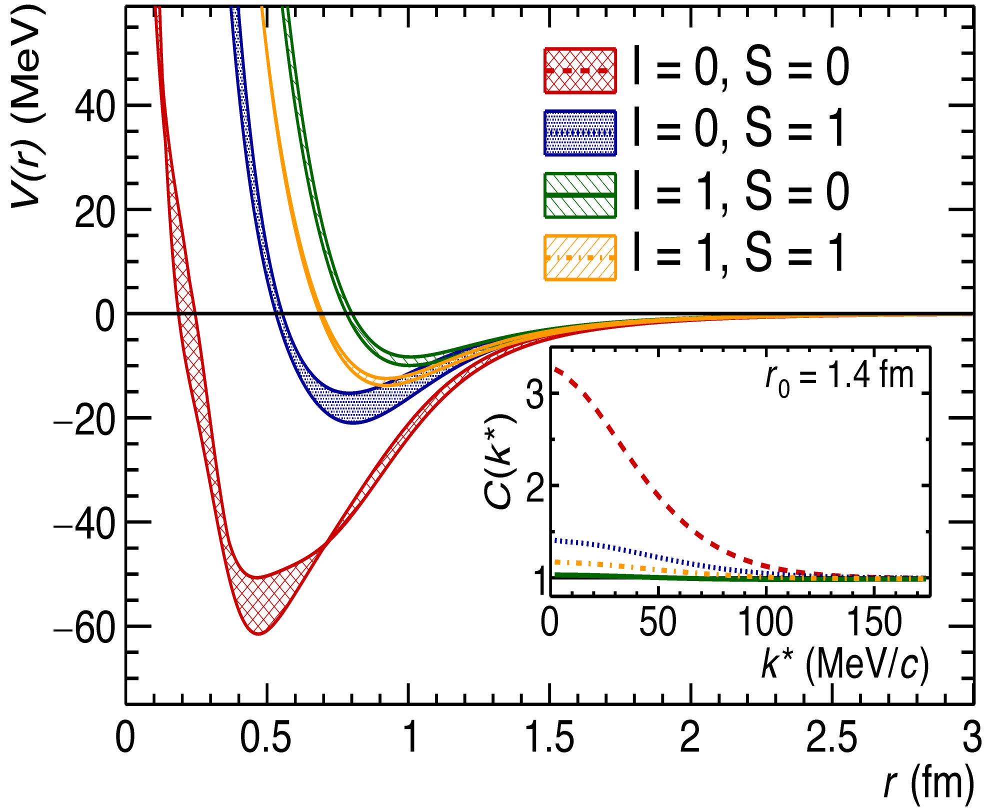
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

