Recent news from hypernuclei

APCTP Conf. ExHIC, Pohang, Korea, Sept. 2022

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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, arXiv:2204.02264

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

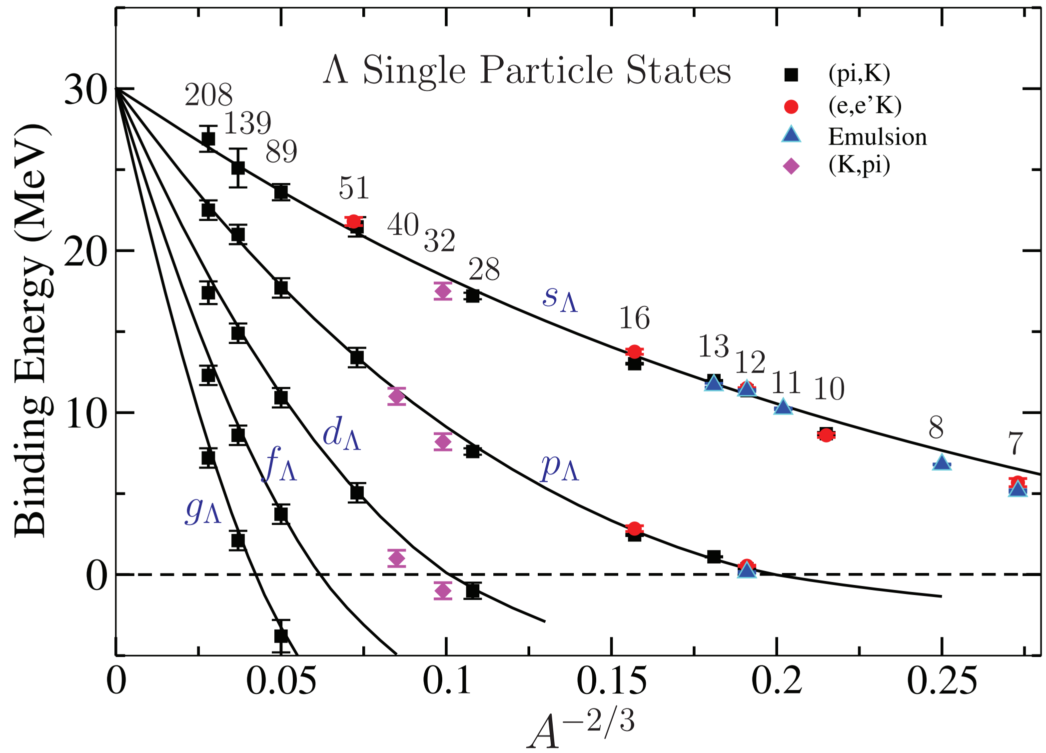
J-PARC E07 $1s_{\Xi^-}$ assignments in ^{14}N are questioned.

E. Friedman, A. Gal, arXiv:2209.01606

Λ**NN vs.** Λ**N content of** $\mathbf{V}_{\Lambda}^{\mathrm{opt}}$

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

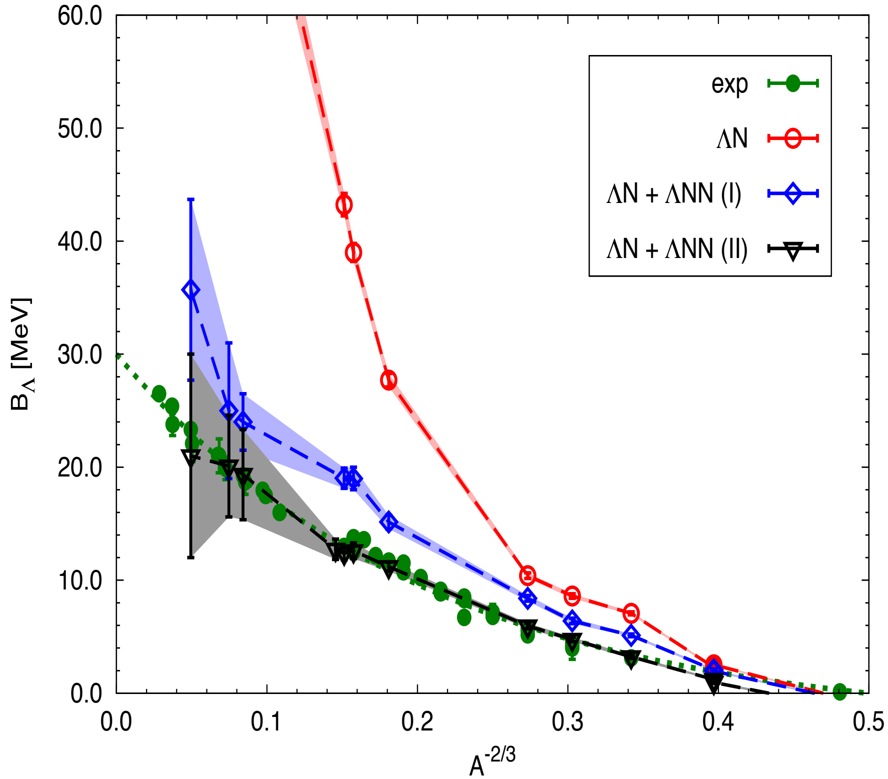
Most 2-body YN models overbind: $|D_\Lambda^{(2)}| > 30$ MeV.

- **NSC and ESC models overbind, with $D_\Lambda^{(2)} \sim -40$ MeV.**
- **χEFT(LO) overbinds; substantial cutoff dependence.**
- **χEFT(NLO) models have substantial model and cutoff dependence; some might underbind.**

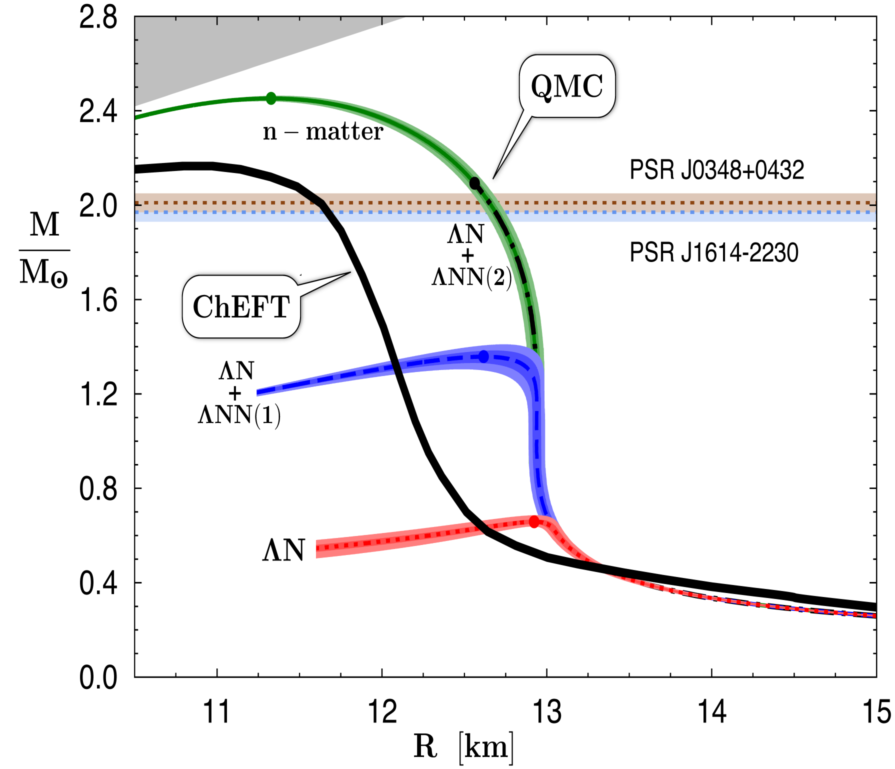
Underbinding would be disastrous for neutron-star matter considerations, implying attractive ΛNN contribution $D_\Lambda^{(3)}$ which will soften the EoS at sufficiently large density.

