H dibaryon constrained by hypernuclei

ECT* THEIA-SPICE Workshop, Trento, Italy, May 2024

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- **Q: does observing $\Lambda\Lambda$ hyp exclusively by weak decay ($\tau_w \sim 10^{-10}$ s) rule out a deeply bound H(uuddss) ?**
- **A: ${}^{6}_{\Lambda\Lambda}$He 3-body model gives $\tau_s({}^{6}_{\Lambda\Lambda}\text{He}\rightarrow\text{H}+{}^{4}\text{He})\gg\tau_w$ for $m_H \leq m_\Lambda + m_n$, so a deeply bound H is fine.**
- **Q: how slow is the $\Delta\mathcal{S}$=2 weak decay H$\rightarrow$2n with respect to τ(Universe)$\approx (13.8 \times 10^9$ yrs) ?**
- **A: constrained by Λ hyp lifetimes, τ_w(H$\rightarrow$2n)$\sim 10^5$ s, by far too short to make H dark-matter candidate.**

A. Gal, arXiv:2404.12801

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...

The elusive H dibaryon

A stable H(uuddss) predicted by Jaffe PRL 38 (1977) 195

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

- **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].

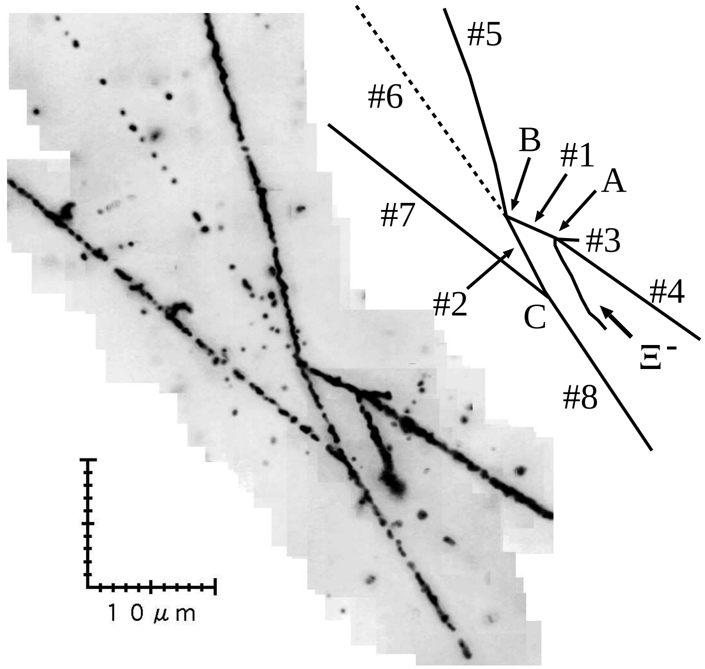
- **Deeply bound H below Λn, m$_H\leq$2.05 GeV, ruled out in BaBar's Υ(2S,3S)$\rightarrow$H$\bar{\Lambda}\bar{\Lambda}$ search** [PRL 122 (2019) 072002].

- **H is weakly bound in LQCD calculations, e.g., Green,...,Wittig, PRL 127 (2021) 242003.**

- **SU(3)$_{\rm f}$ breaking might push it to $\approx$26 MeV in the $\Lambda\Lambda$ continuum, near NΞ threshold:**

  HALQCD Collaboration [NPA 881 (2012) 28] **& Haidenbauer-Meißner** [NPA 881 (2012) 44].

Hypernuclear Constraints: Nagara event



$_{\Lambda\Lambda}^{6}$He **(KEK-E373) PRL 87 (2001) 212502, PRC 88 (2013) 014003**

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

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

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

Dark-Matter H Dibaryon?

Work triggered by Farrar's 2003-4 idea that a deeply bound H dibaryon would make a long-lived Dark-Matter particle.

G.R. Farrar, Int'l. J. Theor. Phys. 42 (2003) 1211.

G.R. Farrar, G. Zaharijas, Phys. Rev, D 70 (2004) 014008.

A recent review: G.R.F+Z. Wang, arXiv:2306.03123 [hep-ph].

assuming (i) compact 6q configurations of size down to 0.2 fm and (ii) outdated hard-core BB strong-interaction potentials.

Here, we try to do better...

