News from emulsion Ξ^- capture events

ECT* Workshop EXOTICO, Oct. 2022

E. Friedman, A. Gal, HU, Jerusalem, Israel

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

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

$1p_{\Xi^-}$—^{14}N $\leftrightarrow$ $1p_{\Xi^0}$—^{14}C coupling helps reach $1p_{\Xi^0}$—^{14}C, assigned $1s_{\Xi^-}$—^{14}N by E07.

E. Friedman, A. Gal, arXiv:2209.01606

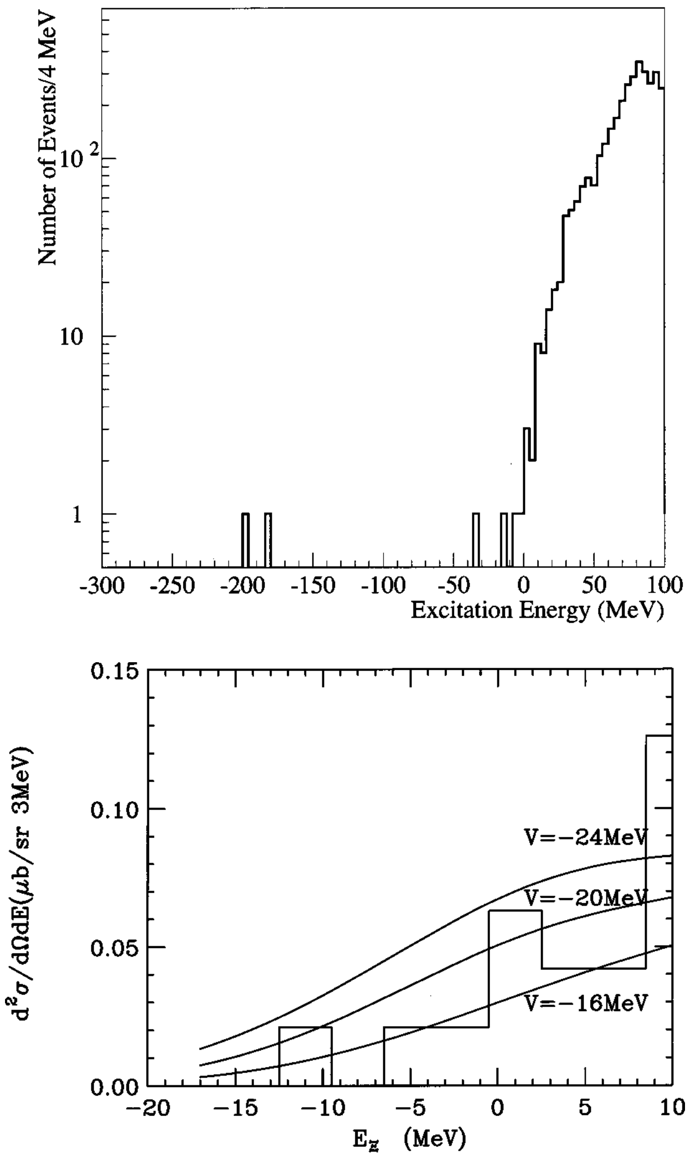
Ξ^- nuclear physics

from counter experiments,

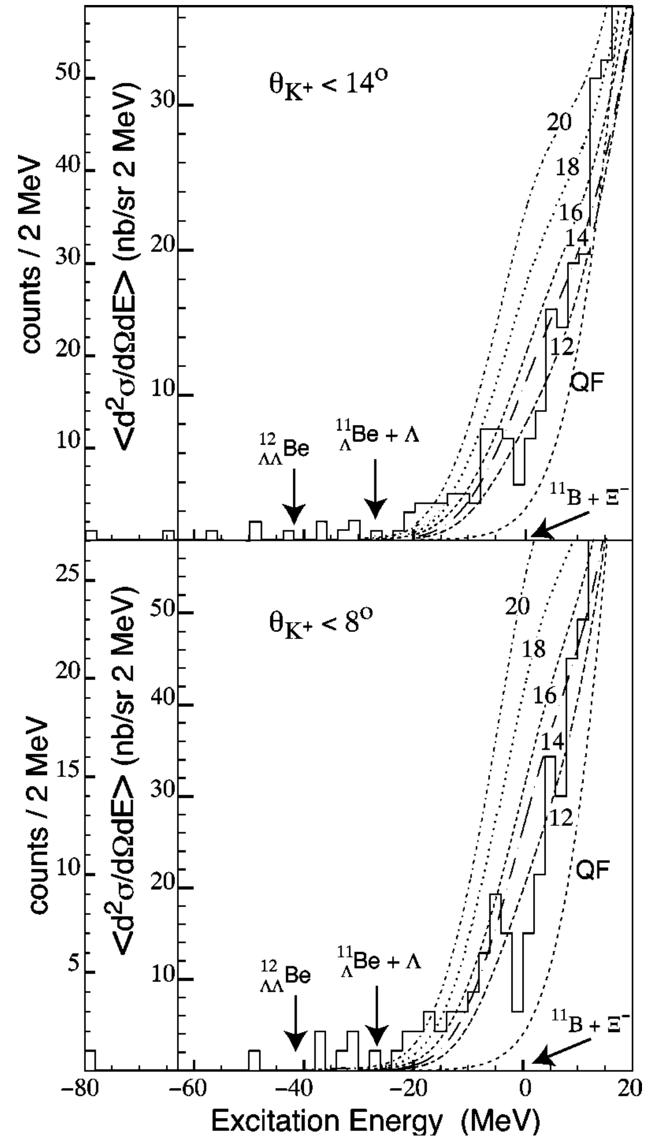
from theory and femtoscopy,

& from capture in emulsion nuclei

E224 (KEK)

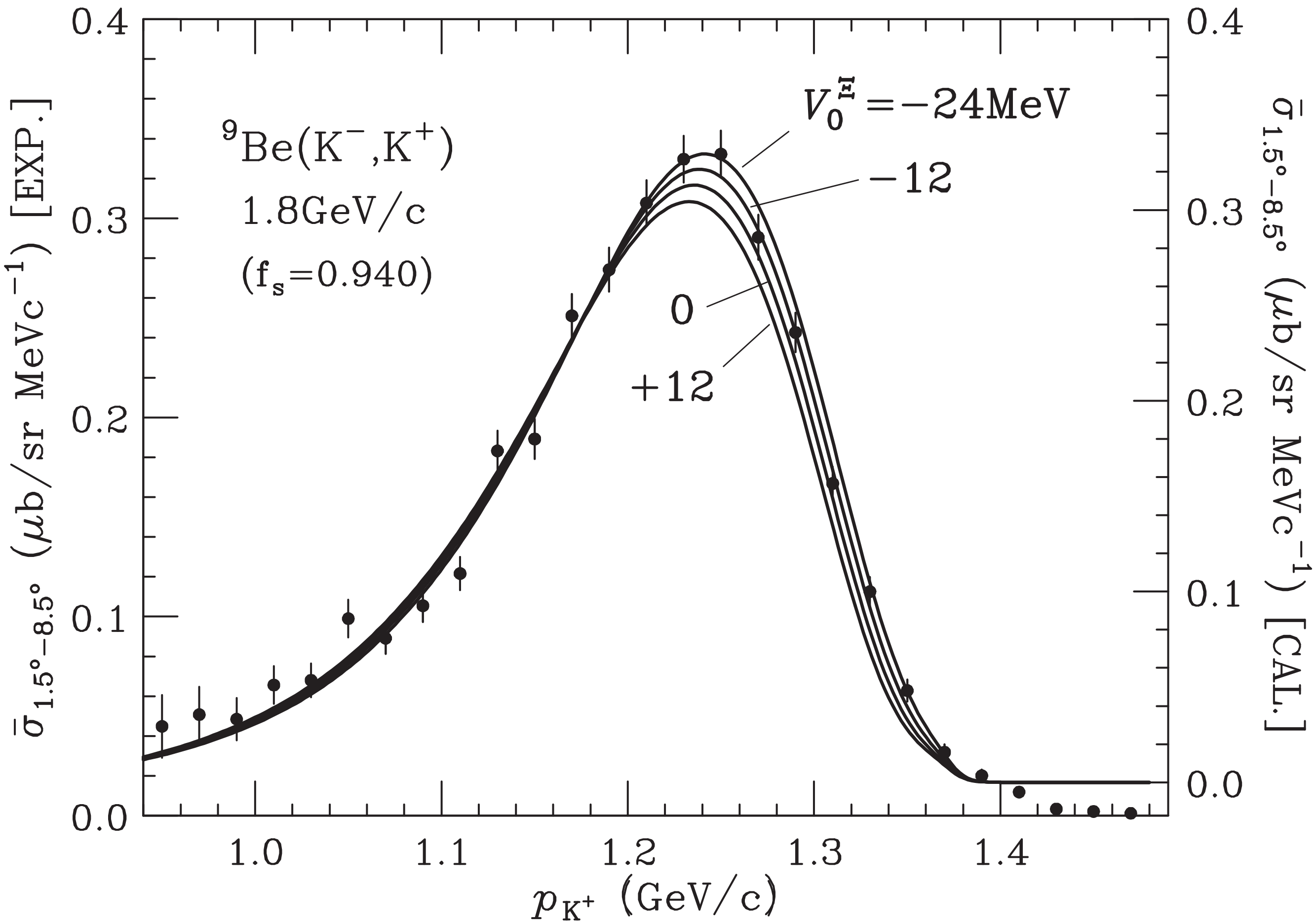


E885 (BNL)



^{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.