attractive HAL-QCD – yes

repulsive Nijmegen ESC16 – no

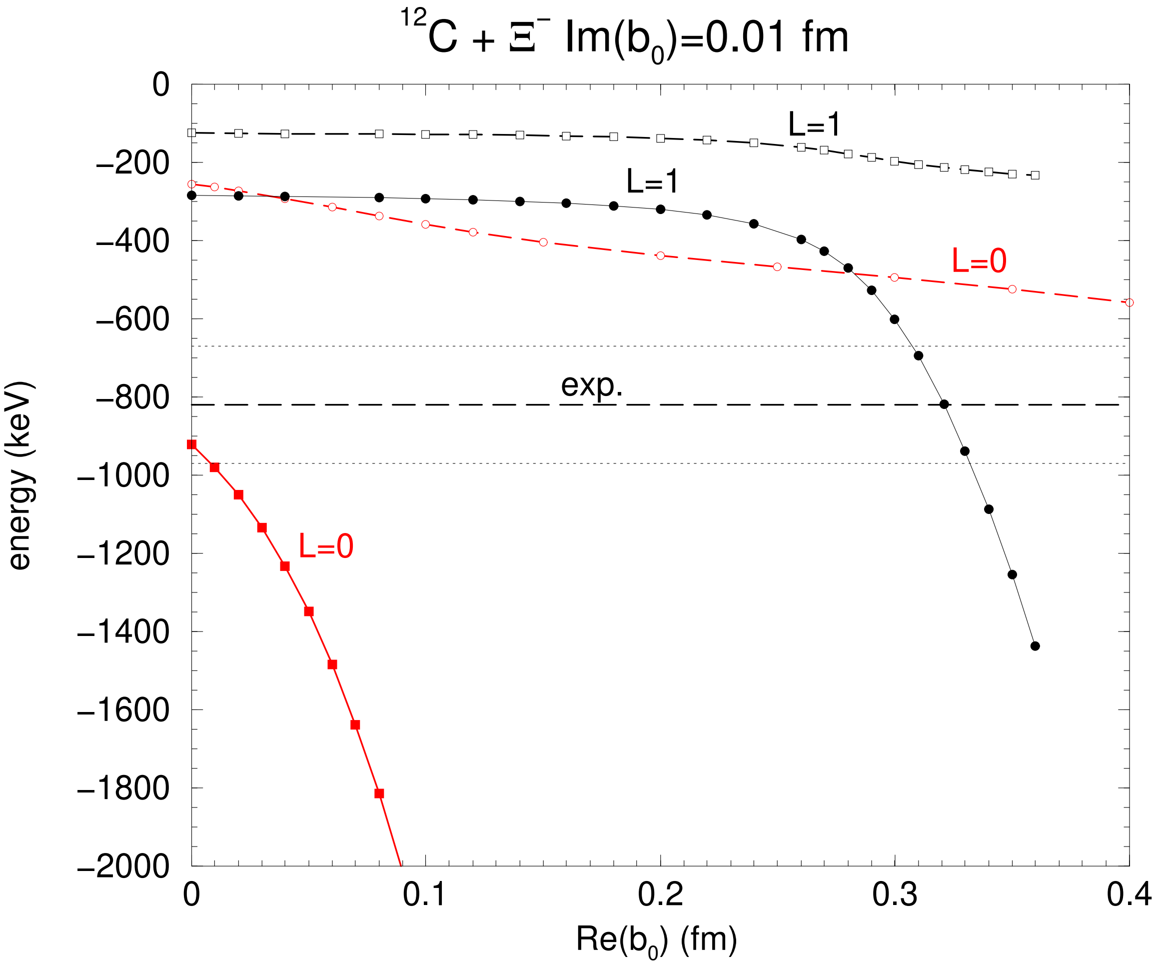




Two-body Ξ^- capture emulsion events

Experiment	Event	^{A}Z	$^{A'}_{\Lambda}$Z'+$^{A''}_{\Lambda}$Z"	B_{Ξ^-} (MeV)
KEK E176	10-09-06	^{12}C	$^{4}_{\Lambda}$H+$^{9}_{\Lambda}$Be	0.82±0.17
KEK E176	13-11-14	^{12}C	$^{4}_{\Lambda}$H+$^{9}_{\Lambda}$Be*	0.82±0.14
KEK E176	14-03-35	^{14}N	$^{3}_{\Lambda}$H+$^{12}_{\Lambda}$B	1.18±0.22
KEK E373	KISO	^{14}N	$^{5}_{\Lambda}$He+$^{10}_{\Lambda}$Be*	1.03±0.18
J-PARC E07	IBUKI	^{14}N	$^{5}_{\Lambda}$He+$^{10}_{\Lambda}$Be	1.27±0.21

- Ξ^- capture occurs mostly from 3D atomic state (B$_{\Xi^-}$ $=$ 126, 175 keV in ^{12}C, ^{14}N, respectively).
- To form 1s$^2_\Lambda$ in $\Xi^- p \rightarrow \Lambda\Lambda$ need $l_{\Xi^-} = l_p$, hence expect capture from a Coulomb-assisted $1p_{\Xi^-}$ nuclear state bound by ∼1 MeV, evolving by Strong Interaction from a 2P atomic state.