H(uuddss) model wavefunction

- **Symmetric L=0, Antisymmetric 1_S(S=0), 1_F, 1_C.**
- $\Psi_H = N_6 \exp\left(-\frac{\nu}{6}\sum_{i<j}^{6}(\vec{r}_i - \vec{r}_j)^2\right)$
- $\Psi_H = \psi_{B_a}(\rho_a, \lambda_a) \times \psi_{B_b}(\rho_b, \lambda_b) \times \psi_{B_a B_b}(r)$
- $\psi_{B_a B_b} = \left(\frac{3\nu}{\pi}\right)^{\frac{3}{4}} \exp(-\frac{3\nu}{2} r^2)$, **Need to add SFC factors.**
- $< r^2_{B_a} > = < r^2_{B_b} > = < r^2_{B_a B_b} > = \frac{9}{8\nu}$, $< r^2_H > = \frac{5}{8\nu}$.

$\sqrt{< r^2_{\Lambda\Lambda} >}$ (fm) vs. $B_{\Lambda\Lambda}$ (MeV)

$B_{\Lambda\Lambda}$	5	20	50	100	200	300	400
$\sqrt{< r^2_{\Lambda\Lambda} >}$	2.134	1.206	0.854	0.689	0.560	0.501	0.463

calculated for a short-range potential $C_0^{(\lambda)}\delta_\lambda(r)$, λ=4 fm^{-1},

where $\delta_\lambda(r) = \left(\frac{\lambda}{2\sqrt{\pi}}\right)^3 \exp\left(-\frac{\lambda^2}{4} r^2\right)$, $\int \delta_\lambda(r)\, d^3 r = 1$.

${}_{\Lambda\Lambda}^{6}$He model wavefunction

- **Use a** $\Lambda-\Lambda-{}^4\mathrm{He}$ **model inspired by a** $\not\pi$**EFT study of s-shell** $\Lambda\Lambda$ **hypernuclei in PLB 797 (2019) 134893 by Contessi-Schaefer-Barnea-Gal-Mareš.**
- $\Phi_{{}_{\Lambda\Lambda}^{6}\mathrm{He}} = \phi_{\Lambda\Lambda}(r_{\Lambda\Lambda})\,\Phi_{\Lambda\Lambda}(R_{\Lambda\Lambda})\,\phi_\alpha, \quad \sqrt{< r^2_{\Lambda\Lambda} >}$**=3.65±0.10 fm.**
- **For Gaussians,** $\sqrt{< R^2_{\Lambda\Lambda} >}=\sqrt{< r^2_{\Lambda\Lambda} >}/2$**.**
- **Short-Range suppression:**
  $\tilde{\phi}_{\Lambda\Lambda}(r_{\Lambda\Lambda}) = (1-j_0(\kappa r_{\Lambda\Lambda}))\;\phi_{\Lambda\Lambda}(r_{\Lambda\Lambda}),\;\; \kappa$**=2.534 fm**$^{-1}$ **fitting a G-matrix calculation by Maneu-Parreño-Ramos, PRC 98 (2018) 025208.**
- **To evaluate** ${}_{\Lambda\Lambda}^{6}$**He**$\to H + {}^4$**He decay rate (next page), represent final state by** $\tilde{\psi}_{\Lambda\Lambda}(r_{\Lambda\Lambda}) \times \exp{(i\vec{k}_H \cdot \vec{R}_H)}$**, where** $\tilde{\psi}_{\Lambda\Lambda}(r_{\Lambda\Lambda}) = \psi(r_{\Lambda\Lambda})/\sqrt{1000}$ **to account for SFC structure.**
- **Recall: no short-range suppresssion for H (**1_F **BB).**