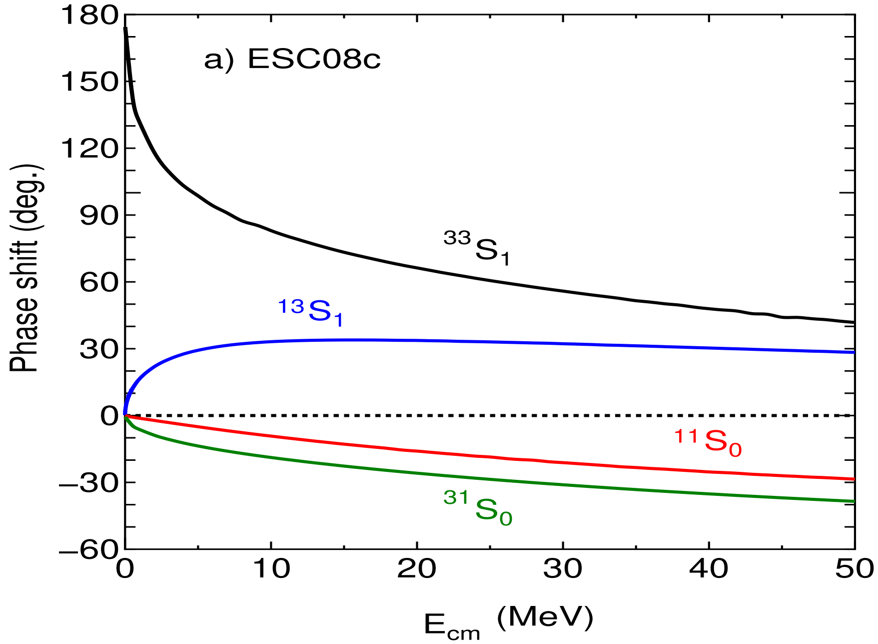
QF calculation, Harada-Hirabayashi (PRC 2021),

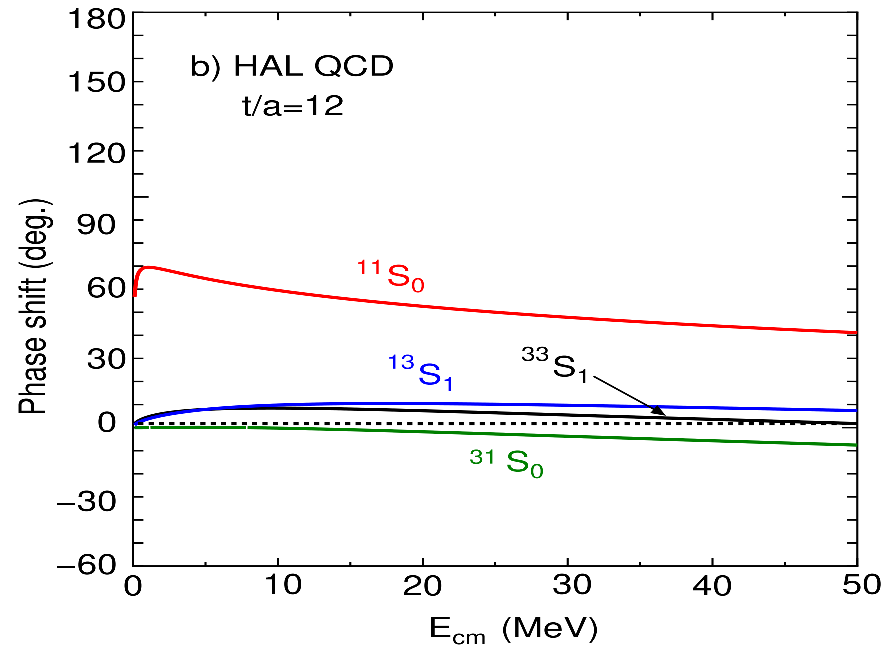
concludes V_Ξ=17±6 MeV. Yet, no Ξ^- bound state