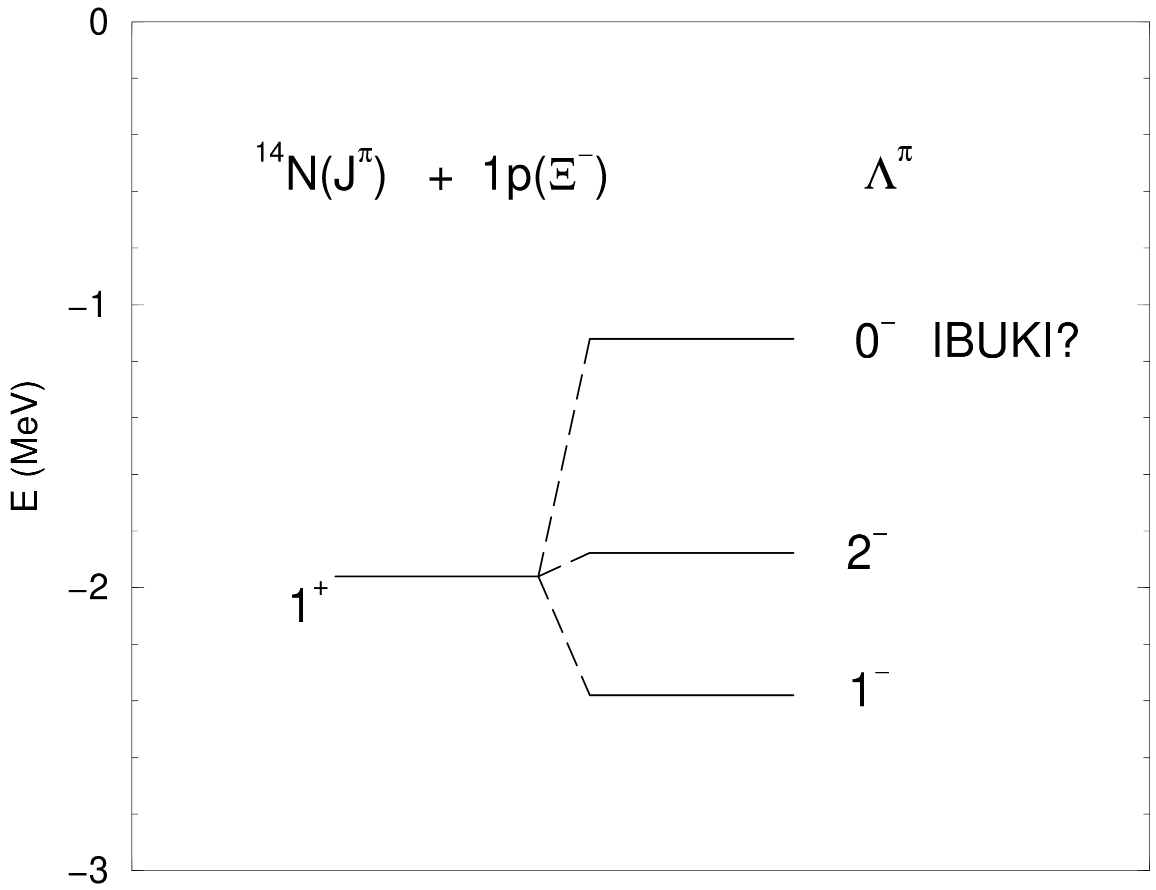
$V_{\rm opt}$=tρ ~ $b_0\rho(r)$: scan over Re b_0

Rearrangement: 3P→2P, 2S→1S, 2P→1p, 1S→1s

1p fit: Re b_0=0.32±0.01 fm ⇒ V_Ξ=24.3±0.8 MeV

Pauli corrected: 21.9±0.7 MeV. It fails in ^{14}N:

$B^{\Xi^-}_{1p}$(calc.)=1.96±0.25 vs. $B^{\Xi^-}_{1p}$(exp.)=1.15±0.20 MeV



$^{14}\mathrm{N}_{\mathrm{g.s.}}(1^{+})$ **split by shell-model residual interaction**