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

Hyperon puzzle: QMC 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 SHF methodology

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 $B_\Lambda(A)$ data points [ρ_0=0.17 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 $M_{\rm eff}(\Lambda)$ contribution.

- Missing Pauli correlations (WRW97) start as $\rho^{4/3}$, affecting higher density powers, e.g., ρ^2.
- Waas-Rho-Weise, NPA 617 (1997) 449, has been practised in K^- atom calculations.

WRW density dependence of V_Λ

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

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

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

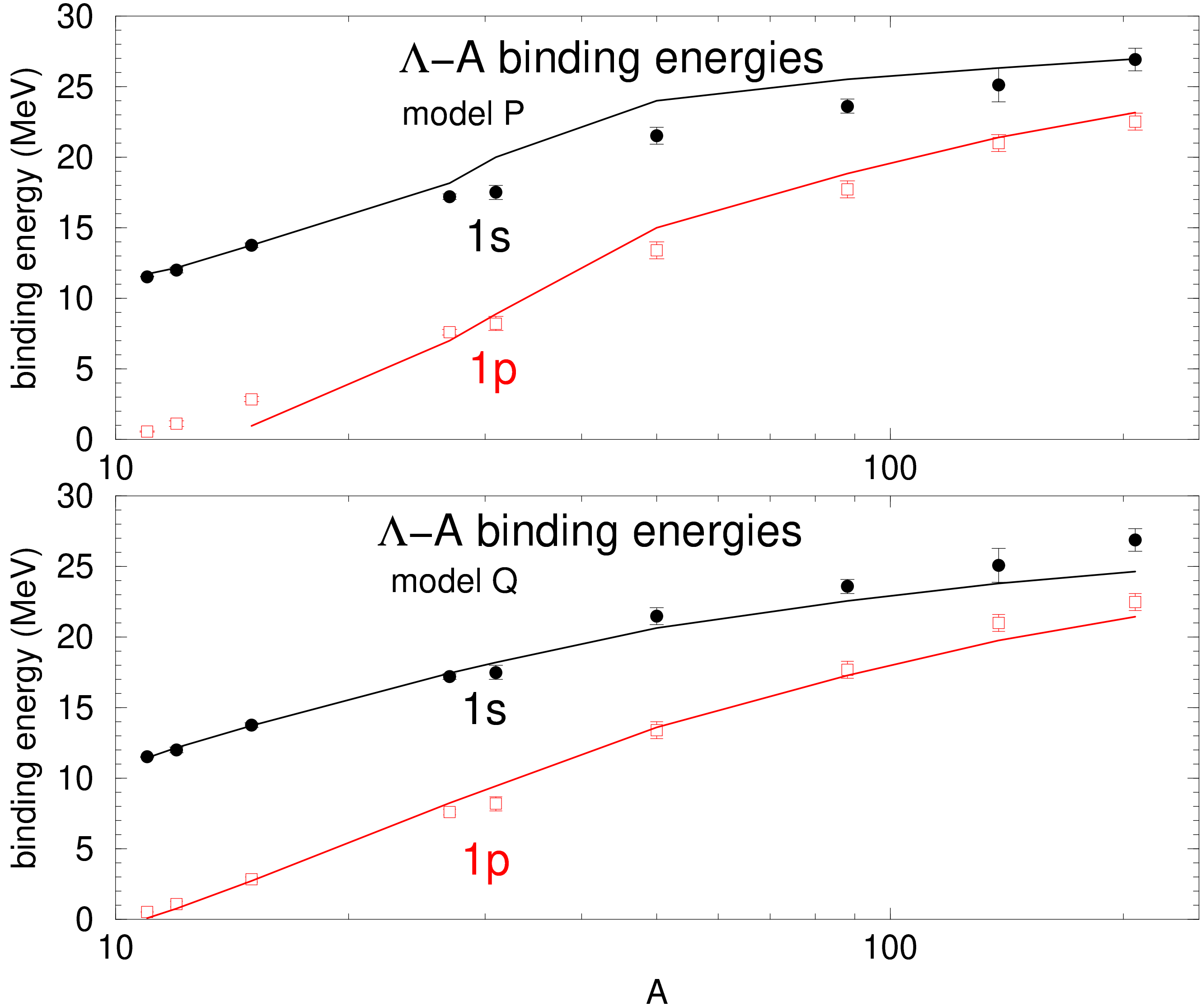
Short-range correlations negligible at $\rho \le \rho_0$.

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

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

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

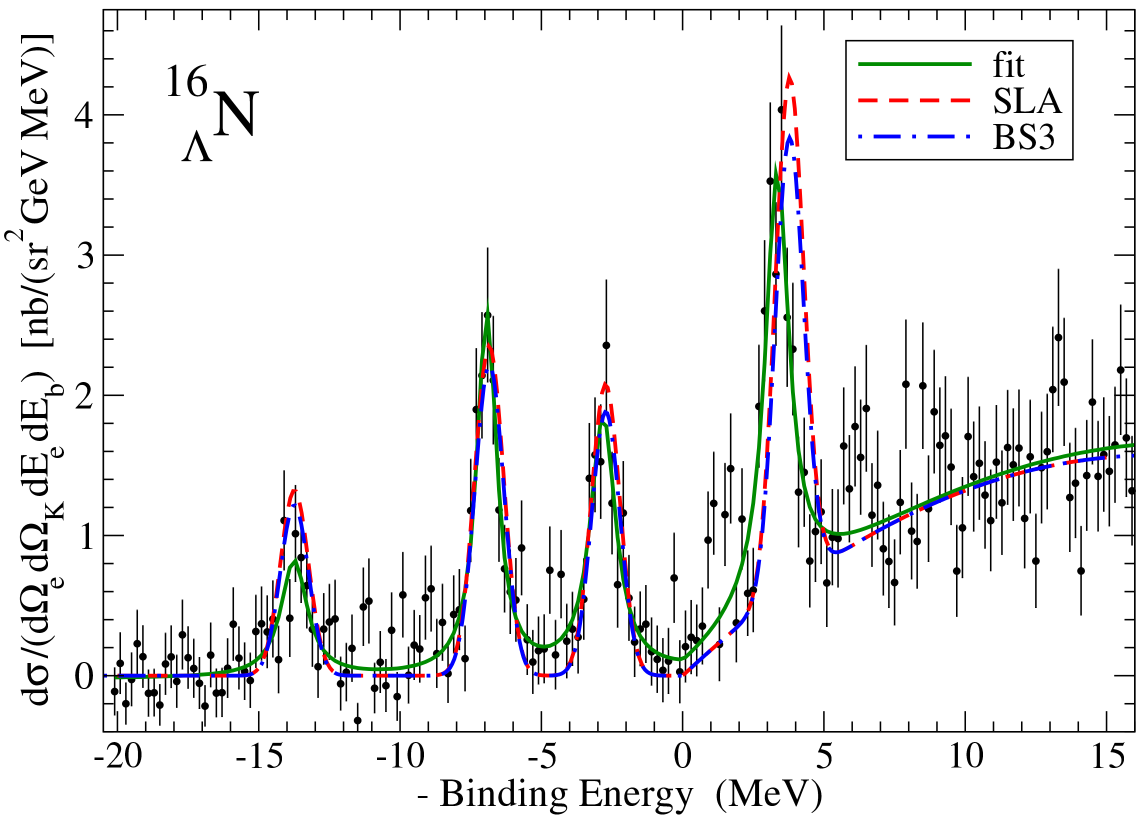
Applying Pauli to $V_\Lambda^{(3)}(\rho)$ has a minor effect.