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: $V_\Xi^{LQCD}=4\pm2$ MeV

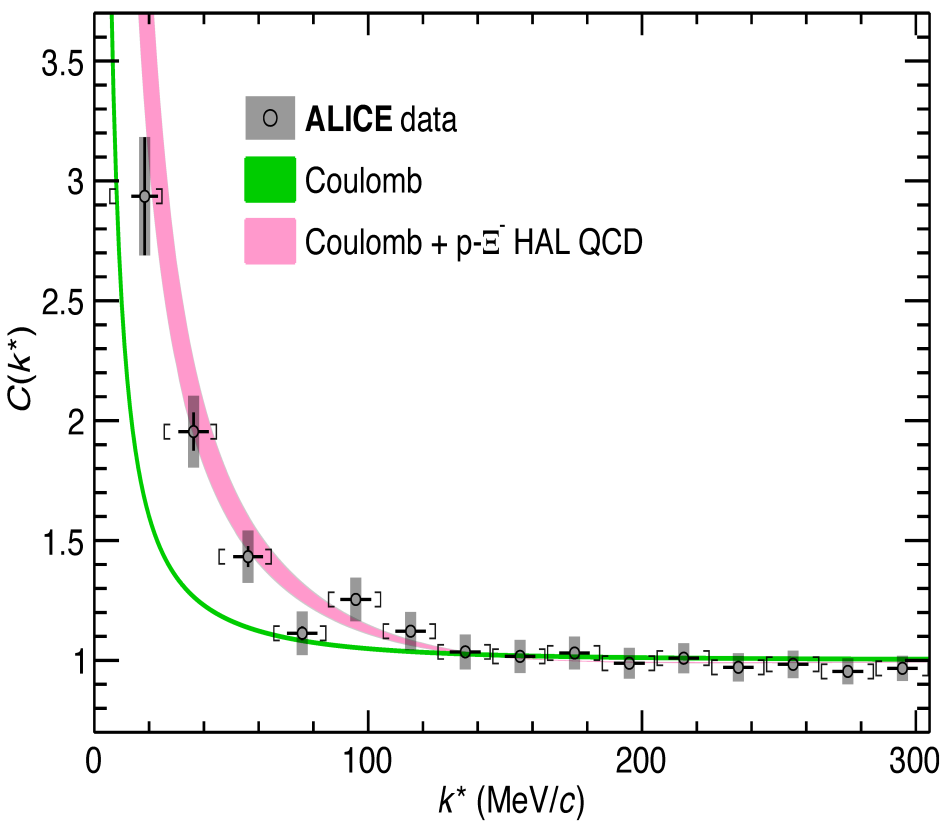
Kohno, PRC 100 (2019) 024313: $V_\Xi^{EFT}\approx 10$ MeV

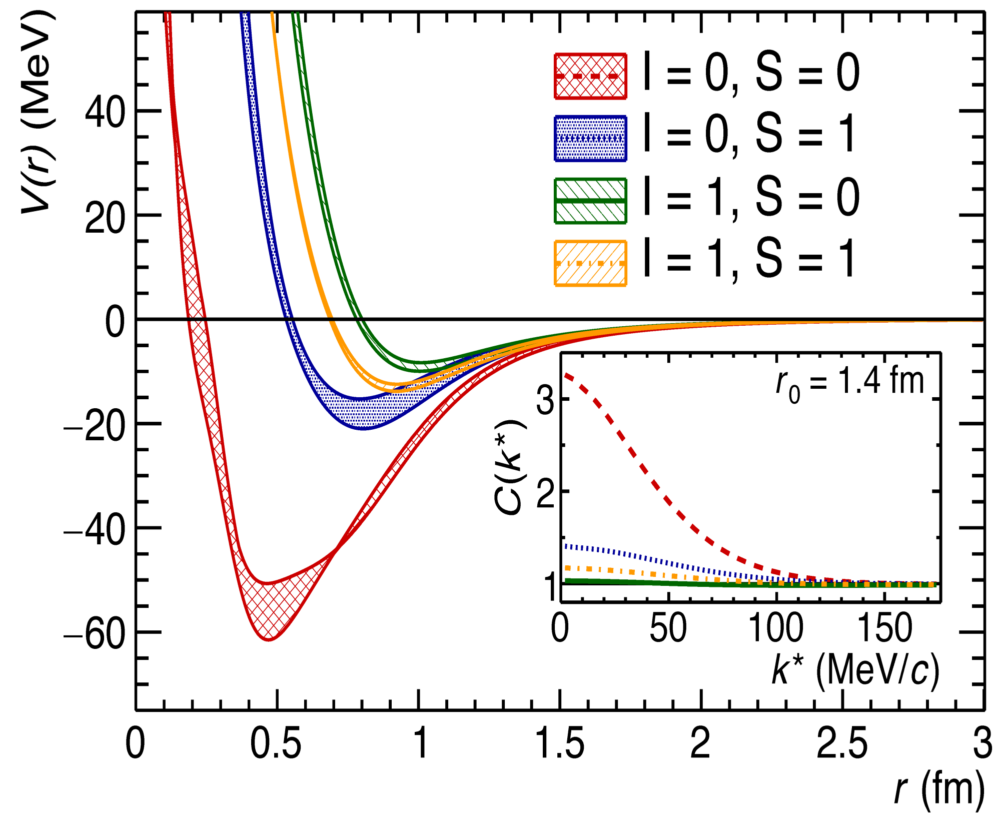
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

