Lessons from Ξ^- capture events in emulsion

2023 ECT* Rockstar Workshop, Trento, Italy, Oct. 2023

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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

Assigned $1s_{\Xi^-}$—^{14}N events reinterpreted as $1p_{\Xi^0}$—^{14}C.

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

Remarks on the elusive H dibaryon

time permitting...

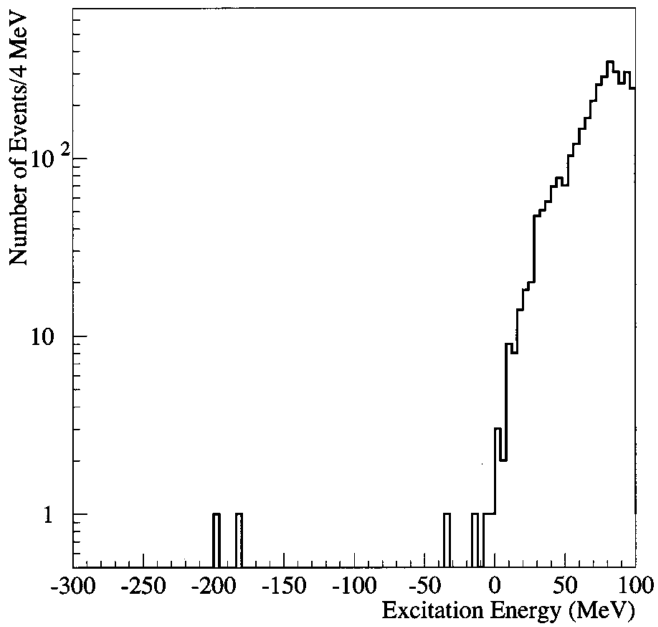
Ξ^- nuclear physics

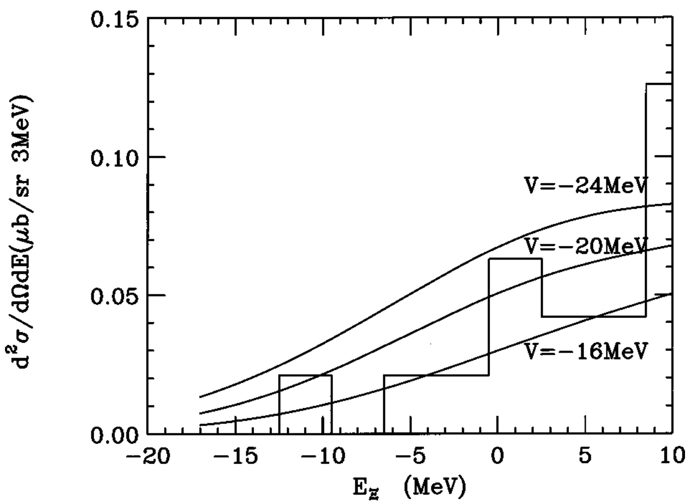
from counter experiments,

from theory and femtoscopy,

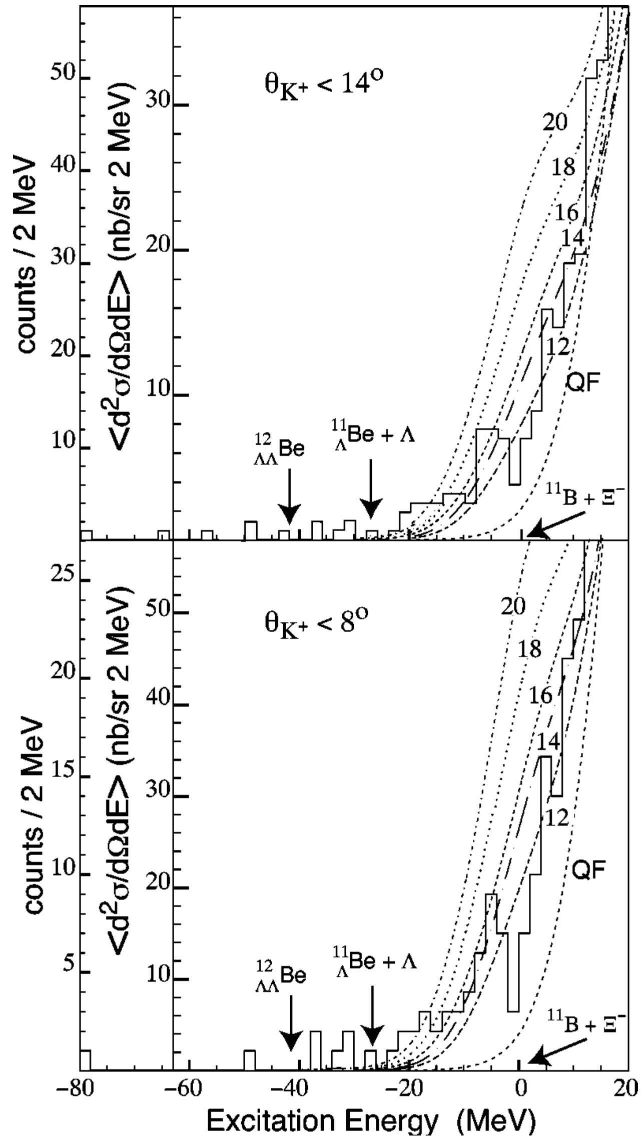
& from capture in emulsion nuclei

E224 (KEK)