$B_\Lambda^{1s,1p}(A)$ 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

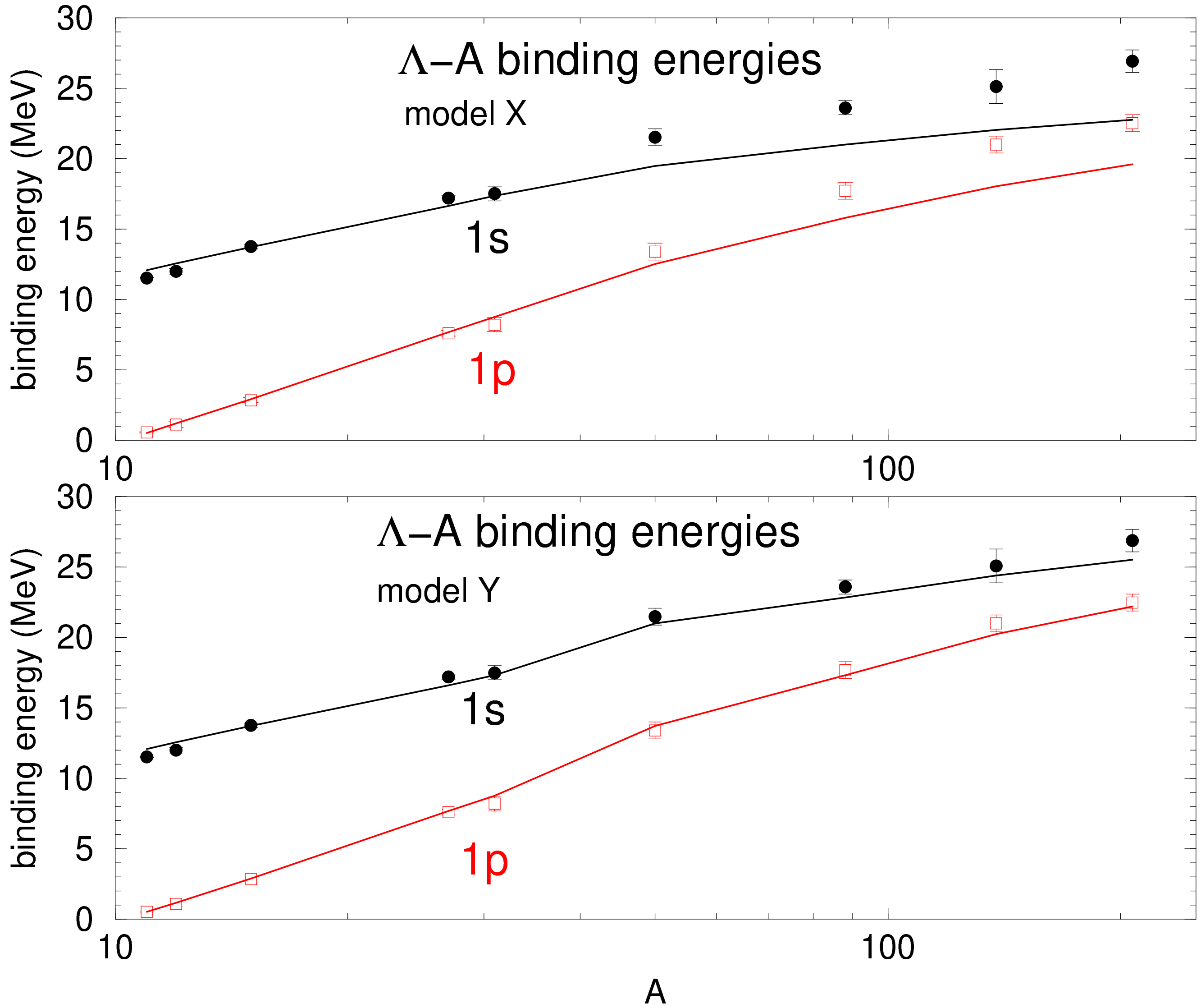


$^{16}_{\Lambda}$N spectrum from JLab Hall A (e,e'K^{+}) experiment

PRL (2009) & PRC 99 (2019) 054309

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

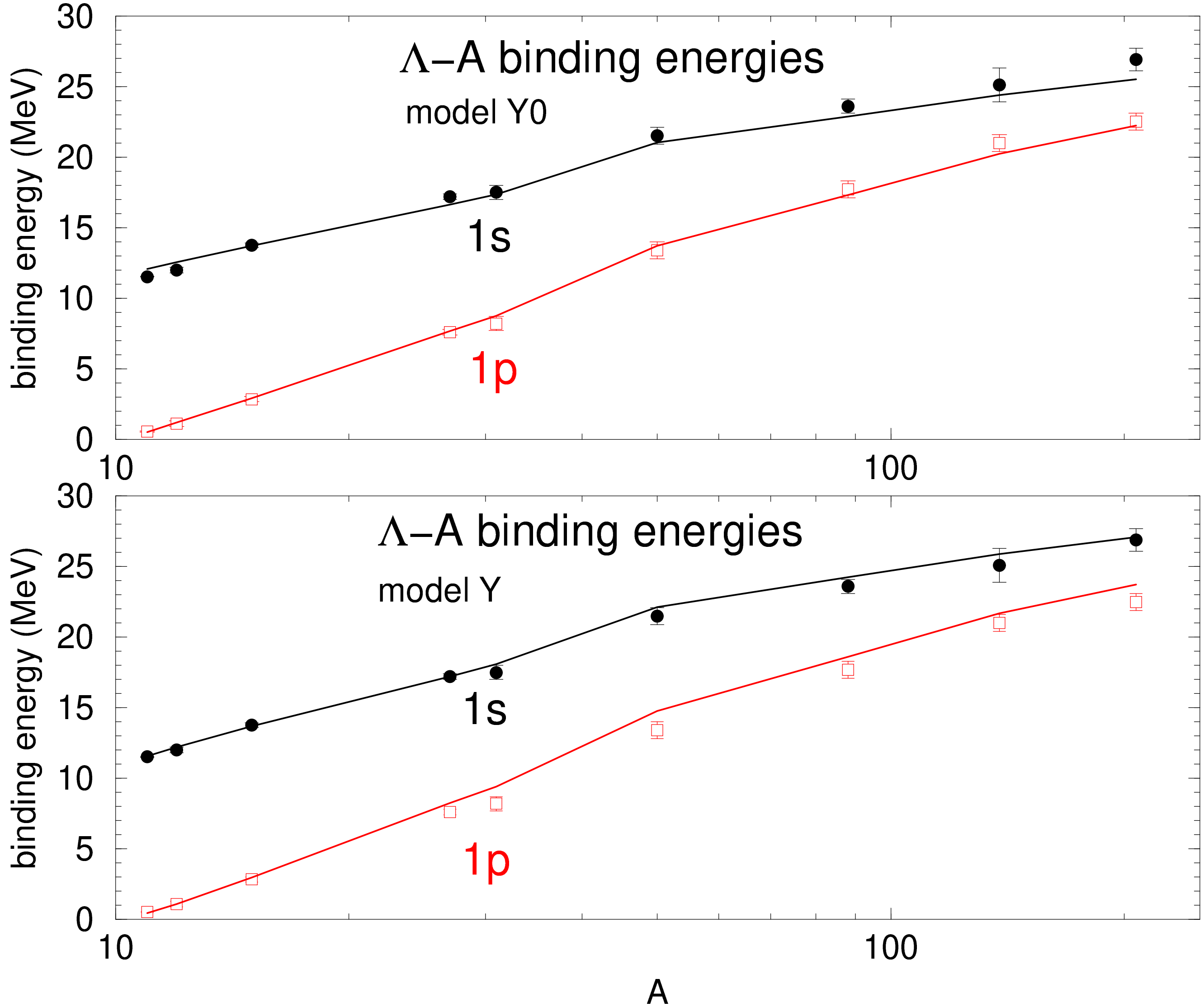
(ii) end of p-shell, very simple s.p. structure



$B_\Lambda^{1s,1p}$(A) in Models X,Y fitted to $^{16}_{\Lambda}$N.   Yes Pauli

$b_0 \neq 0$, $B_0 \neq 0$ in both Models X,Y

Neutron excess decoupled from rest in Model Y



Sensitivity of $B_\Lambda^{1s,1p}(A)$ in Model Y to 1/A corrections.

