Ξ^- nuclear constraints from capture events

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V_Ξ from Ξ^- capture events

All five KEK & J-PARC $\Xi^- + {}^{A}$Z $\to {}^{A'}_{\Lambda}$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

Questioning E07 $1s_{\Xi^-}$ assignments in ^{14}N

events assigned $1s_{\Xi^-}$—^{14}N by E07

are reinterpreted $1p_{\Xi^0}$—^{14}C.

E. Friedman, A. Gal, PLB 837 (2023) 137640

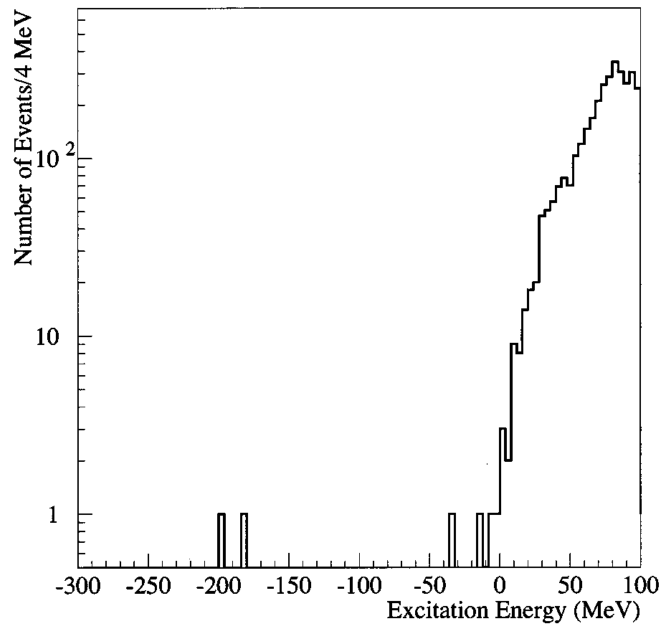
Ξ^- nuclear physics

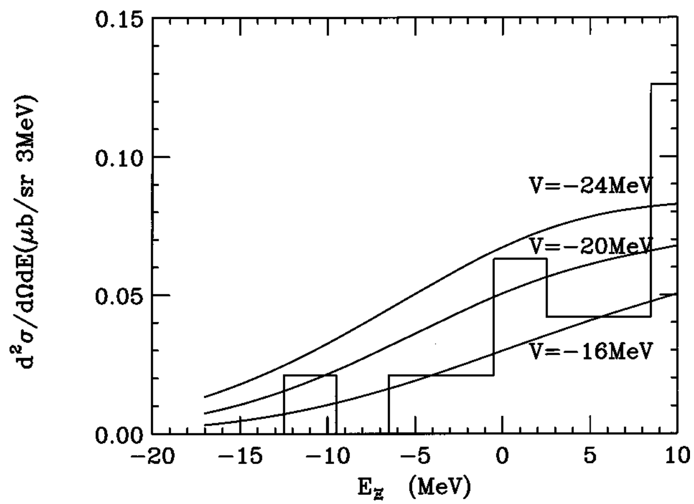
from counter experiments,

from theory and femtoscopy,

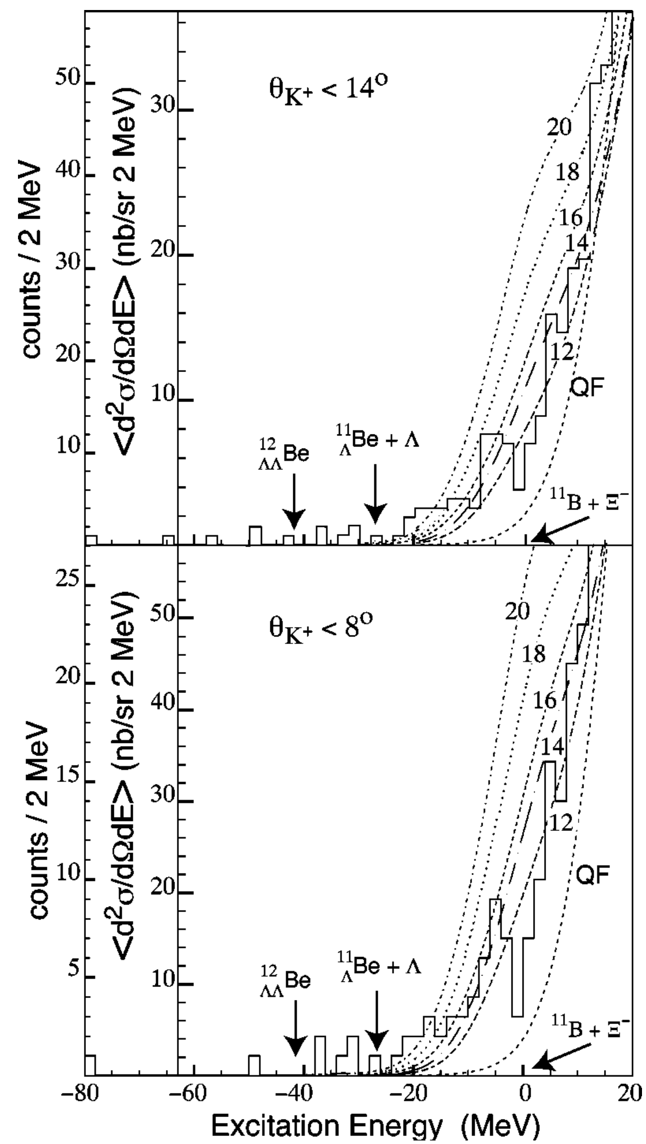
& from capture in emulsion nuclei

E224 (KEK)