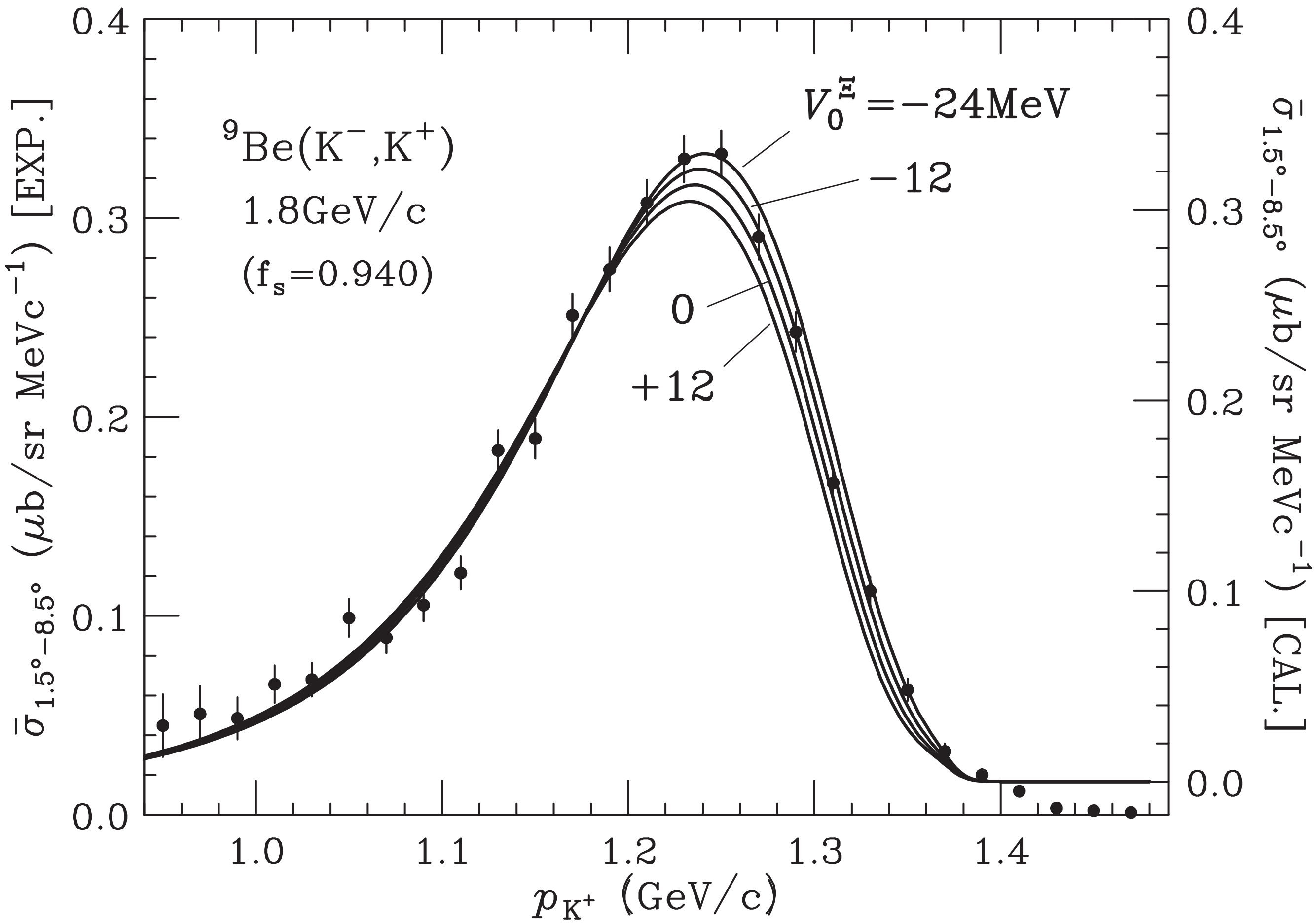


E885 (BNL)



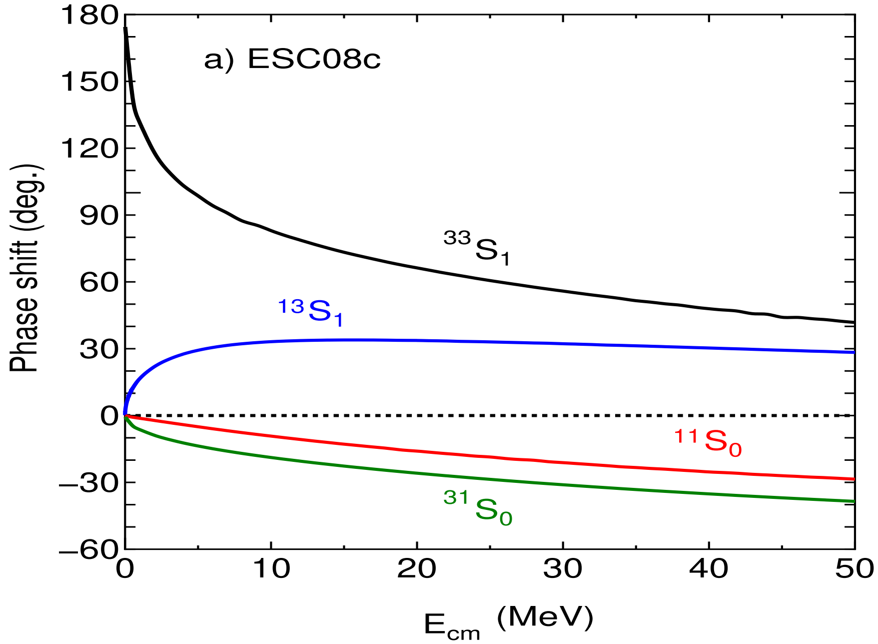
^{12}C(K$^-$,K$^+$) counter experiments, end of 1990s.