$b_0 \neq 0$, $B_0 \neq 0$, Yes Pauli, and decoupled neutron excess.

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

- **DD optical potential methodology applied to Λ-nucleus single-particle spectra across the periodic table.**
- **Pauli corrected ΛN term, plus ΛNN term.**
- **Isospin dependence in ΛNN term: neutron-excess density decoupled from symmetric nuclear-matter density.**
- **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.**
- **Implications to dense neutron-star matter.**

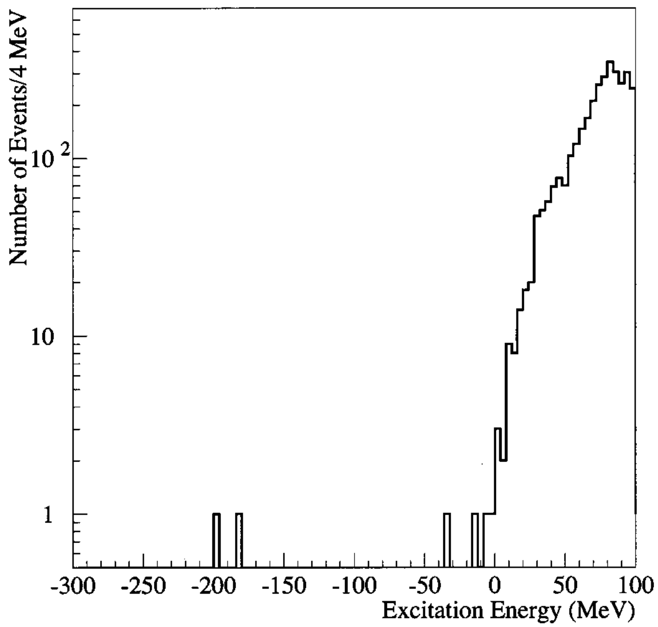
Ξ^- nuclear physics

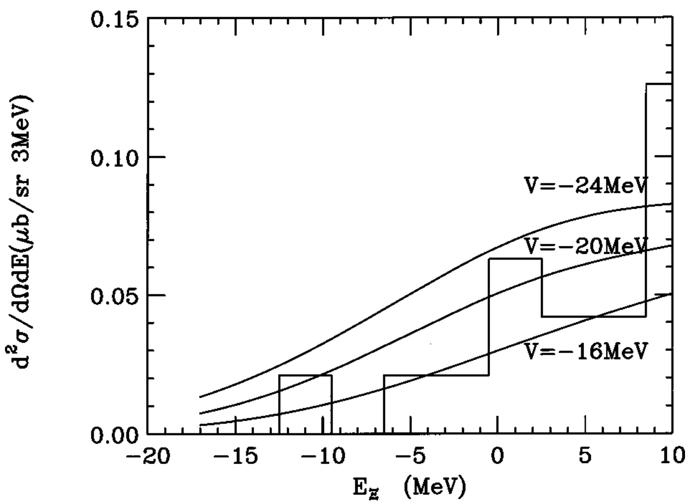
from counter experiments,

from theory and femtoscopy,

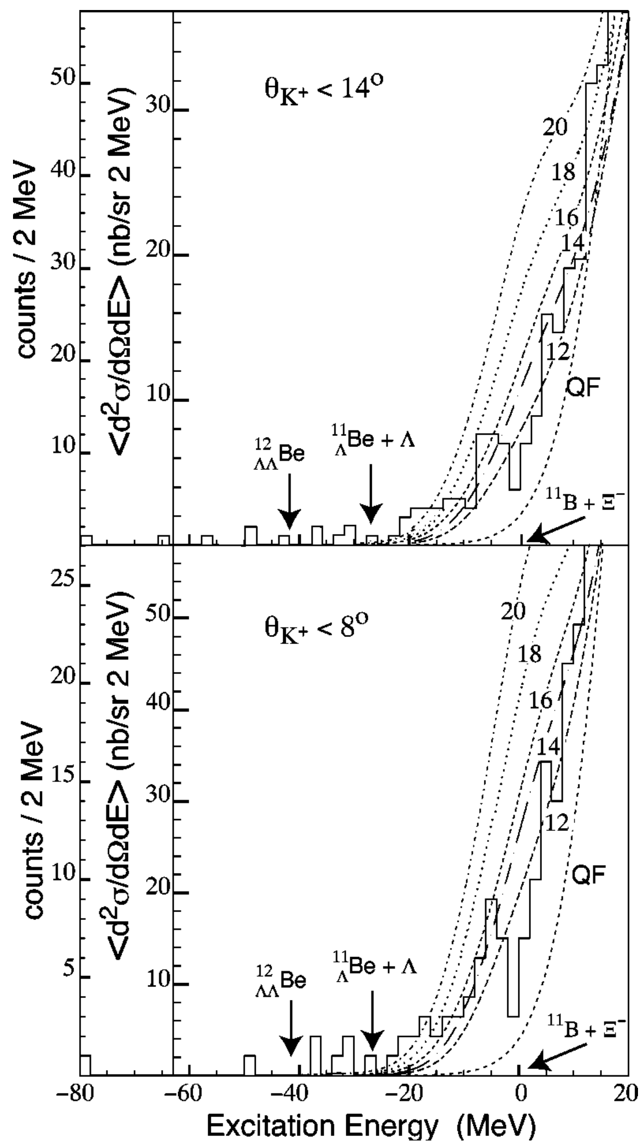
& from capture in emulsion nuclei

E224 (KEK)