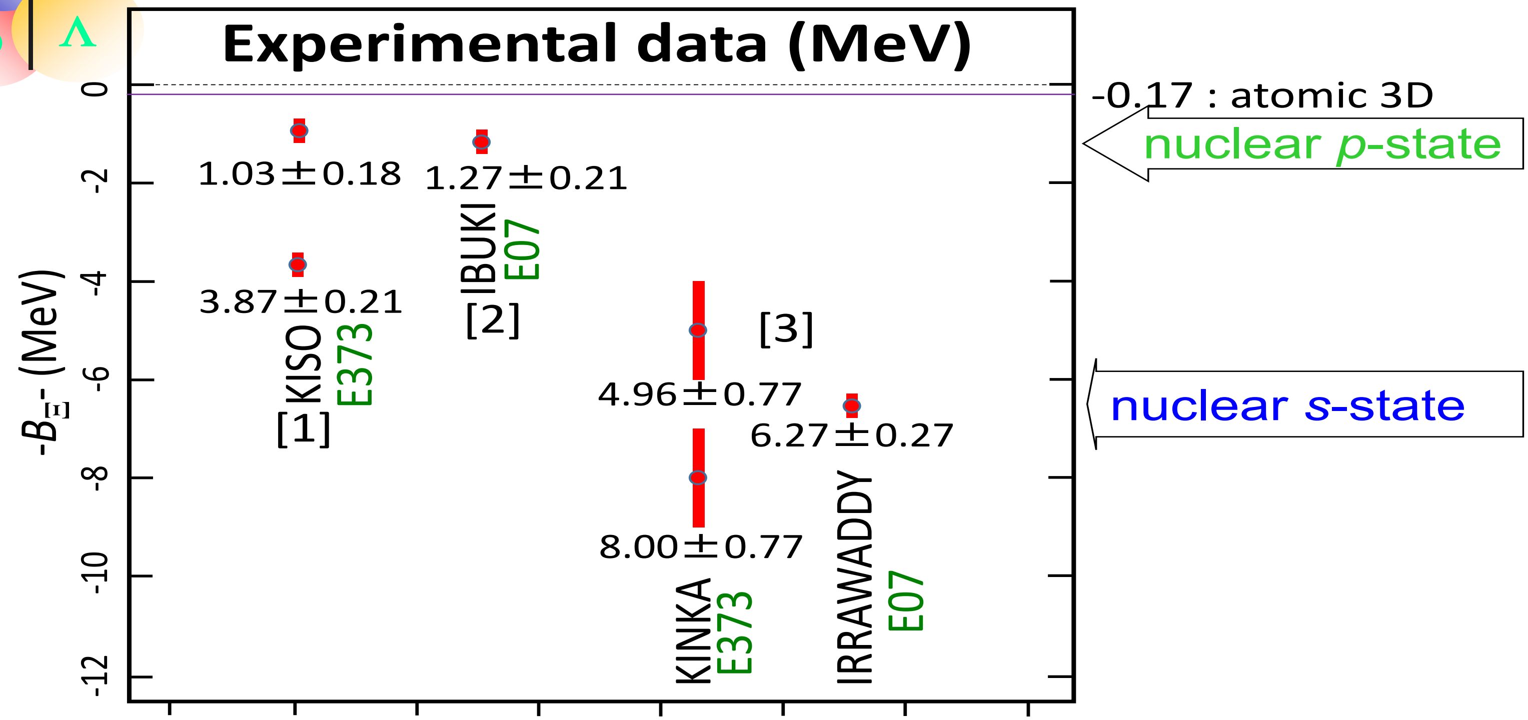
$$\mathbf{F}^{(2)}_{\Xi N}\ \mathbf{Q}_{N}\cdot\mathbf{Q}_{\Xi}\qquad\qquad \mathbf{Q}=\sqrt{\tfrac{4\pi}{5}}\,\mathbf{Y}_{2}(\hat{r})$$

$$\mathbf{F}^{(2)}_{\Xi N}=-3\ \mathrm{MeV}\Rightarrow \mathbf{B}^{\Xi^-}_{1p}(0^{-})=1.12\pm0.25\ \mathrm{MeV}$$

agrees with $\mathbf{B}^{\Xi^-}_{1p}(\mathrm{exp.})=1.15\pm0.20\ \mathrm{MeV}$

J-PARC E07 ^{14}N events

Level scheme of Ξ hypernucleus ($^{15}_{\Xi}$C [Ξ^--^{14}N])