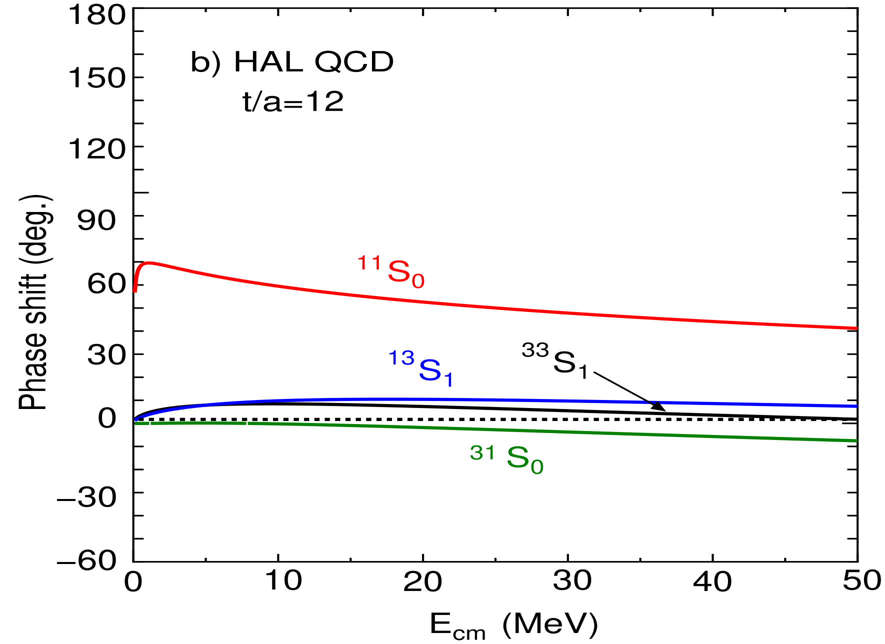
Unresolved bound states, if any, V_Ξ of order 15 MeV



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

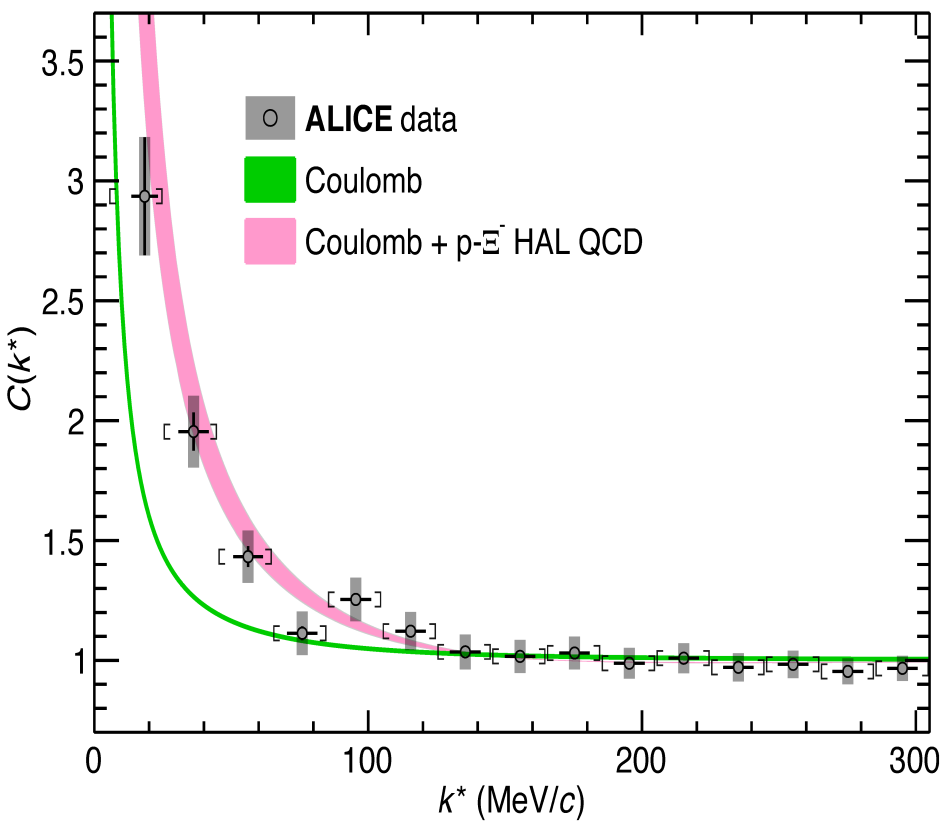
Kohno, PRC 100 (2019) 024313: $V_\Xi^{\rm EFT} \approx 10$ MeV