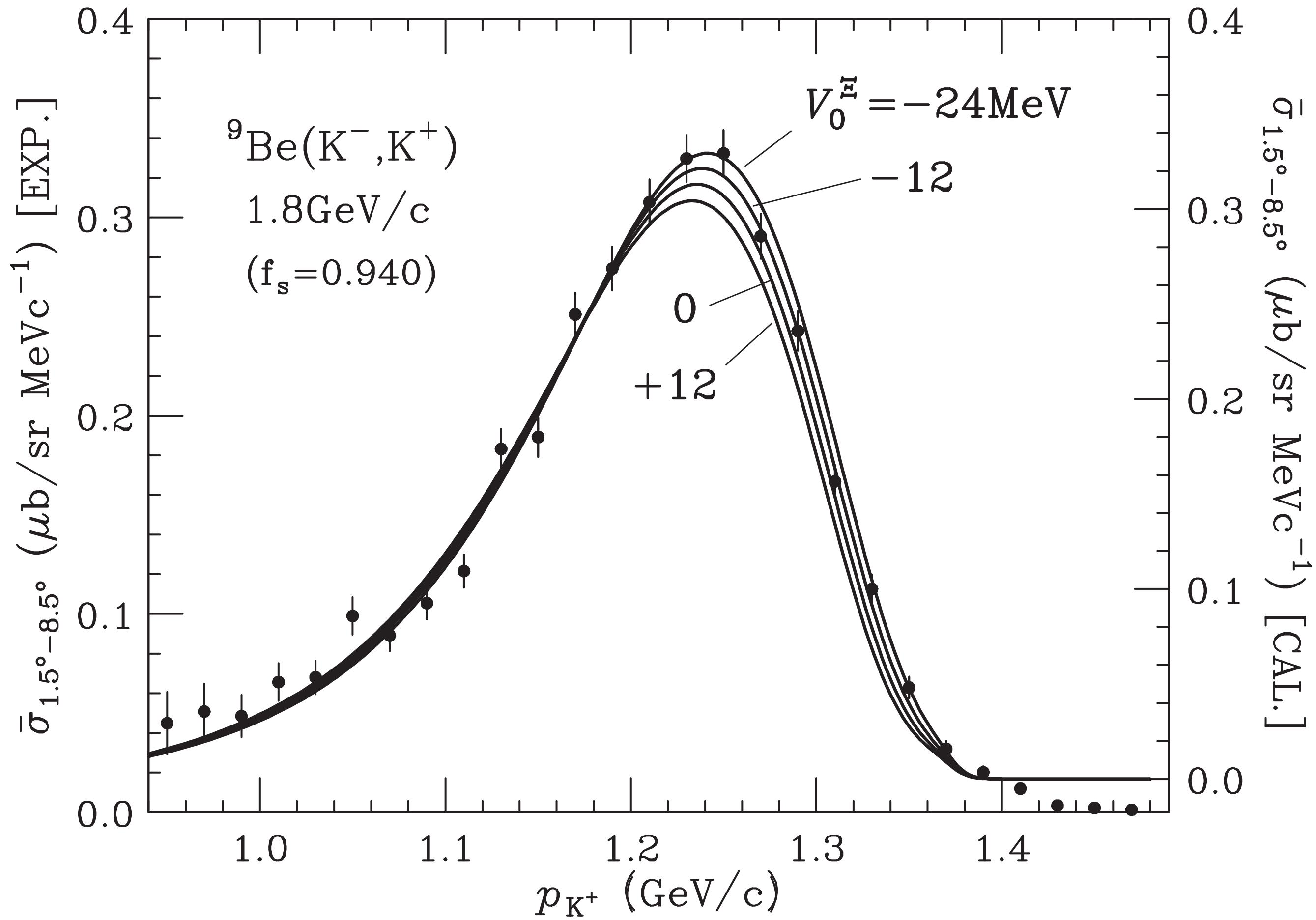


E885 (BNL)



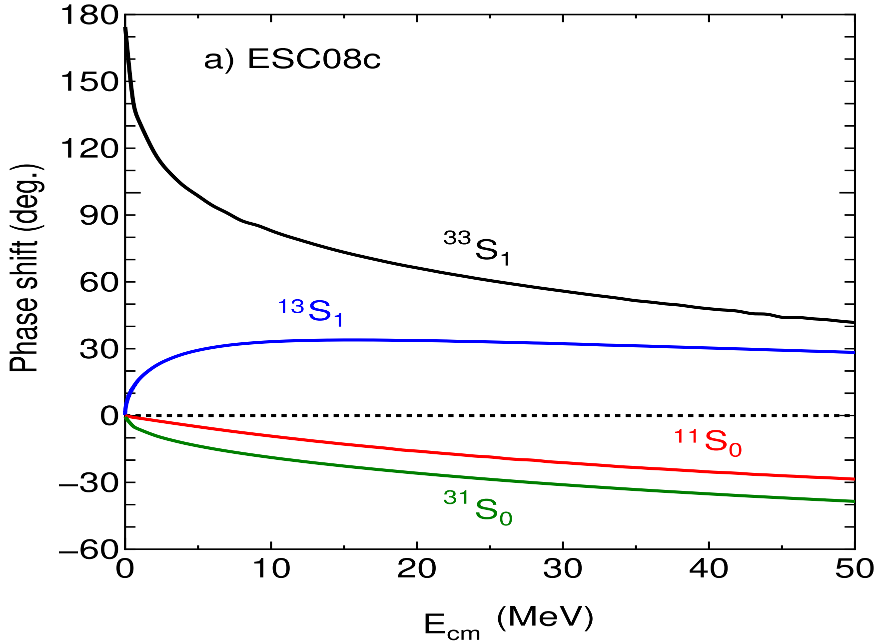
${}^{12}C(K^-,K^+)$ counter experiments, end of 1990s.

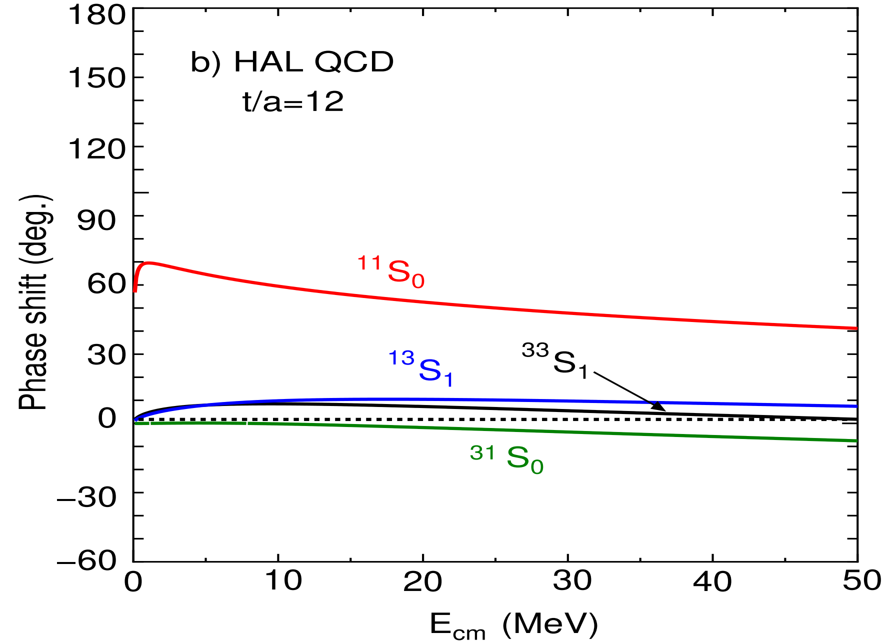
Unresolved bound states, if any, V_Ξ of order 15 MeV



BNL AGS-906 on ^{9}Be claiming a stable $^{4}_{\Lambda\Lambda}$H.
QF calculation, Harada-Hirabayashi (PRC 2021),
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≤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

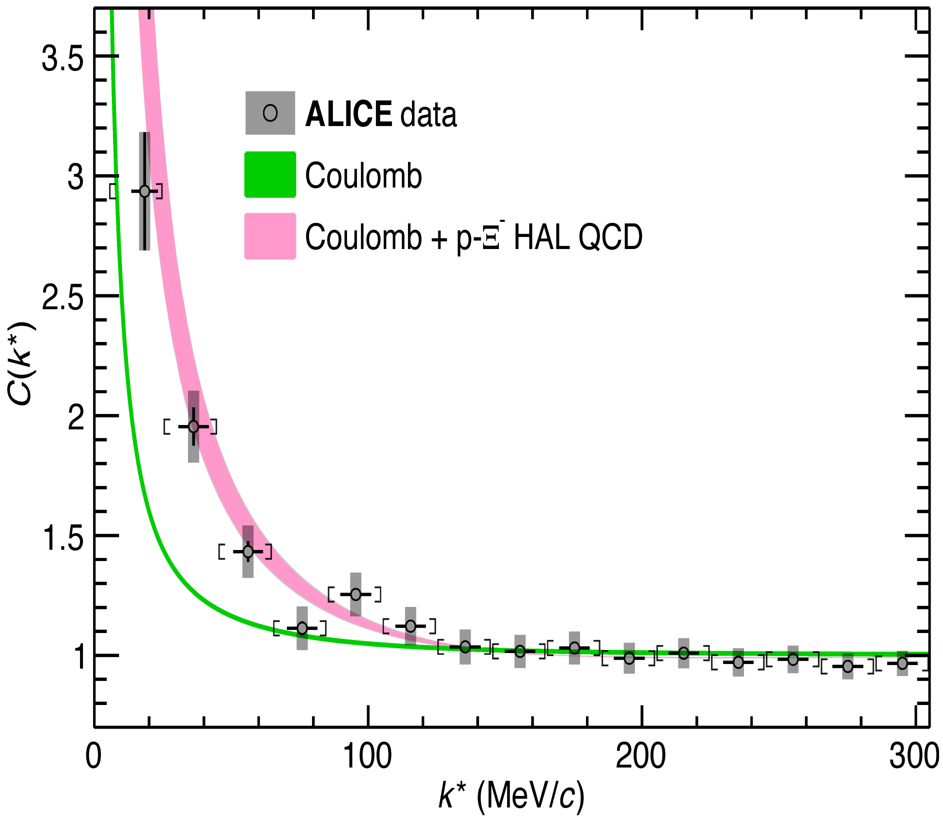
Kohno, PRC 100 (2019) 024313: $V_{\Xi}^{\rm EFT} \approx$ 10 MeV