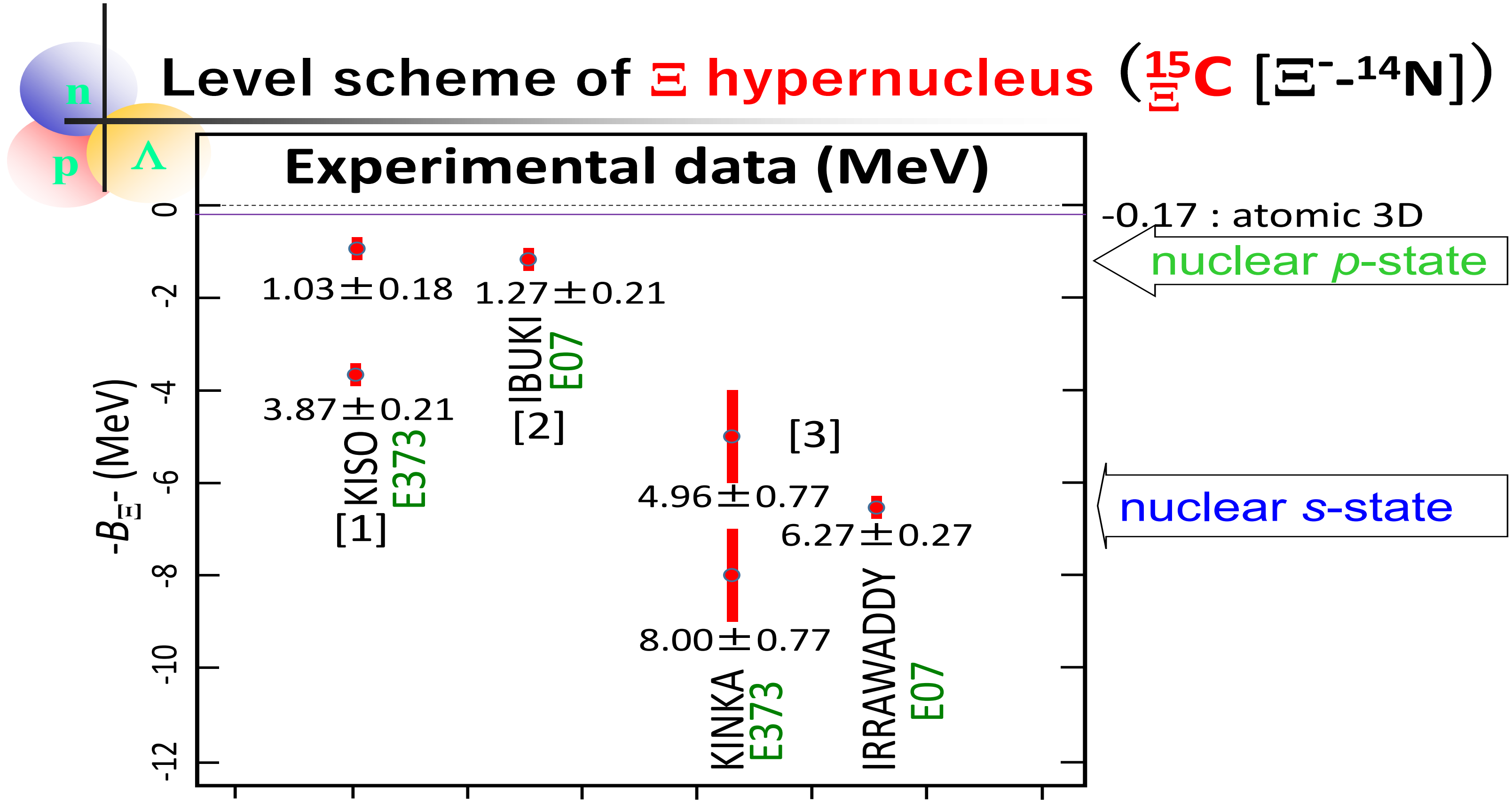
attractive HAL-QCD – yes

repulsive Nijmegen ESC16 – no





J-PARC E07 ^{14}N Ξ^- capture 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