[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Yoshimoto et al., PTEP 2021 073D02

$1s_{\Xi^-}$ states reported only in ^{14}N

IRRAWADDY: $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + \mathrm{n}$

KINKA: $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$

Twin Λ: capture & decay vertices

****** IBUKI (J-PARC E07)** PRL 126 (2021) 062501

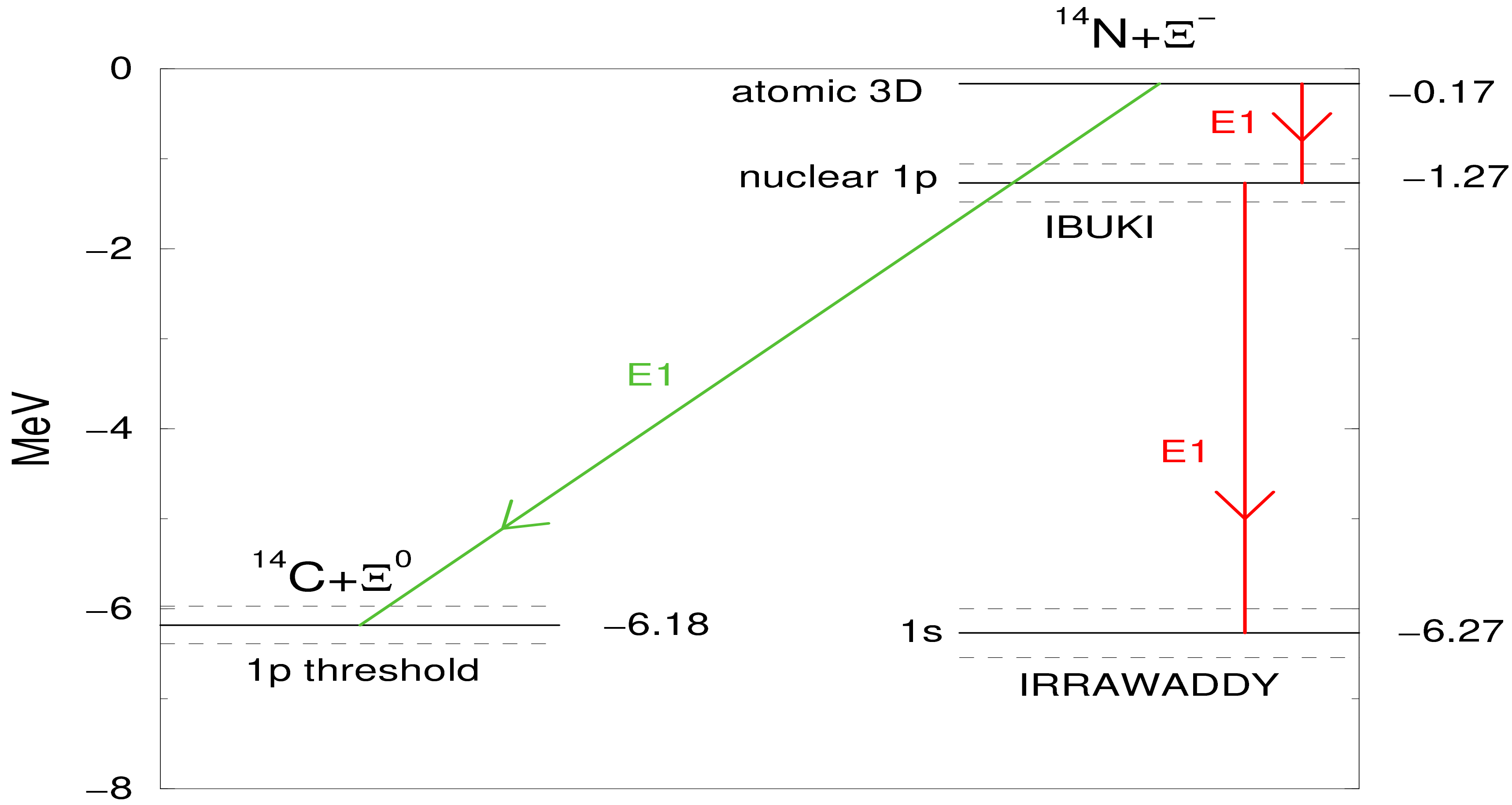
- **A:** capture $\Xi^-_{1p} + {}^{14}\mathrm{N} \to {}^{5}_{\Lambda}\mathrm{He} + {}^{10}_{\Lambda}\mathrm{Be}$
- **B:** decay ${}^{5}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + \mathrm{p} + \pi^-$
- **C:** decay ${}^{10}_{\Lambda}\mathrm{Be} \to$ 3 or 4 nuclei + neutrons