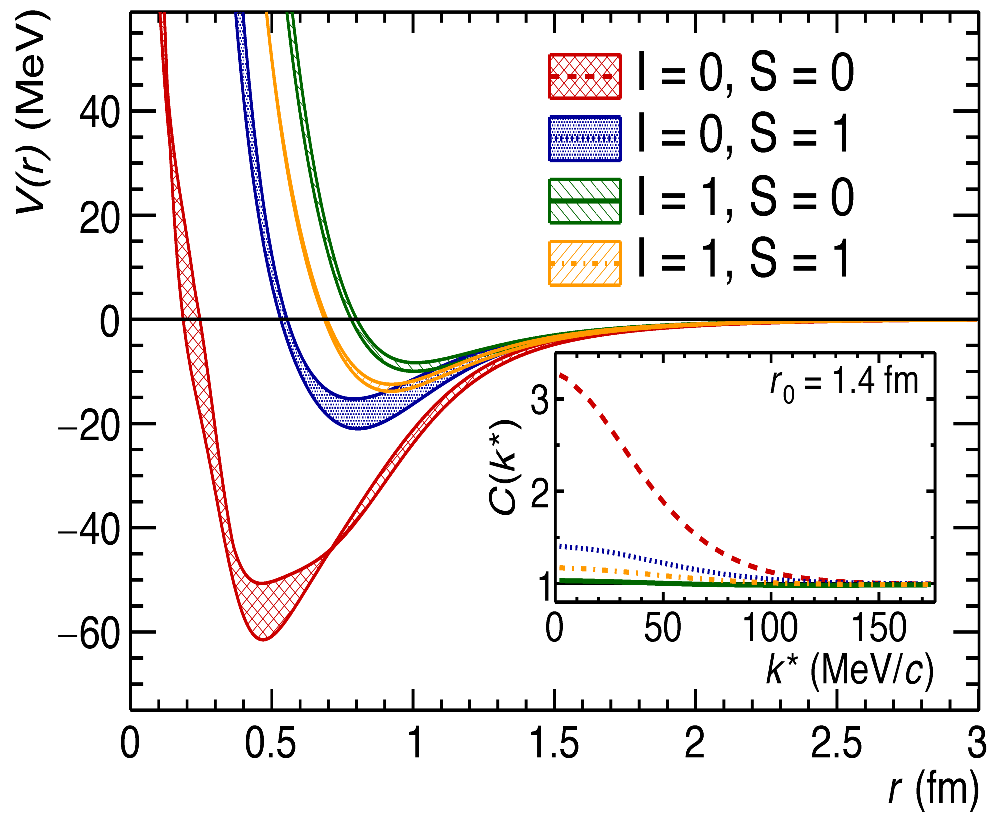
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

attractive HAL-QCD – yes

repulsive Nijmegen ESC16 – no





Twin Λ: capture & decay vertices

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

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

Exclude KINKA (KEK E373) PTEP 2021 073D02

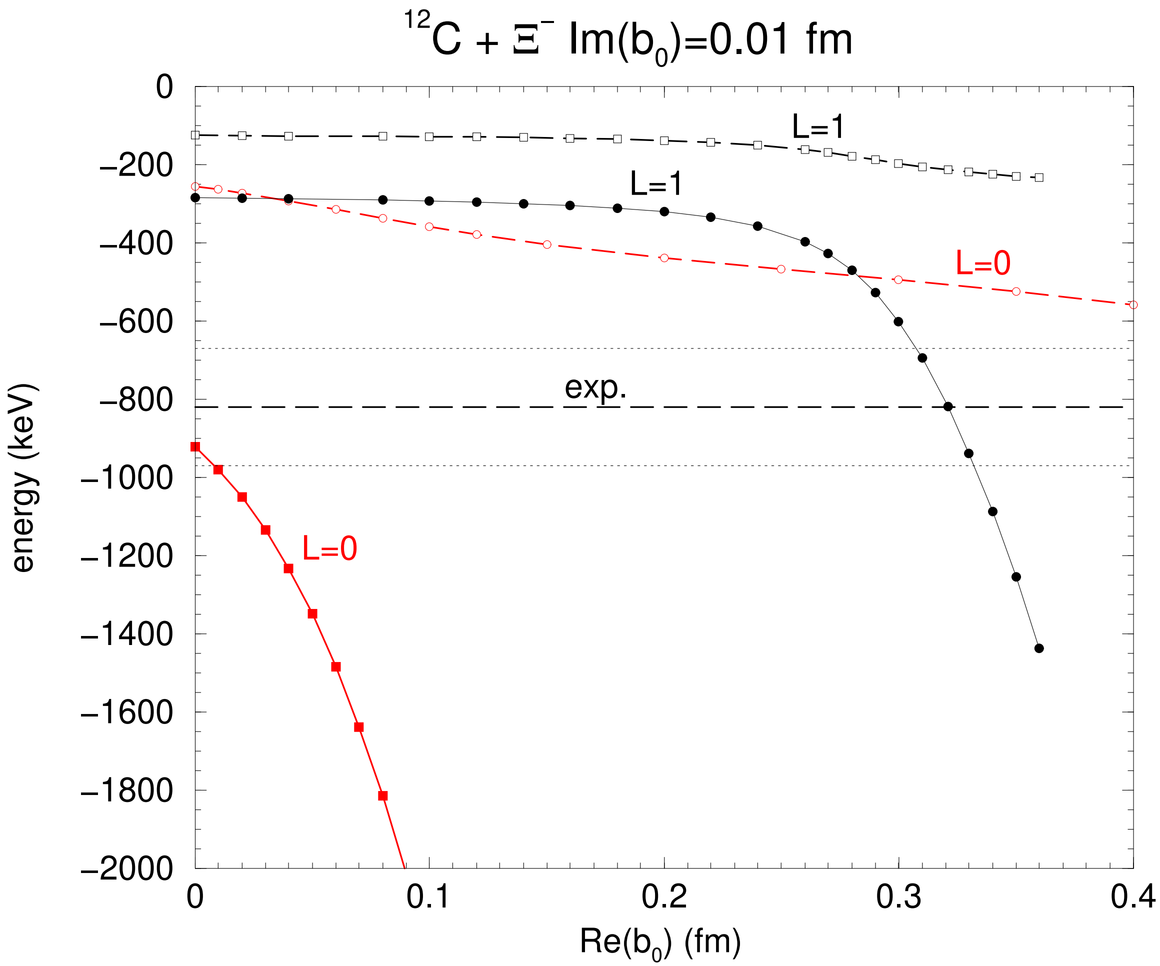
- **A: capture** $\Xi^-_{1s} + {}^{14}\mathrm{N} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$
- **B: decay** ${}^{9}_{\Lambda}\mathrm{Be} \rightarrow {}^{6}\mathrm{He} + 2\mathrm{p} + \mathrm{n}$
- **C: decay** ${}^{5}_{\Lambda}\mathrm{He} \rightarrow$ **2 nuclei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

Furthermore, $1s_{\Xi^-}$ capture rate is only a few % of $1p_{\Xi^-}$ capture rate

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 $\Xi^- p \to \Lambda\Lambda$ need $l_{\Xi^-} = l_p$, hence expect capture from a Coulomb-assisted $1p_{\Xi^-}$ nuclear state bound by $\sim$1 MeV, evolving by Strong Interaction from a 2P atomic state.