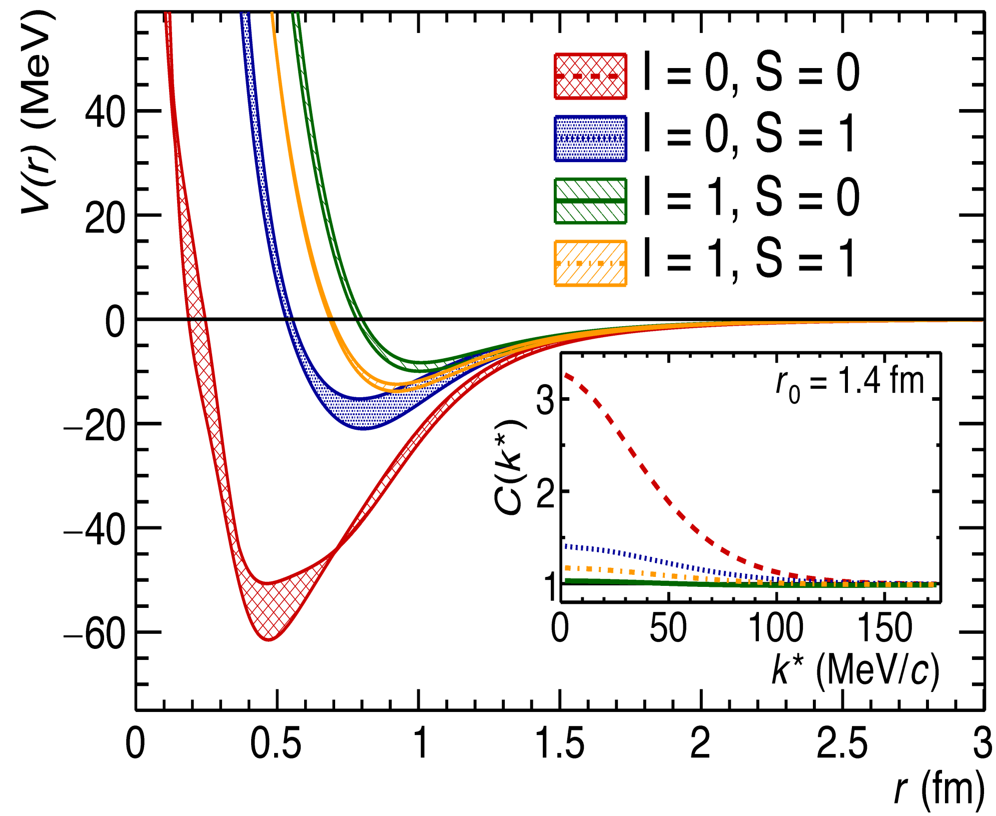
Femtoscopy study of p-Ξ^- correlations

ALICE, PRL 123 (2019) 112002

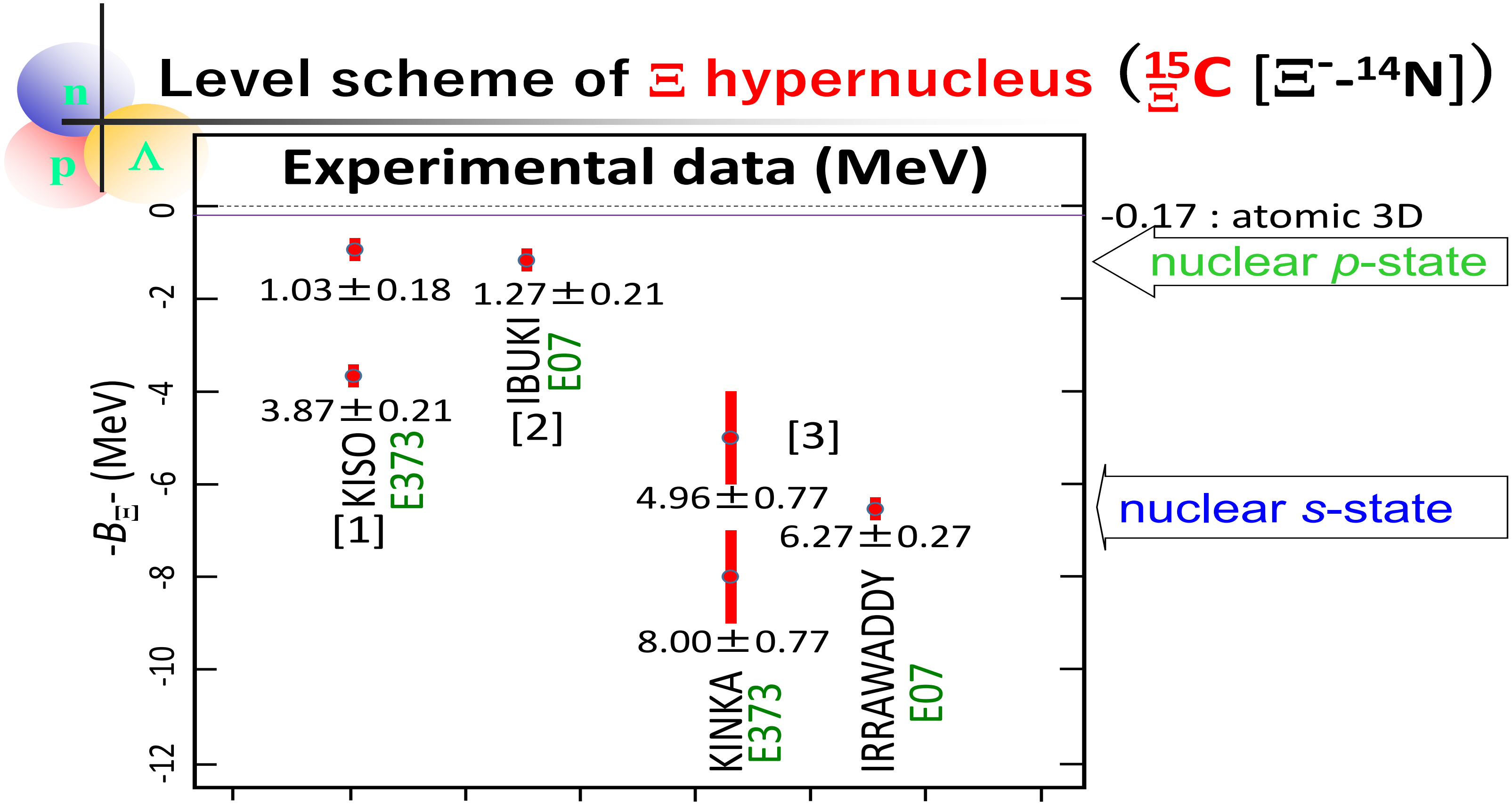
attractive HAL-QCD – yes

repulsive Nijmegen ESC16 – no





J-PARC E07 ^{14}N events



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

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

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**