KEK E176 too observed $1p_{\Xi^-}$ nuclear states in ^{12}C & ^{14}N

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

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**

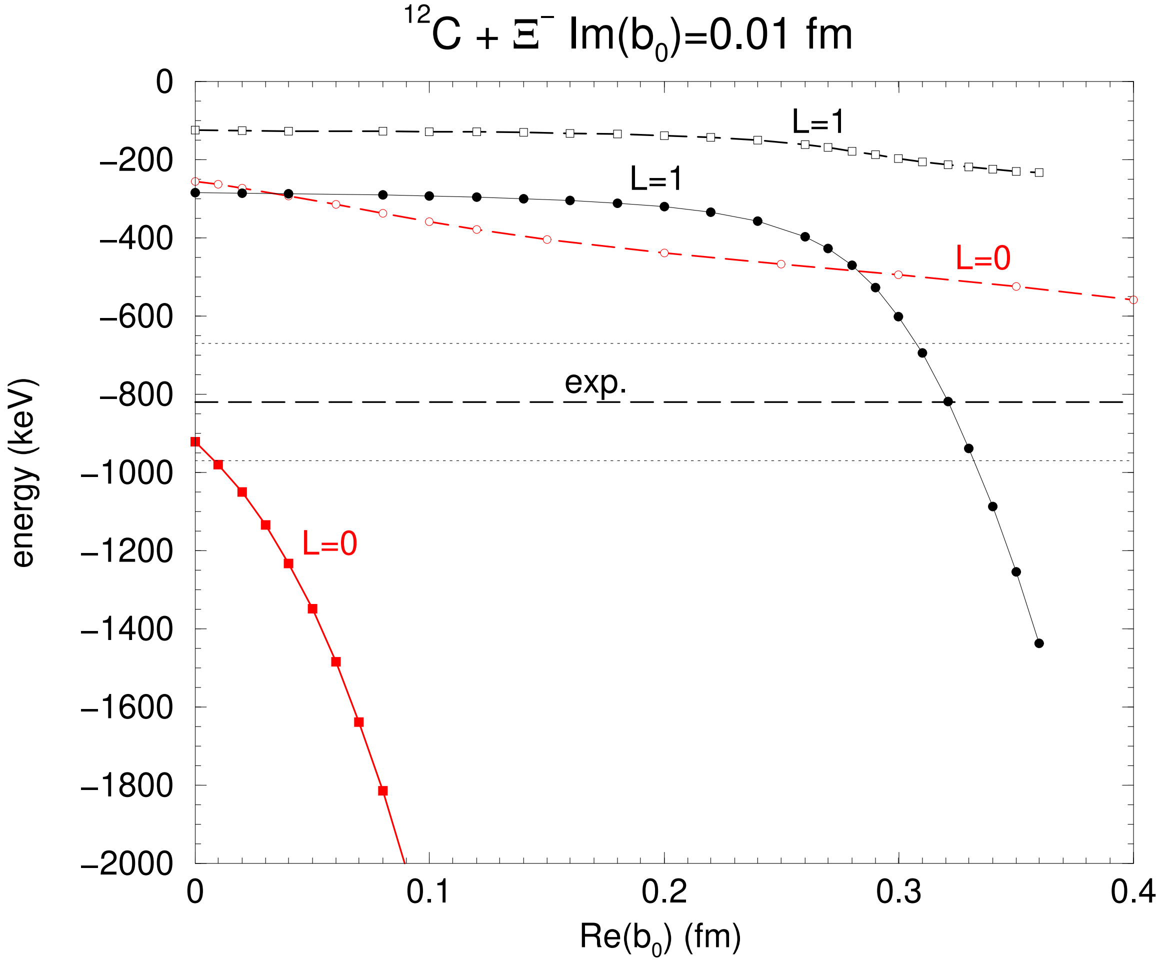
- **A: capture** $\Xi^-_{1s} + {}^{14}\mathrm{N} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$
- **B: decay** ${}^{9}_{\Lambda}\mathrm{Be} \to {}^{6}\mathrm{He} + 2\mathrm{p} + \mathrm{n}$
- **C: decay** ${}^{5}_{\Lambda}\mathrm{He} \to$ **2 nuclei + neutrons**

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

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.



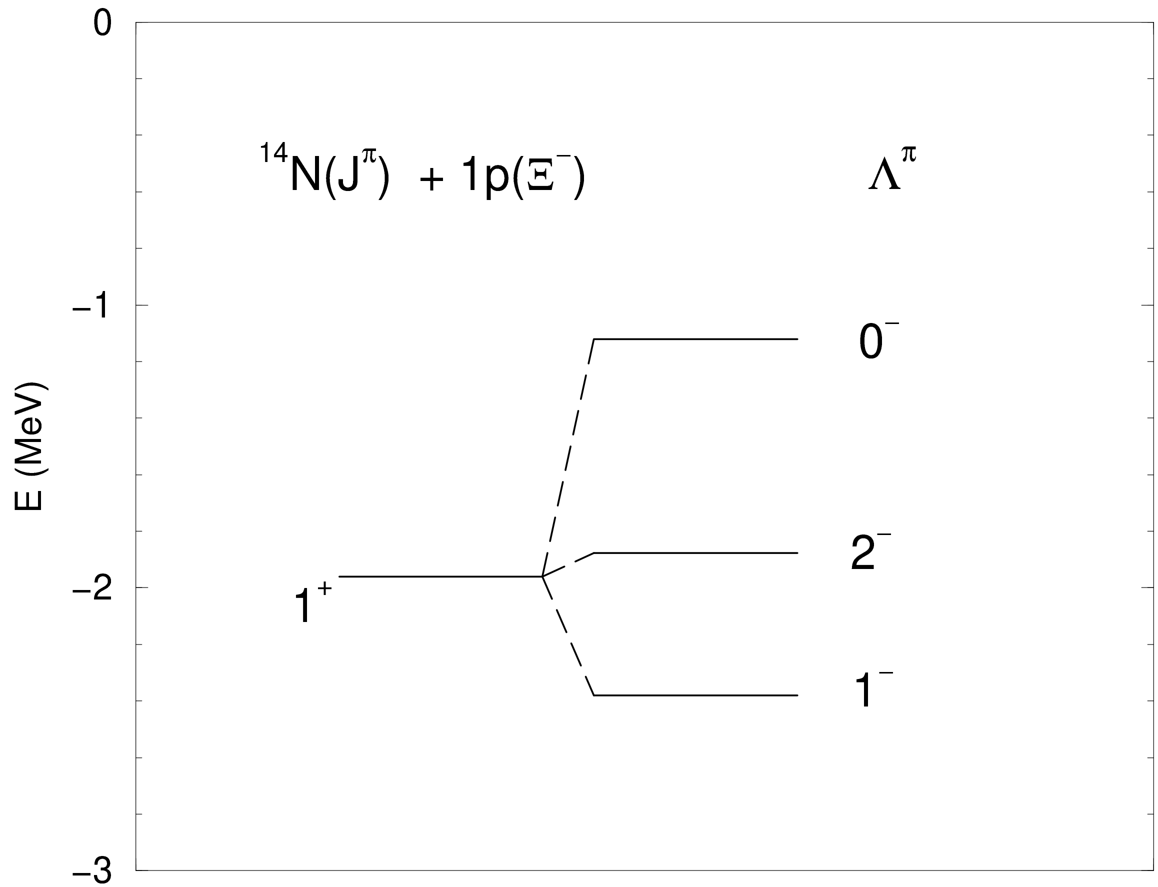
$V_{opt} = t\rho \sim b_0 \rho(r)$: scan over Re b_0