${}_{\Lambda\Lambda}^{6}$He$\rightarrow H + {}^{4}$He decay rate

- $\Gamma({}_{\Lambda\Lambda}^{6}\mathrm{He} \rightarrow H + {}^{4}\mathrm{He}) = \frac{\mu_{H\alpha}\, k_H}{(2\pi\hbar c)^2} \int |<\Psi_f|V_{\Lambda\Lambda}|\Psi_i>|^2\, \mathrm{d}\hat{\vec{k}}_H$, where $<\Psi_f|V_{\Lambda\Lambda}|\Psi_i>$ is a product of two factors.
- **1st factor:** $<\tilde{\psi}_{\Lambda\Lambda}|C_0^{(\lambda=4)}\delta_{\lambda=4}(r_{\Lambda\Lambda})|\tilde{\phi}_{\Lambda\Lambda}>$, **where** $C_0^{(\lambda=4)} = -152$ **MeV**$\times$**fm**^{3} **fitted to** $a_{\Lambda\Lambda} = -0.8$ **fm. SRC reduction: a factor of 4 to 5. Altogether this matrix element varies from −59 to −53 keV as B$_{\Lambda\Lambda}$ is increased from 100 to 400 MeV.**
- **2nd factor:** $\int \exp(i\vec{k}_H \cdot \vec{R})\Phi_{\Lambda\Lambda}(R)\mathrm{d}^3\vec{R}$, **overlap integral between a** $\Lambda\Lambda - \alpha$ **smooth Gaussian** $\Phi_{\Lambda\Lambda}(R_{\Lambda\Lambda})$ **in** ${}_{\Lambda\Lambda}^{6}$**He and the** $H - \alpha$ **oscillatory plane-wave** $\exp(i\vec{k}_H \cdot \vec{R}_H)$**. Strong cancellations occur, reducing it as** k_H **increases.**

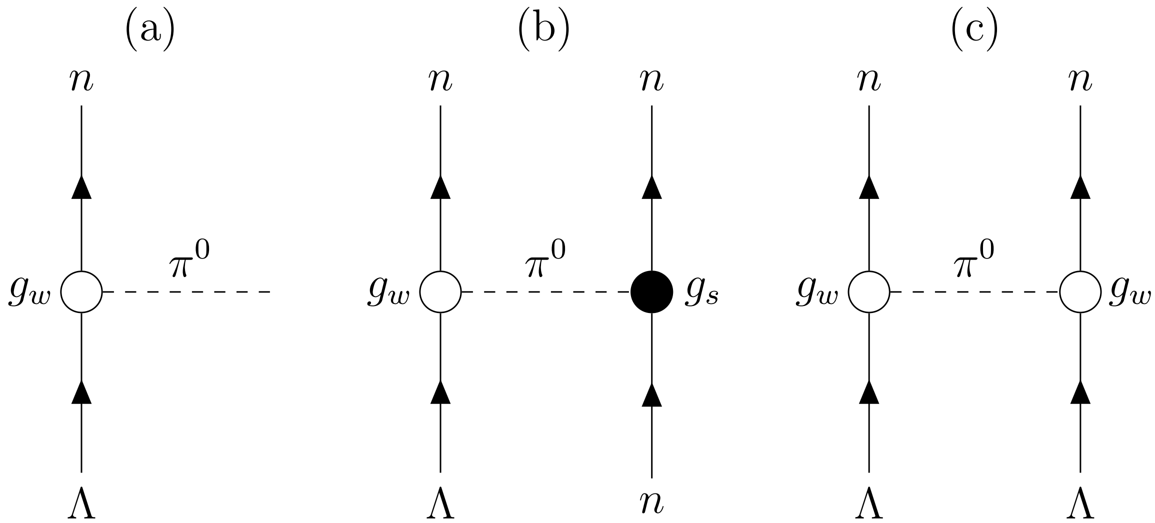
${}_{\Lambda\Lambda}^{6}$He $\rightarrow H + {}^{4}$He decay rate Γ and decay time $\hbar/\Gamma$.

$B_{\Lambda\Lambda}$ (MeV)	k_H (fm^{-1})	Γ (eV)	τ (s)
100	**2.547**	$0.782 \cdot 10^{-2}$	$0.841 \cdot 10^{-13}$
200	**3.612**	$0.501 \cdot 10^{-8}$	$1.315 \cdot 10^{-7}$
300	**4.377**	$0.679 \cdot 10^{-14}$	$0.970 \cdot 10^{-1}$
400	**4.980**	$2.436 \cdot 10^{-20}$	$2.703 \cdot 10^{4}$
176	**3.393**	$1.550 \cdot 10^{-7}$	$4.245 \cdot 10^{-9}$

$B_{\Lambda\Lambda}$=176 MeV corresponds to $m_H = m_\Lambda + m_n$.