**** KINKA (KEK E373)** PTEP 2021 073D02

- **A:** capture $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$
- **B:** decay ${}^{9}_{\Lambda}\mathrm{Be} \to {}^{6}\mathrm{He} + 2\mathrm{p} + \mathrm{n}$
- **C:** decay ${}^{5}_{\Lambda}\mathrm{He} \to$ 2 nuclei + neutrons

Furthermore, $1\mathrm{s}_{\Xi^-}$ capture rate is only
a few % of $1\mathrm{p}_{\Xi^-}$ capture rate

$1s_{\Xi^-}$ reinterpreted as $1p_{\Xi^0}$



Friedman-Gal, PLB 837 (2023) 137640

Ξ^0 relevance unique to ^{14}N, not in ^{12}C or ^{16}O.

Ξ^-p ↔ Ξ^0n ch. exch. induces $^{14}\mathrm{N}+\Xi^-_{1p} \leftrightarrow {}^{14}\mathrm{C}+\Xi^0_{1p}$ mixing.

$^{14}\mathrm{N}+\Xi^-_{3D}$ decays by E1 to both $^{14}\mathrm{N}+\Xi^-_{1p}$, $^{14}\mathrm{C}+\Xi^0_{1p}$.

Remarks on SHF Calculations

Guo-Zhou-Schulze, PRC 104 (2021) L061307

Suppressing SHF nonlocal terms and assuming $m^*_\Xi = m_\Xi$, the SHF Ξ mean field depth $V_\Xi(\rho_0)$ in n.m. density ρ_0=0.17 fm^{-1} is fixed by fitting

$$V_\Xi(\rho_N) = [V_\Xi^{(2)}(\rho_N) = a_0\rho_N] + [V_\Xi^{(3)}(\rho_N) = a_3\rho_N^2]$$

in ^{14}N to $B_{\Xi^-}(1s) \approx$ 8.00 MeV (KINKA) and $B_\Xi(1p) \approx$ 1.15 MeV (KISO & IBUKI).

Method	Pauli	$V_\Xi^{(2)}(\rho_0)$	$V_\Xi^{(3)}(\rho_0)$	$V_\Xi(\rho_0)$ (MeV)
SHF	No	34.1	−20.4	13.7
$V_{\rm opt}$	No	27.5	−12.6	14.9
$V_{\rm opt}$	Yes	24.6	−11.0	13.6

Ξ^- capture: Summary & Outlook

- V$_\Xi(\rho_0)$=24.3±0.8 $\Rightarrow$ 21.9±0.7 MeV with Pauli, from twin-Λ two-body Ξ^-_{1p}-^{12}C capture events.
- KEK-E224 & BNL-E885: V$_\Xi(\rho_0)\approx$16±2 MeV.
- BNL-E906: V$_\Xi(\rho_0)$=17±6 MeV (QF in ^{9}Be).
- EFT & LQCD suggest V$_\Xi(\rho_0)\leq$10 MeV.
- SHF using E07 ^{14}N input: V$_\Xi\approx$14±1 MeV, with attractive ΞN & repulsive ΞNN terms.
- Why all E07 Ξ^-_{1s}-assigned events are in ^{14}N? A Ξ^0_{1p}–^{14}C assignment is more natural.
- Challenge: find one good Ξ^-_{1s}-^{12}C capture event.

Thanks for your attention!