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

Fit exp.: Re $b_0 = 0.32 \pm 0.01$ fm ⇒ $V_{\Xi} = 24.3 \pm 0.8$ MeV

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

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



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

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

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

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

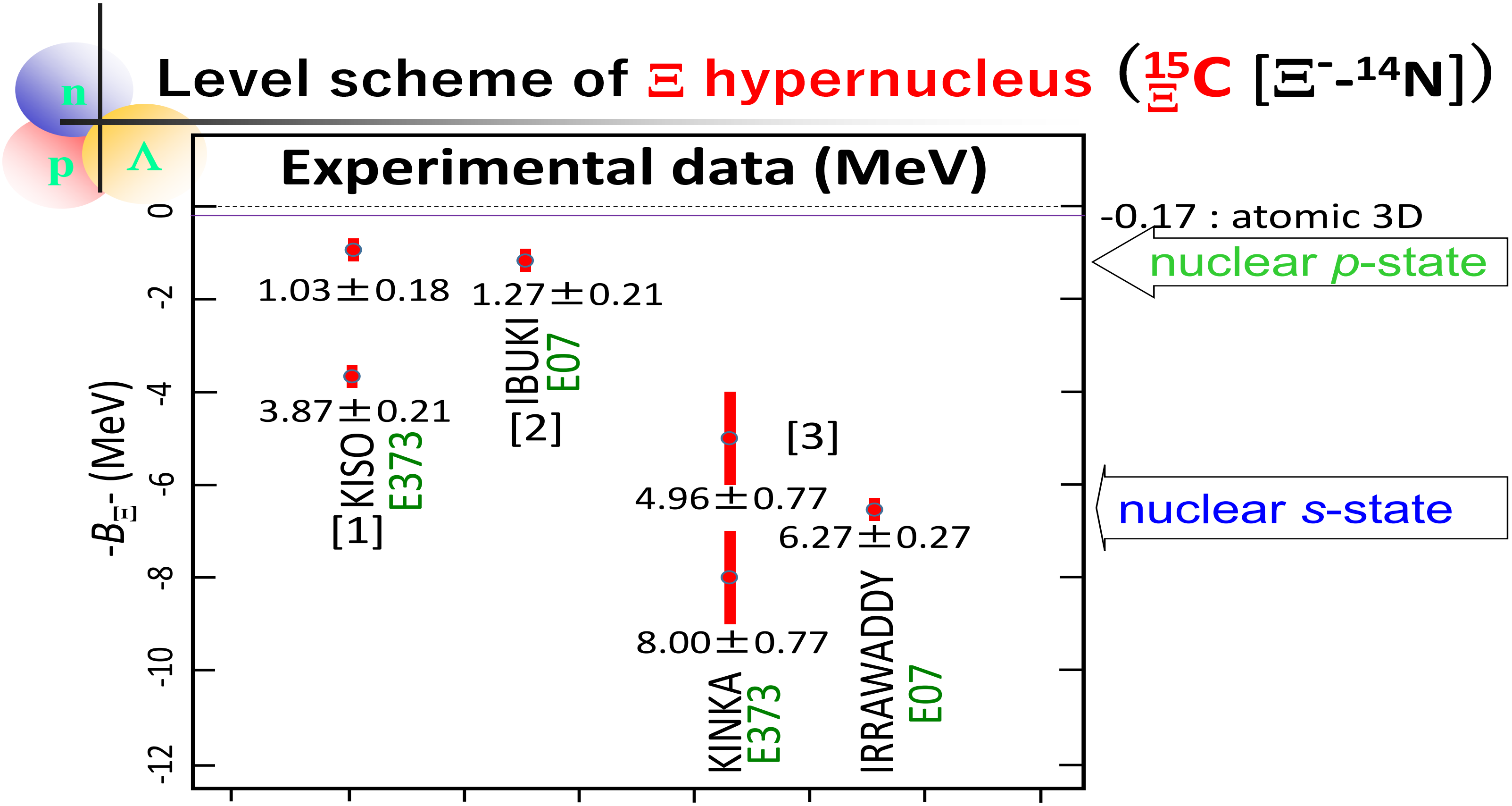
$V_\Xi(\rho_N) = [V_\Xi^{(2)}(\rho_N) = a_0\rho_N] + [V_\Xi^{(3)}(\rho_N) = a_3\rho_N^2]$

in ^{14}N to $B_{\Xi^-}(1s) \approx$ 8.00 MeV (KINKA)

and $B_\Xi(1p) \approx$ 1.13 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