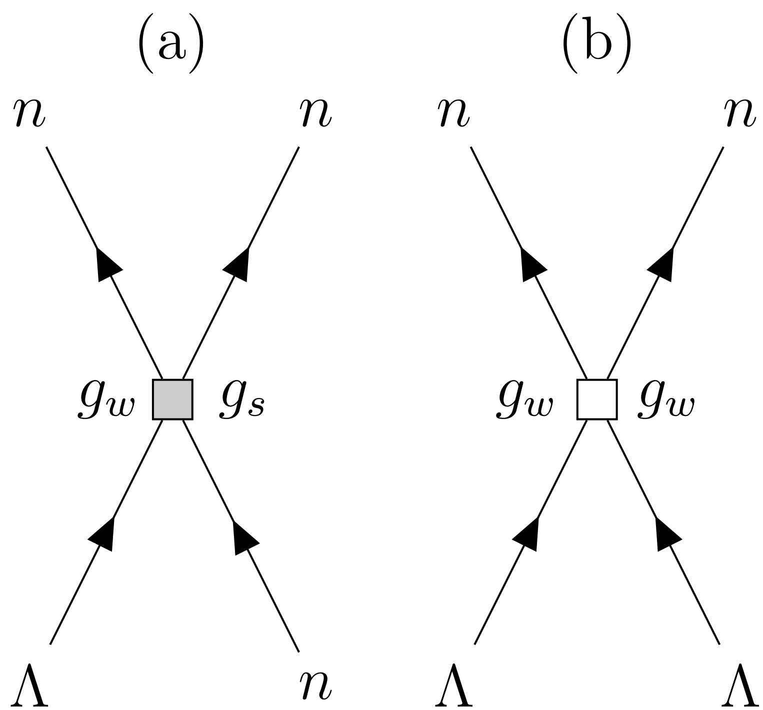
- **${}_{\Lambda\Lambda}^{6}$He $\rightarrow H + {}^{4}$He strong-interaction lifetime becomes longer than Λ hypernuclear lifetimes of order 10^{-10} s for m_H below $m_\Lambda + m_n$, where decay of H requires a $\Delta\mathcal{S} = 2$ H$\rightarrow$nn weak decay, assuming H is above nn.**
- **A lower-mass H would be in conflict with nuclear stability limits, e.g. ^{16}O.**

$\Lambda n \to nn$ and $\Lambda\Lambda \to nn$ weak decays



- **Figure shows how free-space $\Lambda \to n\pi^0$ weak decay vertex is embedded in one-pion exchange (OPE) diagrams for $\Delta\mathcal{S} = 1$ $\Lambda n \to nn$ and $\Delta\mathcal{S} = 2$ $\Lambda\Lambda \to nn$ weak transitions in hypernuclei or in H decay.**
- **For ${}^1S_0$ transitions, OPE contributes little at the large momentum transfers involved.**

$\Lambda n \to nn$ and $\Lambda\Lambda \to nn$ weak decays



- **Use low-energy constants (LECs) $C^{(\lambda)}_{\Delta S}$ proportional to g_w for $\Lambda n \to nn$ and to g_w^2 for $\Lambda\Lambda \to nn$ in ${}^1S_0$ transitions, thereby replacing g_s(OPE) $\approx$ 13.6 effectively by $g_s \sim 1$.**
- **EFT approach for nonmesonic weak decay of hypernuclei: Parreño-Bennhold-Holstein, PRC 70 (2004) 051601(R).**

H→nn decay rate Γ_H and decay time $\tau_H = \hbar/\Gamma_H$

$B_{\Lambda\Lambda}$ (MeV)	k_n (fm^{-1})	Γ_H (eV)	τ_H (s)
176	**2.109**	$2.366 \cdot 10^{-21}$	$2.782 \cdot 10^{5}$
200	**1.955**	$2.211 \cdot 10^{-21}$	$2.977 \cdot 10^{5}$
300	**1.130**	$1.365 \cdot 10^{-21}$	$4.820 \cdot 10^{5}$

$B_{\Lambda\Lambda}$=176 MeV corresponds to $m_H = m_\Lambda + m_n$.

- **Extract $C_1^{(\lambda)}$ for a given λ by evaluating $\Gamma_n(C_1)$,** $\Gamma_n = v_{\Lambda n}\,\sigma_{\Lambda n\to nn}\,\rho_n$, **requiring** $\Gamma_n = \frac{1}{2}\Gamma_{hyp}$ **where** $\Gamma_{hyp} = \hbar/(\tau_{hyp} \approx 210\,\mathrm{ps})$.
- **Use** $C_2^{(\lambda)} = g_w\, C_1^{(\lambda)} = (G_F\, m_\pi^2)\, C_1^{(\lambda)} = (2.21 \times 10^{-7})\, C_1^{(\lambda)}$.
- $\Gamma(H \to nn) = \frac{\mu_{nn}\, k_n}{(2\pi\hbar c)^2} \int |< \exp(i\vec{k}_n \cdot \vec{r})|C_2^{(\lambda)} \delta_\lambda(\vec{r})|\tilde{\psi}_{\Lambda\Lambda}(r) > |^2\, d\hat{\vec{k}}_n$.
- **Weaker cancellations over a smaller range than for $\Gamma({}_{\Lambda\Lambda}^{6}\mathrm{He} \to \mathrm{H} + {}^4\mathrm{He})$.**