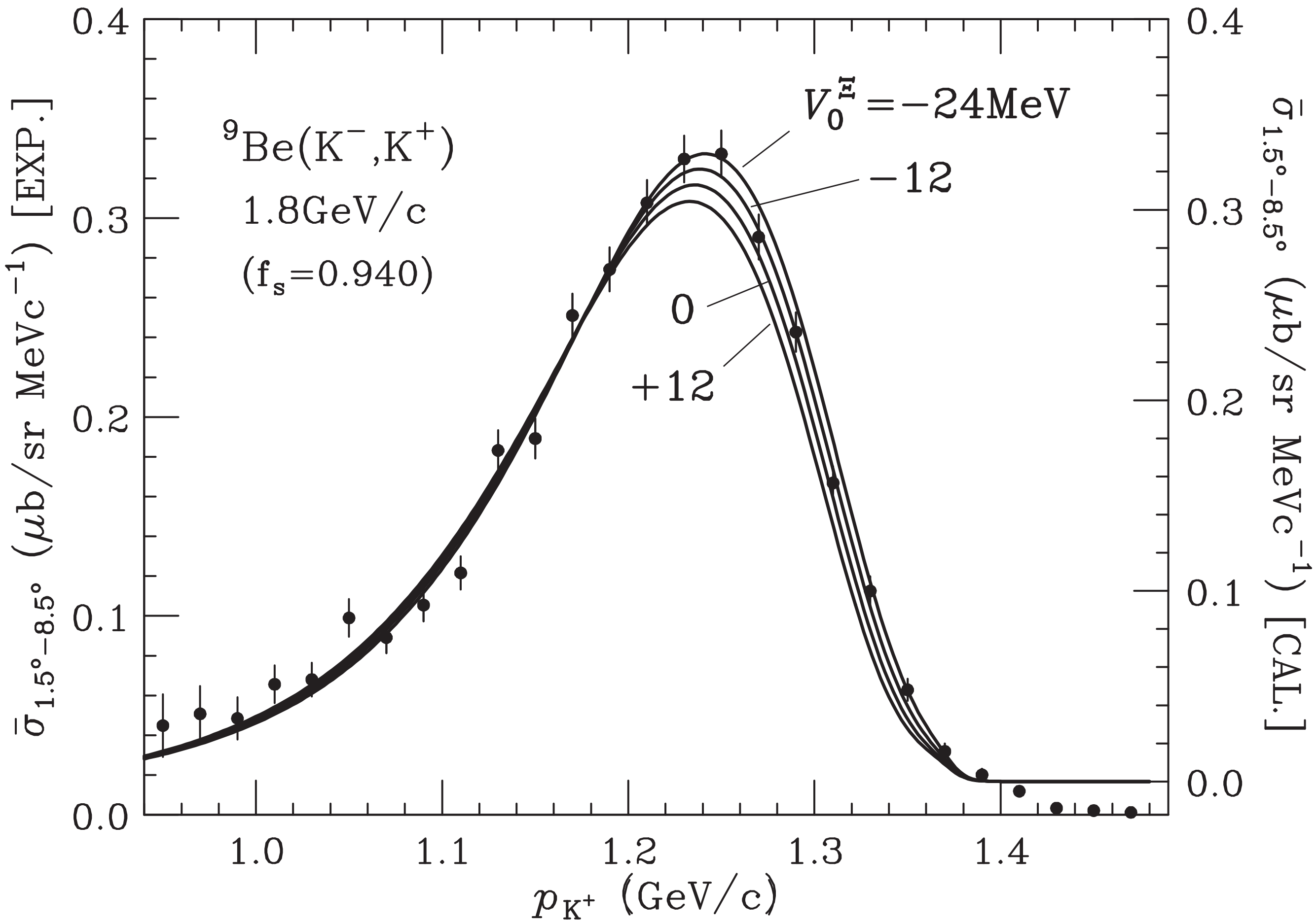


E885 (BNL)