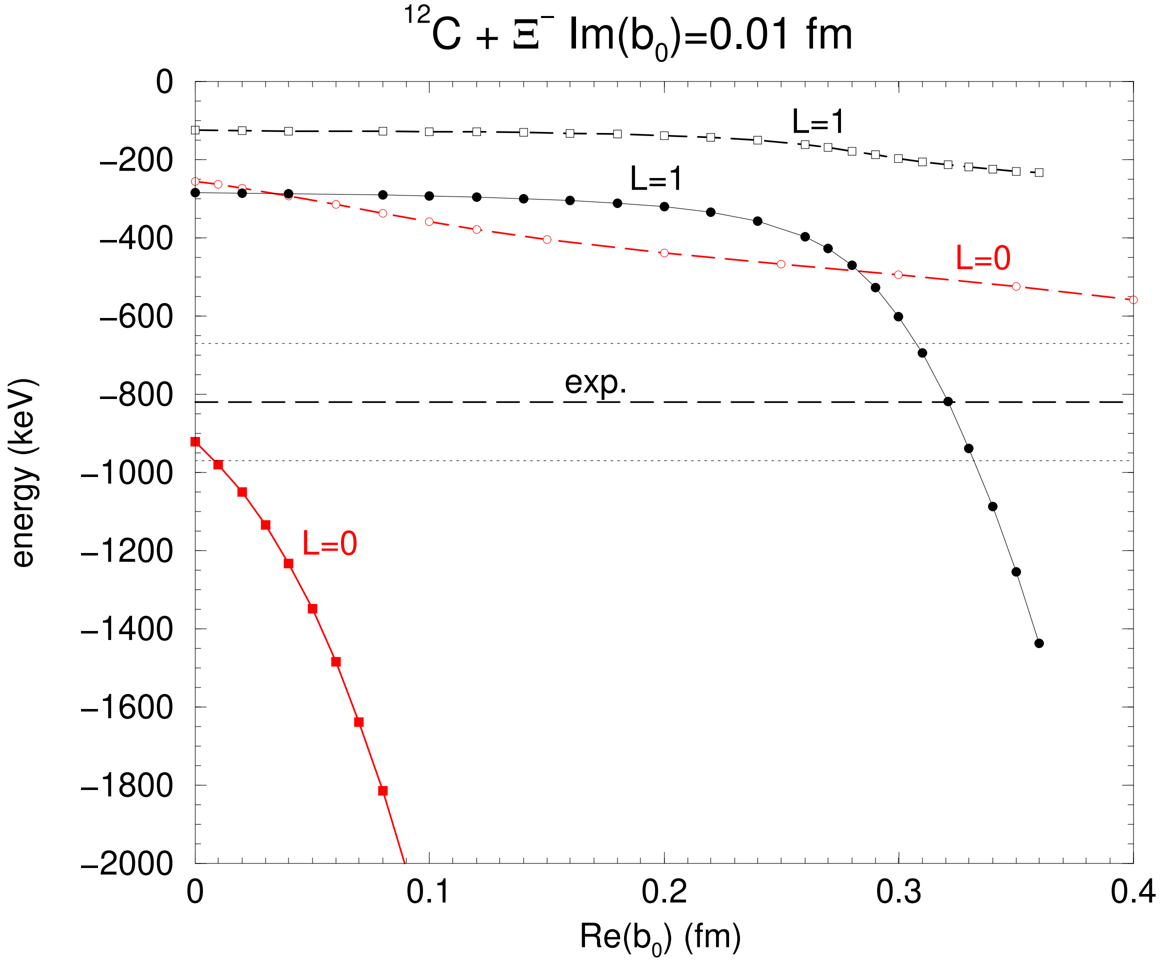
- **A: capture** $\Xi^-_{1s} + {}^{14}\mathrm{N} \to 2\ {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + \mathrm{n}$
- **B or C: decay** ${}^{5}_{\Lambda}\mathrm{He} \to \mathrm{d} + \mathrm{p} + 2\mathrm{n}$
  (or other ones, always with fitted neutrons)

Furthermore, $1\mathrm{s}_{\Xi^-}$ 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.