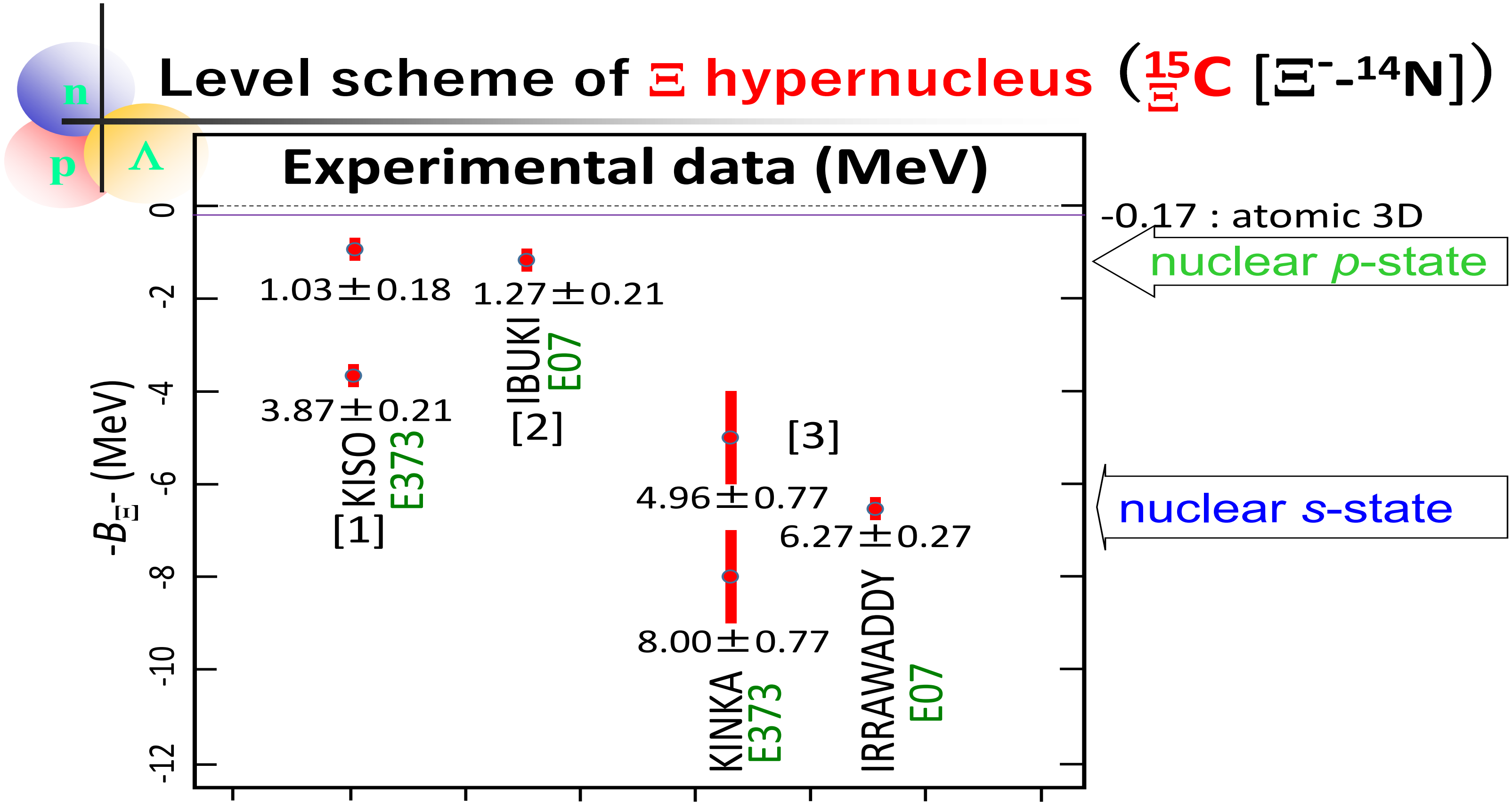
Deeply Bound H Dibaryon: Summary

- **Observing $\Lambda\Lambda$ hypernuclei by their weak decay does not rule out a deeply bound H(uuddss) dibaryon.**
- **Assuming H is deeply bound, between nn and Λn thresholds, its $\Delta\mathcal{S} = 2$ H$\rightarrow$nn lifetime is shorter than 1 yr, disqualifying it from serving as a Dark-Matter particle candidate.**

Thanks for your attention!