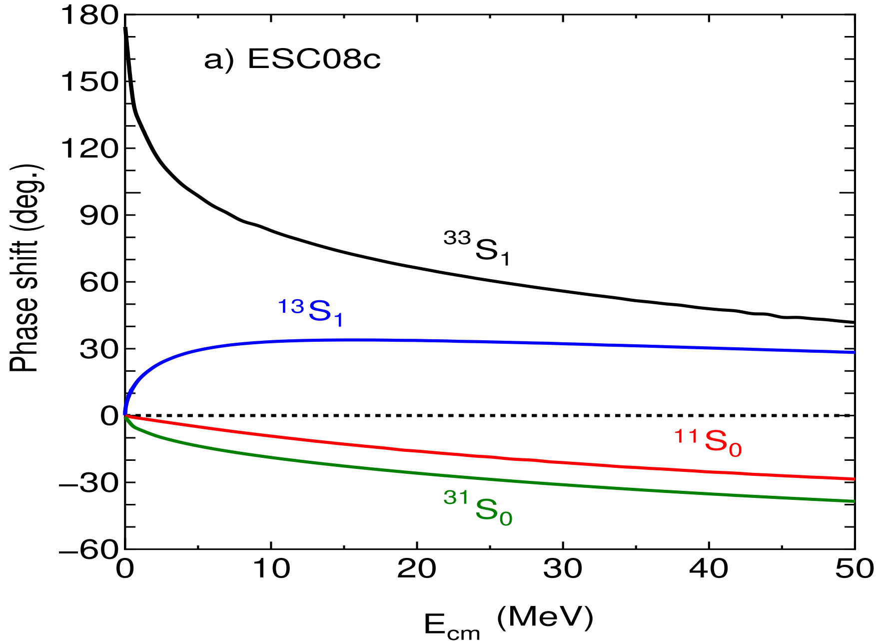
^{12}C(K^{-},K^{+}) counter experiments, end of 1990s.

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

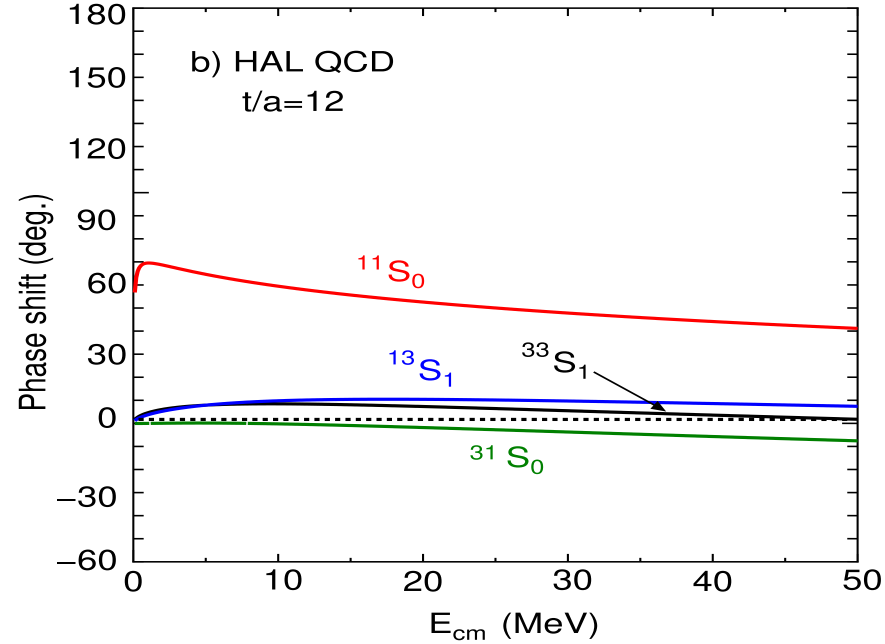


BNL AGS-906 on ^{9}Be. A Quasi-Free fit by Harada & Hirabayashi, PRC 103 (2021) 024605 concludes V_{Ξ}=17±6 MeV. Yet, no Ξ^{-} bound state smoking gun from (K^{-}, K^{+}) experiments. Await J-PARC final E05 & future E70 results.

ΞN s-wave model interactions



Nijmegen ESC08c version



HAL-QCD version

Hiyama et al. PRL 124 (2020) 092501: A≤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