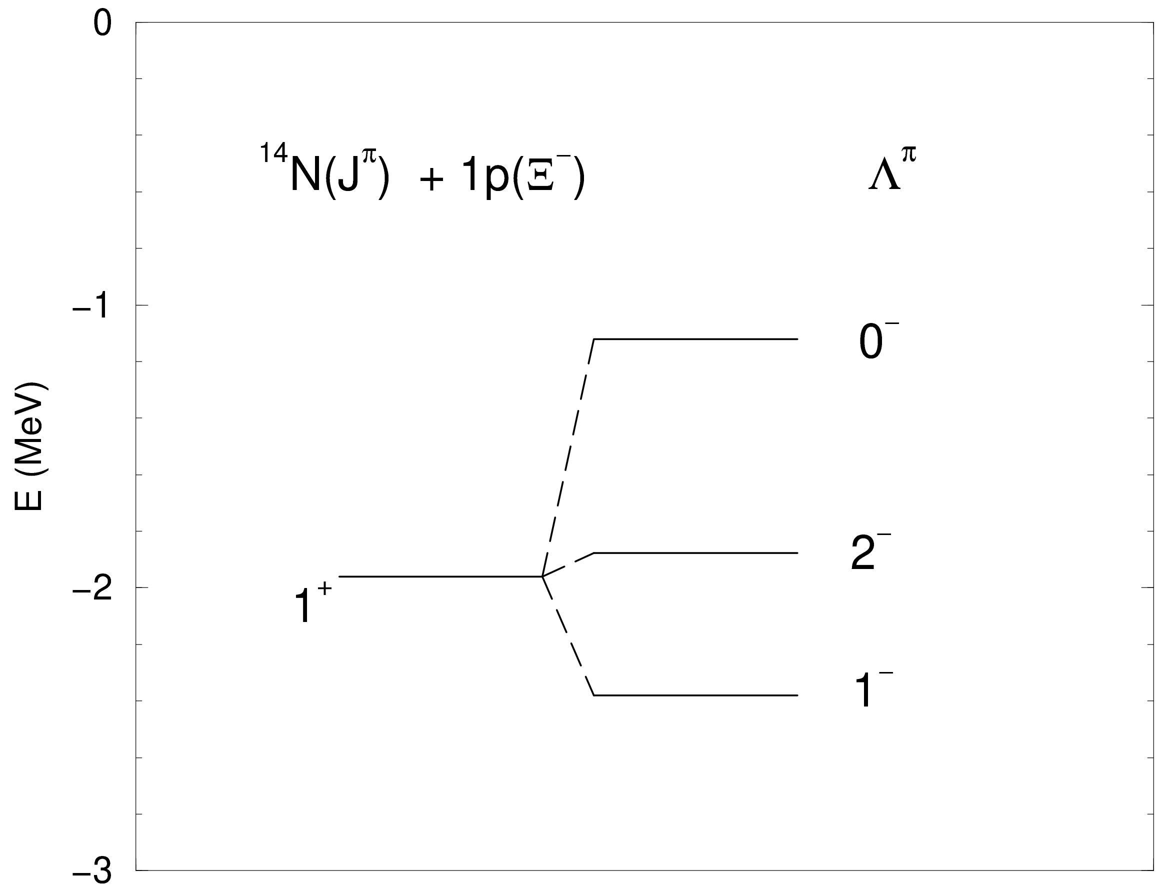
$V_{opt} = t\rho \sim b_0 \rho(r)$: scan over Re b_0

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

Fit exp.: Re b_0=0.32±0.01 fm ⇒ V_{Ξ}=24.3±0.8 MeV

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

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



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

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

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

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

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

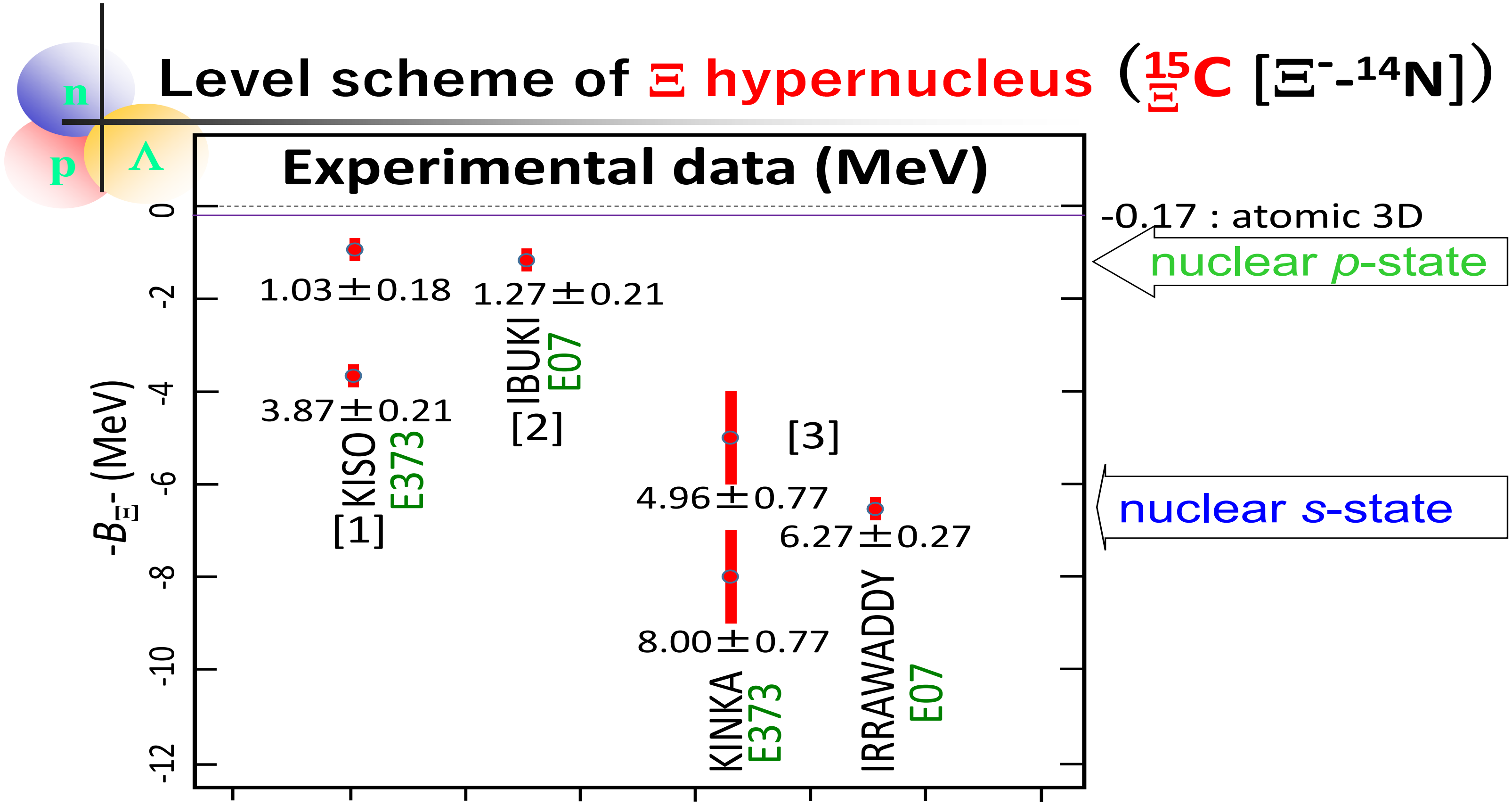
Suppressing SHF nonlocal terms and assuming $m^*_\Xi = m_\Xi$, the SHF Ξ mean field depth $V_\Xi(\rho_0)$ in n.m. density ρ_0=0.17 fm^{-1} is fixed by fitting