3 backup 2023 transparencies

J-PARC E07 ^{14}N events

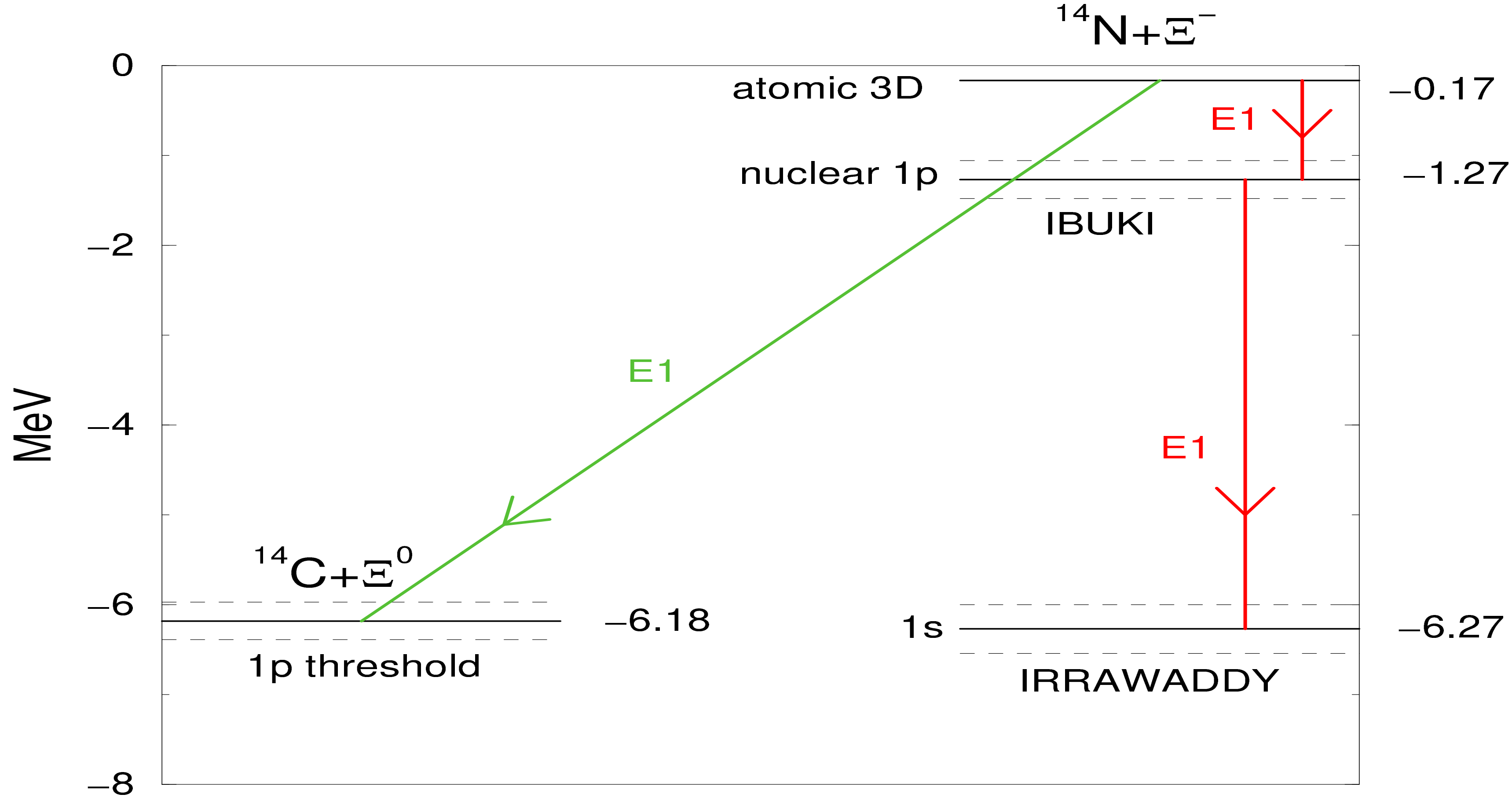


[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Yoshimoto et al., PTEP 2021 073D02

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

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



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

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

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!