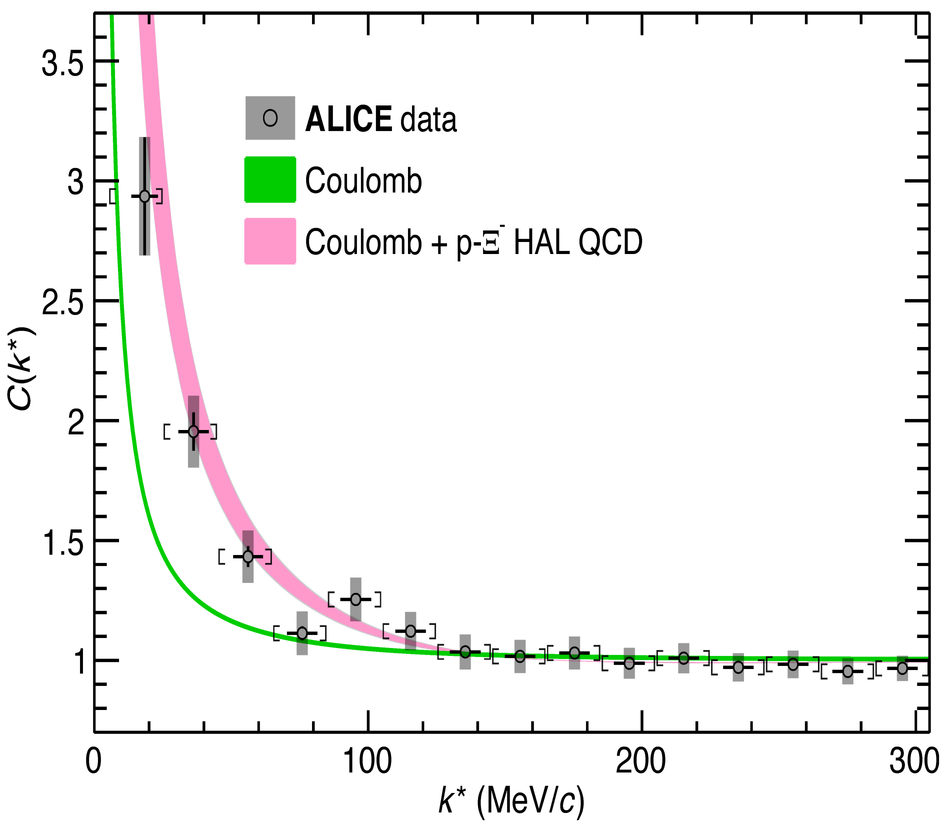
Kohno, PRC 100 (2019) 024313: $V_{\Xi}^{\rm EFT}\approx$ 10 MeV

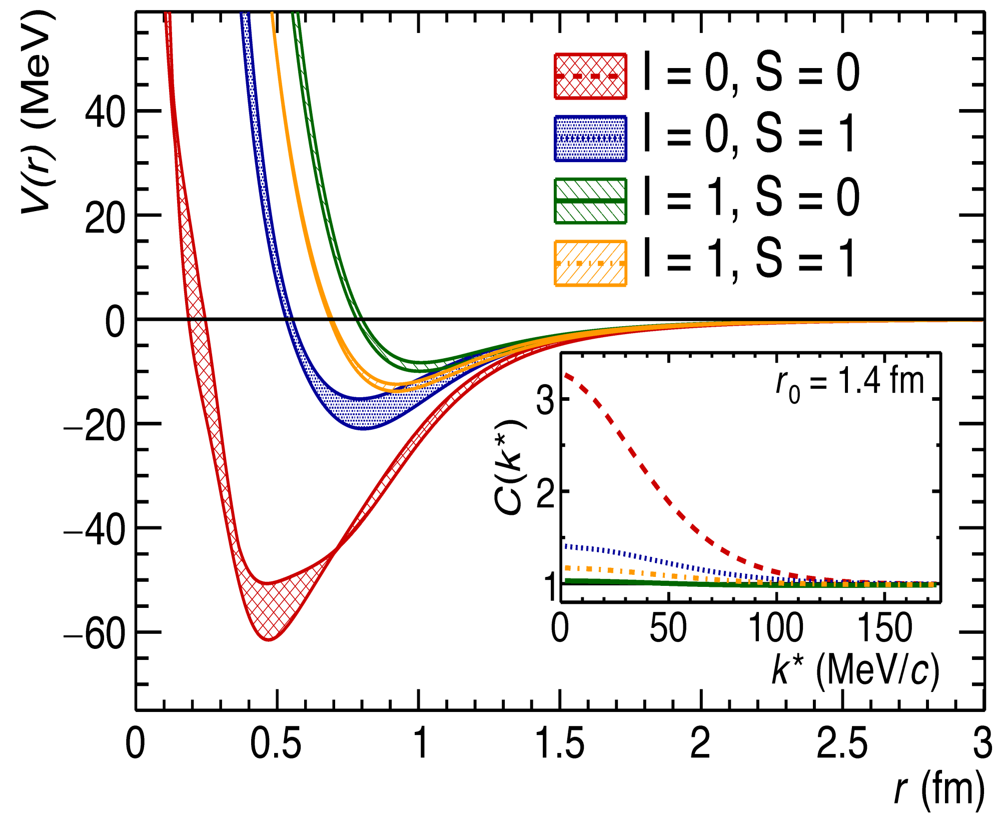
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