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

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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[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
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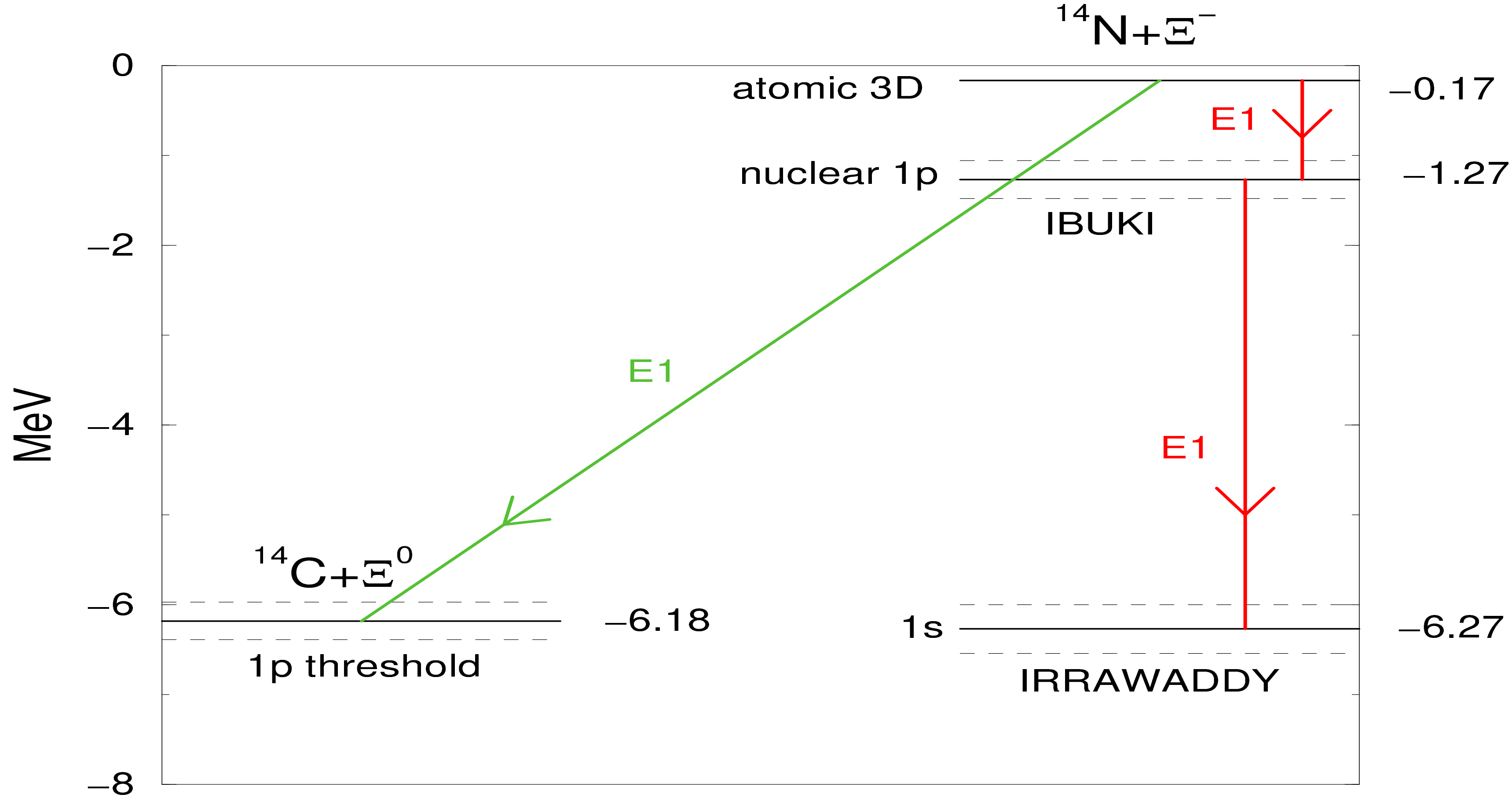
Yoshimoto et al., PTEP 2021 073D02

$1s_{\Xi^-}$ 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)\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!