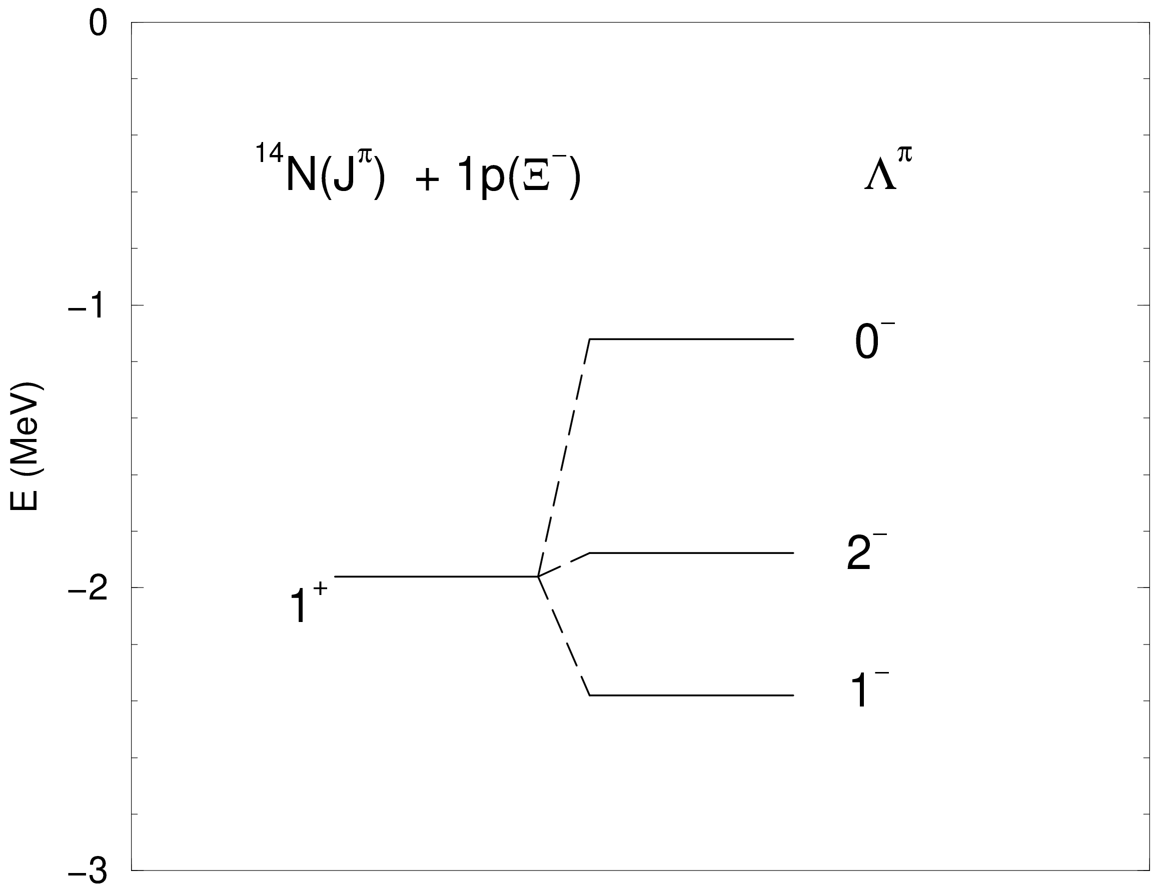
V_{opt}=t$\rho \sim b_0\rho(r)$: scan over Re b_0

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

Fit exp.: Re b_0=0.32±0.01 fm ⇒ V_Ξ=24.3±0.8 MeV

Pauli corrected: 21.9±0.7 MeV, but fails in ^{14}N:

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



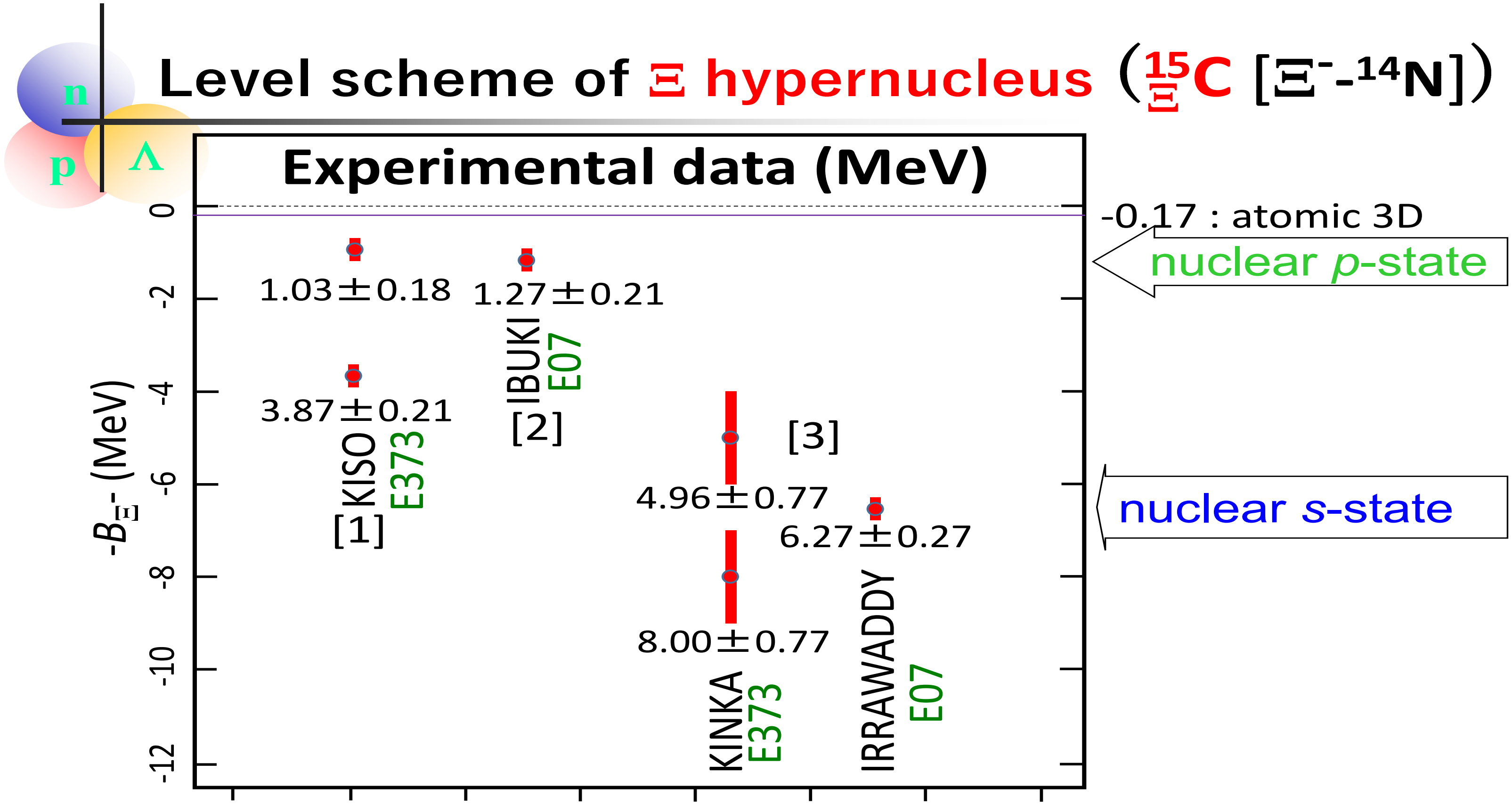
$^{14}\mathbf{N}_{\mathrm{g.s.}}(\mathbf{1}^{+})$ **split by shell-model residual interaction**