attractive HAL-QCD – yes

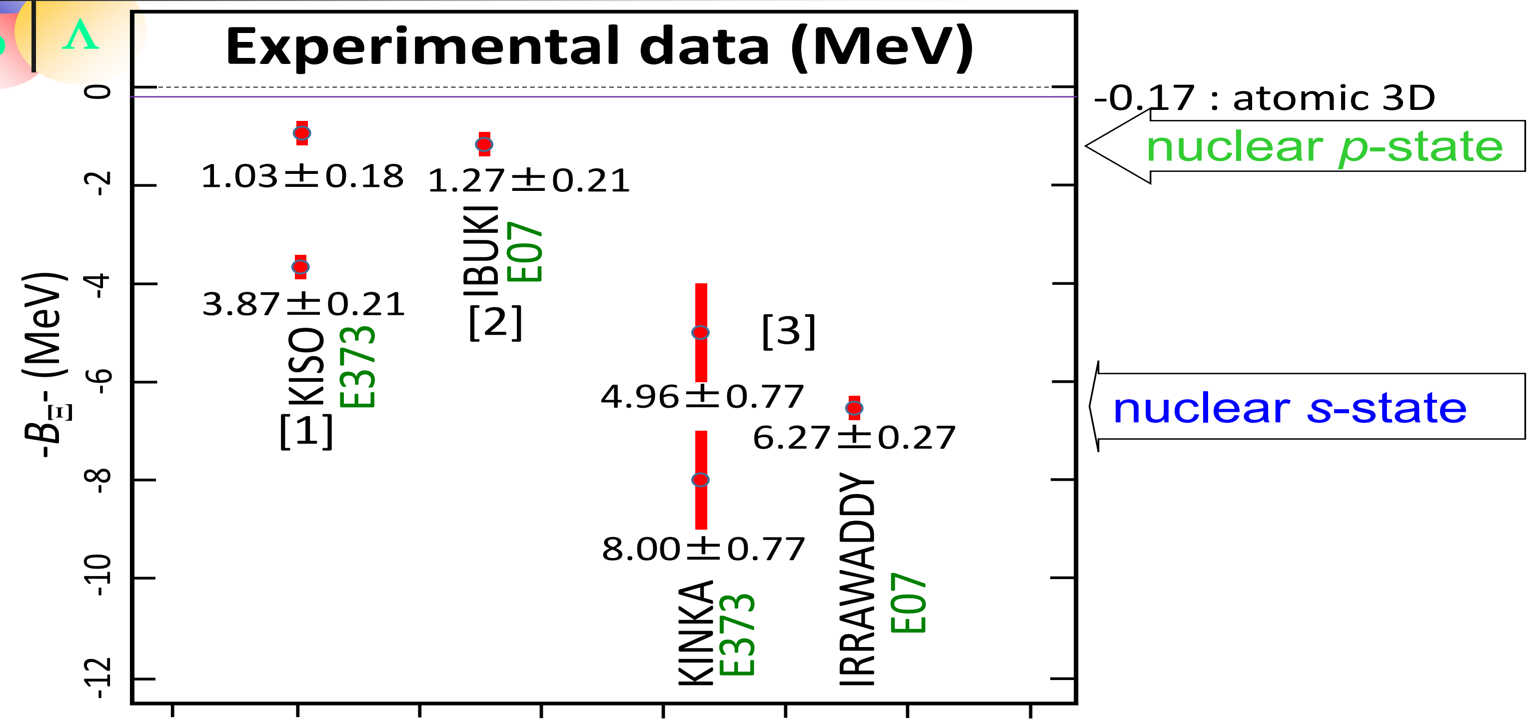
repulsive Nijmegen ESC16 – no





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

IBUKI: $\Xi^-_{1p} + {}^{14}\mathrm{N} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{10}_{\Lambda}\mathrm{Be}$