J-PARC E07 ^{14}N events



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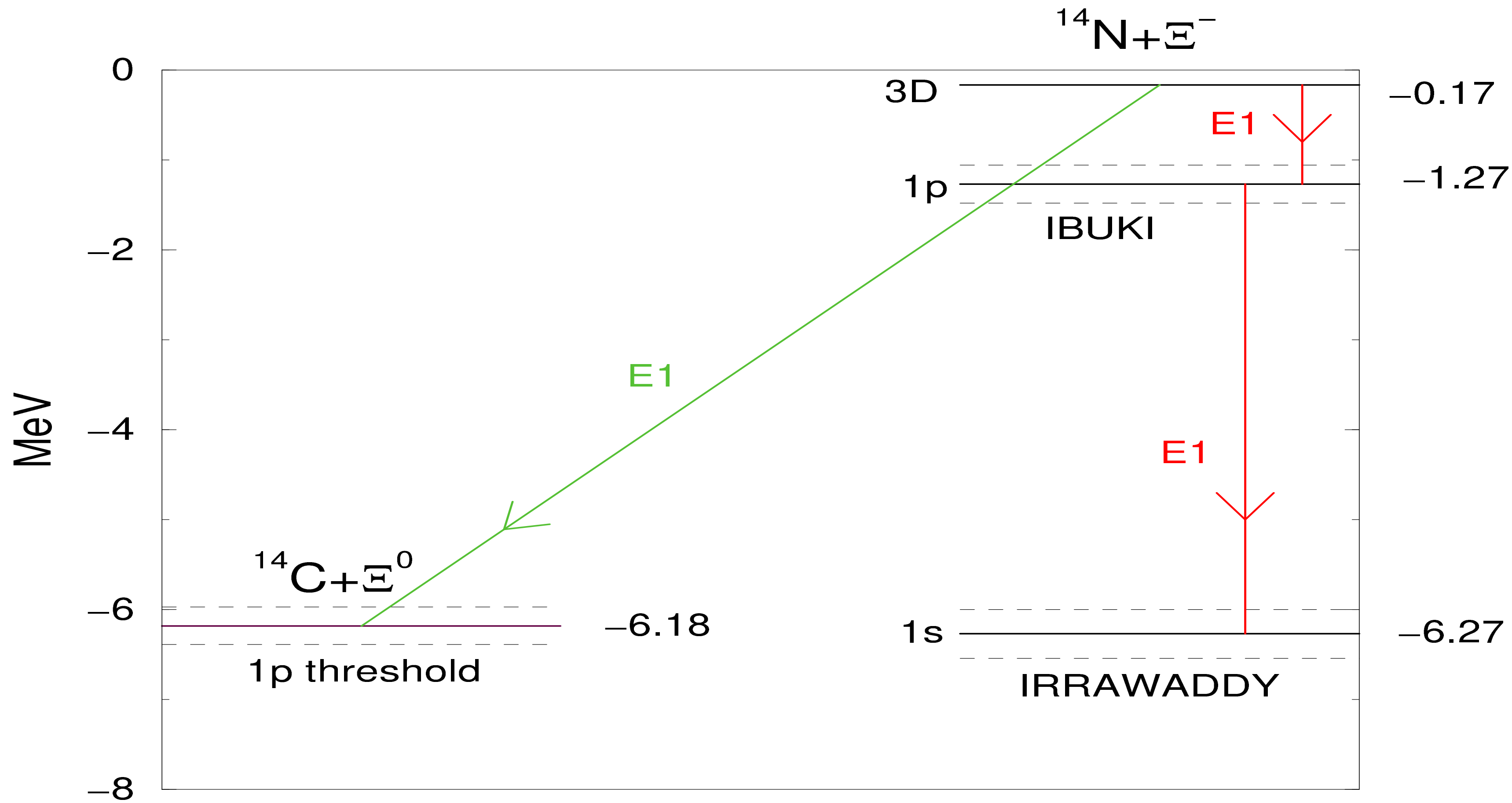
Yoshimoto et al., PTEP 2021 073D02

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

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



Friedman-Gal, arXiv:2209.01606

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

$^{14}\mathrm{N}+\Xi^-_{1p} \to {}^{14}\mathrm{C}+\Xi^0_{1p}$ E1 transition

induced by $\Xi^- p \leftrightarrow \Xi^0 n$ mixing.

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)\approx$16±2 MeV.
- BNL-E906: $V_\Xi(\rho_0)$=17±6 MeV (recent HH).
- 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-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?

Thanks for your attention!