$$\mathbf{F}^{(2)}_{\Xi N}\ \mathbf{Q}_N \cdot \mathbf{Q}_{\Xi} \qquad\qquad \mathbf{Q}=\sqrt{\frac{4\pi}{5}}\,\mathbf{Y}_2(\hat{r})$$

$$\mathbf{F}^{(2)}_{\Xi N}=-3\ \mathbf{MeV} \Rightarrow \mathbf{B}^{\Xi^-}_{1p}(\mathbf{0}^{-})=\mathbf{1.12}\pm\mathbf{0.25}\ \mathbf{MeV}$$

agrees with $\mathbf{B}^{\Xi^-}_{1p}(\mathbf{exp.})=\mathbf{1.15}\pm\mathbf{0.20}\ \mathbf{MeV}$

J-PARC E07 ^{14}N events

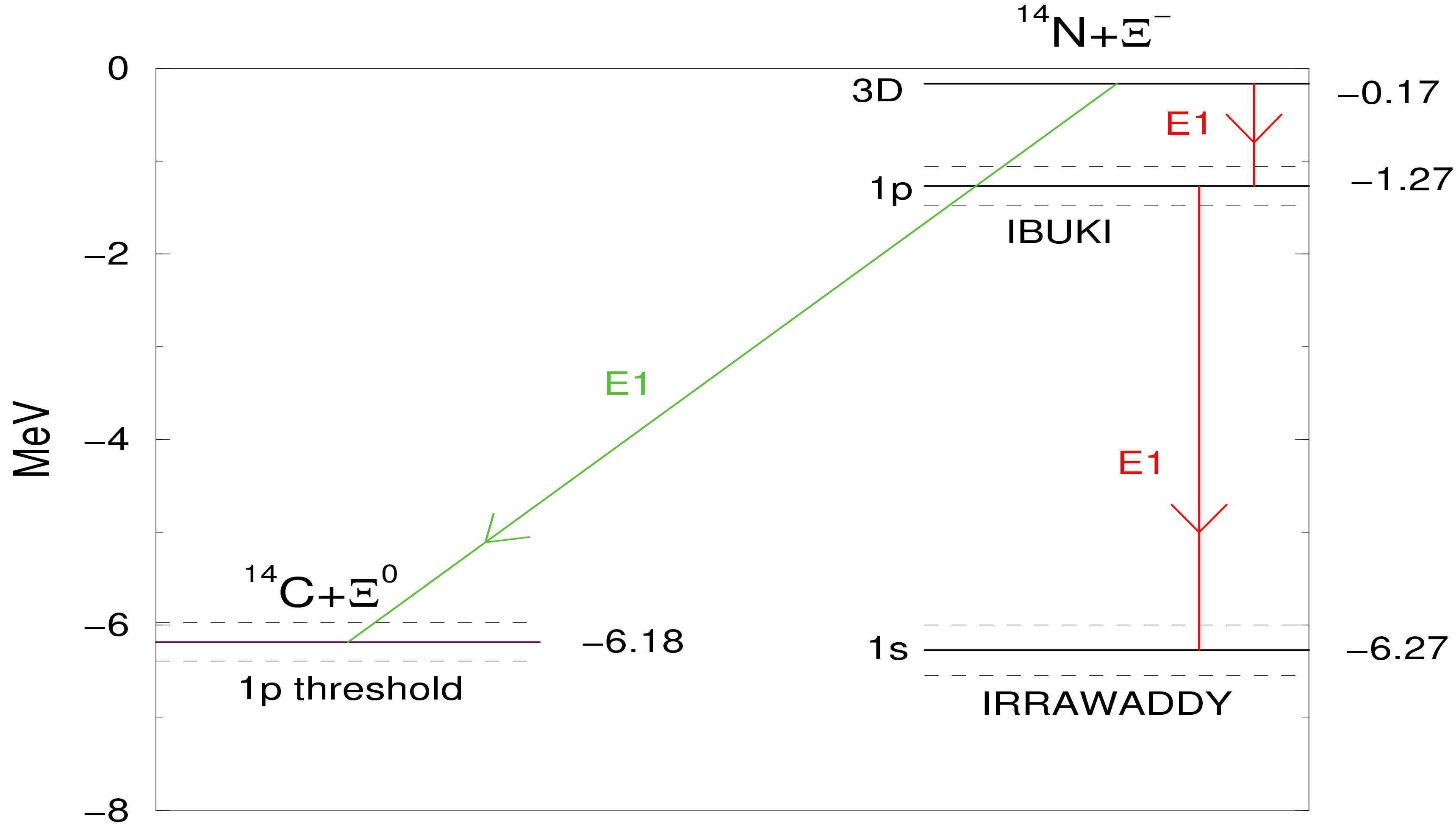


[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Yoshimoto et al., PTEP 2021 073D02

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

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



Friedman-Gal, arXiv:2209.01606

Ξ^0 mixing unique to ^{14}N

Density Dependence of V_Ξ

$$b_0 \to b_0(\rho): \quad \mathrm{Re}\, b_0(\rho) = \frac{\mathrm{Re}\, b_0}{1 + \frac{3k_F}{2\pi}\mathrm{Re}\, b_0^{\mathrm{lab}}}$$

for Pauli correlations, with $k_F=(3\pi^2\rho/2)^{1/3}$, reducing $V_\Xi(\rho_0)$=24.3±0.8 to 21.9±0.7 MeV, with a systematic uncertainty of ≈1 MeV.

- **A similar procedure fitting both 1s & 1p states in $^{16}_{\Lambda}$N: $V_\Lambda(\rho_0)$≈30 MeV (FG22).**
- **$B_{1s}(\Xi^-)$≈10 MeV in ^{12}C, ≈11.5 MeV in ^{14}N, much larger than Kinka's 8.0±0.8 MeV.**
- **Expect $B_{1s}(\Xi^-)$≈8–9 MeV in ^{12}C(K^-, K^+) (J-PARC E05→E70).**
- **Could ΞNN contributions prove useful?**

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

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

in ^{14}N to $B_{\Xi^-}(1s) \approx$ 8.00 MeV (KINKA) and $B_\Xi(1p) \approx$ 1.13 MeV (KISO & IBUKI).

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

Ξ^- capture: Summary & Outlook

- **All five twin-Λ two-body capture events: $V_\Xi(\rho_0)$=24.3±0.8 MeV, down to 21.9±0.7 MeV with Pauli correlations.**
- **KEK-E224 & BNL-E885: $V_\Xi(\rho_0)\approx$16±2 MeV.**
- **BNL-E906: $V_\Xi(\rho_0)$=17±6 MeV (recent HH).**
- **FT & 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-assigned $1s_{\Xi^-}$ events (Kinka...) are in ^{14}N? Need just one good $1s_{\Xi^-}$ event in ^{12}C.**
- **Implications to dense neutron-star matter?**