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

*** IRRAWADDY (J-PARC E07) PTEP 2021 073D02

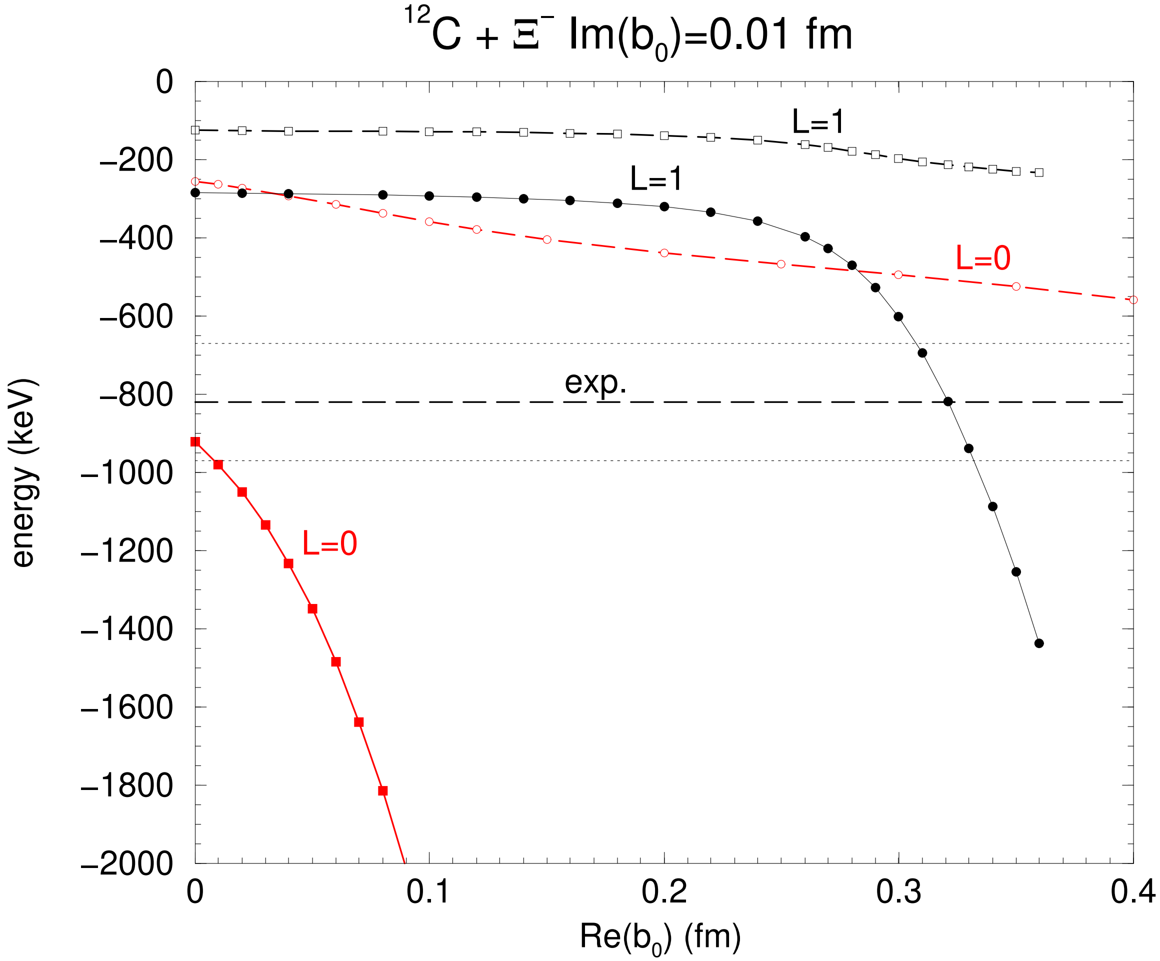
- A: capture $\Xi^-_{1s} + {}^{14}\mathrm{N} \to 2\ {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + \mathrm{n}$
- B or C: decay ${}^{5}_{\Lambda}\mathrm{He} \to \mathrm{d} + \mathrm{p} + 2\mathrm{n}$
  (or other ones, always with fitted neutrons)

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_{Ξ^-} = 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.



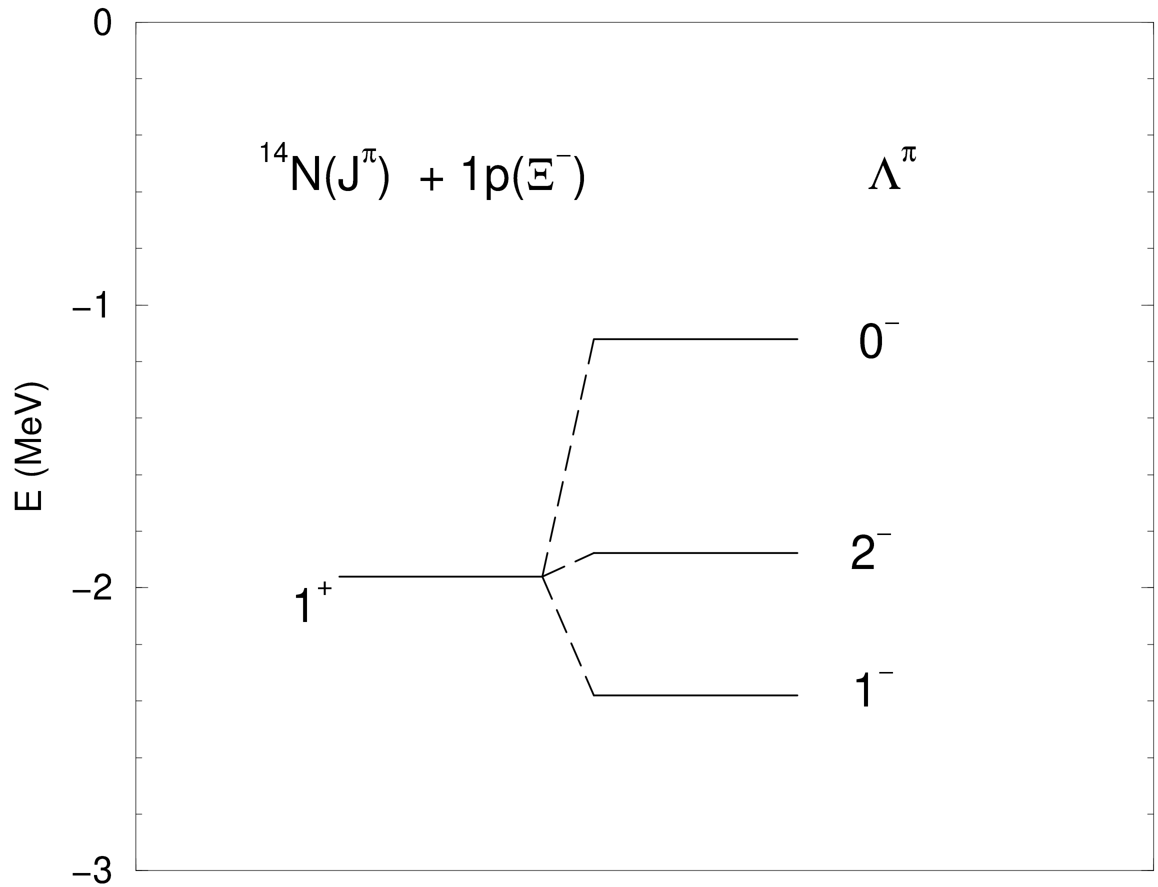
$\mathbf{V_{opt}=t\rho \sim b_0\rho(r)}$: **scan over Re b$_0$**