The Elusive H Dibaryon

Remarks triggered by G. Farar's 2003 idea

to make H a deeply bound dibaryon,

a long-lived Dark-Matter candidate.

Most recent: arXiv:2306.03123 [hep-ph]

The elusive H dibaryon

Jaffe's H(uuddss) [PRL 38 (1977) 195] predicted stable

$$\mathbf{H} \sim \mathcal{A}[\sqrt{\mathbf{1/8}}\ \Lambda\Lambda + \sqrt{\mathbf{1/2}}\ N\Xi - \sqrt{\mathbf{3/8}}\ \Sigma\Sigma,]_{I=S=0}$$

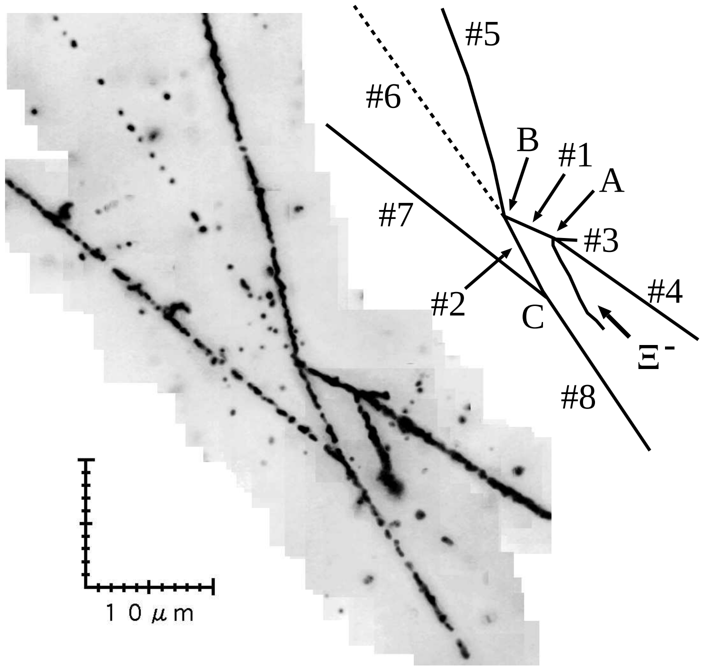
- **No H signal in past (K^-, K^+) experiments at AGS-BNL & PS-KEK. Awaiting J-PARC E42.**
- **Bound H ruled out by STAR study of $\Lambda\Lambda$ correlation femtoscopy [PRL 114 (2015) 022301].**
- **Bound H not ruled out by ALICE study of $\Lambda\Lambda$ correlation femto [PLB 797 (2019) 134822].**
- **Bound H above $\Lambda p \pi^-$, $\sim$37 MeV below $\Lambda\Lambda$, ruled out by ALICE search for a weakly decaying $\Lambda\Lambda$ bound state [PLB 752 (2016) 267].**

- **Bound H above $\Lambda p \pi^-$ ruled out in Belle study of Υ(1S,2S) decays** [PRL 110 (2013) 222002].

- **Deeply bound H below Λn, $m_H \leq 2.05$ GeV, ruled out in BaBar's $\Upsilon(2S,3S) \to H\bar{\Lambda}\bar{\Lambda}$ search** [PRL 122 (2019) 072002].

- **H is weakly bound in LQCD calculations, e.g., PRL 127 (2021) 242003, see Wittig's talk. $SU(3)_f$ breaking might push it to ≈26 MeV in the $\Lambda\Lambda$ continuum, near NΞ threshold: HALQCD Collaboration** [NPA 881 (2012) 28] **& Haidenbauer-Meißner** [NPA 881 (2012) 44].

Constraints from Hypernuclei



Nagara event, $^{\;6}_{\Lambda\Lambda}$He, (KEK-E373) PRL 87 (2001) 212502

$B_{\Lambda\Lambda}(^{\;6}_{\Lambda\Lambda}\mathrm{He}_{\mathrm{g.s.}})$**=6.91±0.16 MeV, uniquely identified.**

- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \to {}^{\;6}_{\Lambda\Lambda}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}^{\;6}_{\Lambda\Lambda}\mathrm{He} \to {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$ **(no** ${}^{\;6}_{\Lambda\Lambda}\mathrm{He} \to {}^{4}\mathrm{He}$ **+ H)**
- **C:** ${}^{5}_{\Lambda}\mathrm{He}$ **nonmesic weak decay to two** Z**=1 recoils + n.**

Few other weakly decaying ${}^{\;A}_{\Lambda\Lambda}$**Z hypernuclei identified.**

Constraints from Hypernuclei

- To forbid ${}_{\Lambda\Lambda}^{6}$He$\rightarrow$H$+{}^{4}$He, set B(H)$\leq$7 MeV. However, ${}_{\Lambda\Lambda}^{6}$He comes out then overbound [Gal, PRL 110 (2013) 179201].
- A correlated $\Lambda\Lambda$ pair in a given ${}_{\Lambda\Lambda}^{A}$Z would decay strongly to a bound H, contrary to observing ${}_{\Lambda\Lambda}^{A}$Z in weak decay. Furthermore,
- H$\rightarrow\Lambda$n weakly, $\tau\sim10^{-10}$ sec. If below Λn, it decays weakly, H$\rightarrow$nn, by π exchange, with τ not much longer than 1yr, $\ll\tau$(Universe).
- Thus, a deeply bound uuddss 'sexaquark' fails as a long-lived Dark-Matter candidate [Gal-Schaefer, in preparation].