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:

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



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

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

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

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

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

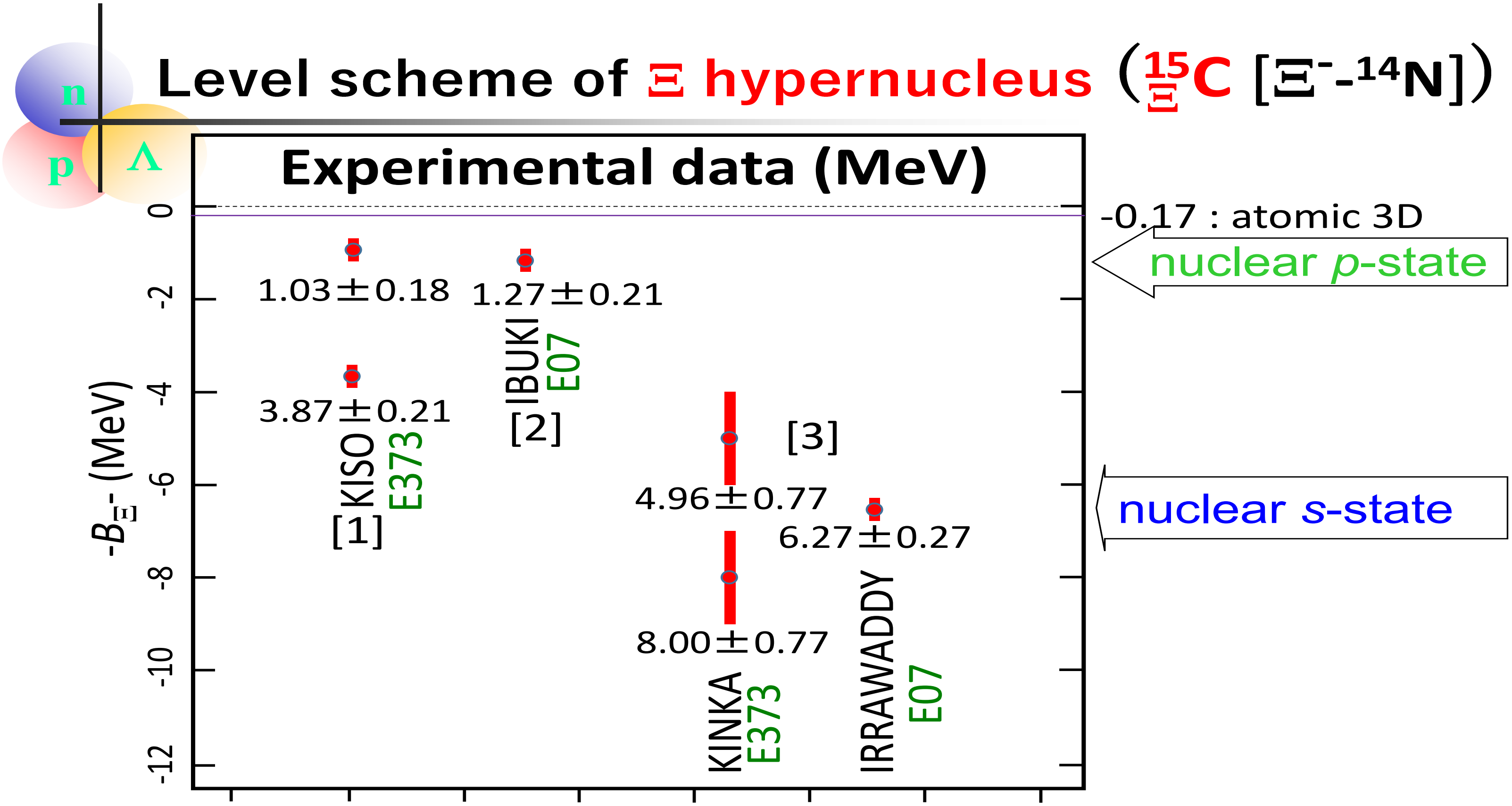
Suppressing SHF nonlocal terms and assuming $m^*_\Xi = m_\Xi$, the SHF Ξ mean field depth $V_\Xi(\rho_0)$ in n.m. density ρ_0=0.17 fm^{-1} is fixed by fitting

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

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_{opt}	No	27.5	$-$12.6	14.9
V_{opt}	Yes	24.6	$-$11.0	13.6

J-PARC E07 ^{14}N events



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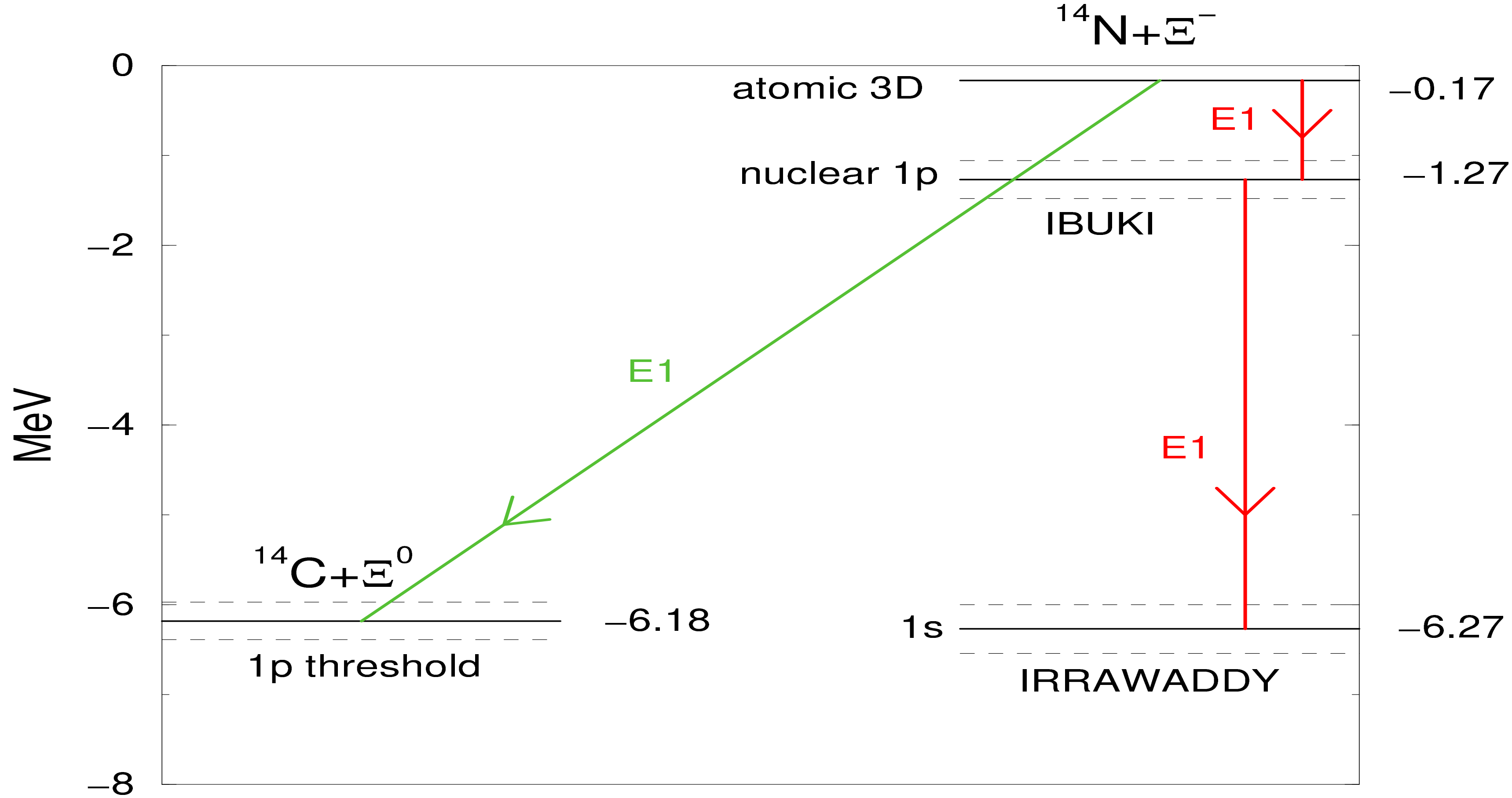
Yoshimoto et al., PTEP 2021 073D02

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

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



Friedman-Gal, PLB 837 (2023) 137640

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

$\Xi^- p \leftrightarrow \Xi^0 n$ 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 $^{14}\mathrm{N}+\Xi^-_{1p}$, $^{14}\mathrm{C}+\Xi^0_{1p}$.

Ξ^- capture: Summary & Outlook

- **V$_\Xi(\rho_0)$=24.3±0.8 ⇒ 21.9±0.7 MeV with Pauli from twin-Λ two-body Ξ^- capture events.**
- **KEK-E224 & BNL-E885: V$_\Xi(\rho_0)$≈16±2 MeV.**
- **BNL-E906: V$_\Xi(\rho_0)$=17±6 MeV (QF in ^{9}Be).**
- **EFT & LQCD suggest V$_\Xi(\rho_0)$≤10 MeV.**
- **SHF using E07 ^{14}N input: V$_\Xi$≈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!