H dibaryon constrained by hypernuclei

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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: ${}_{\Lambda\Lambda}^{\ 6}$He 3-body model gives $\tau_s({}_{\Lambda\Lambda}^{\ 6}\text{He}\to\text{H}+{}^4\text{He})\gg\tau_w$ 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→2n with respect to τ(Universe)≈ $(13.8 \times 10^9$ yrs) ?**
- **A: constrained by Λ hyp lifetimes, τ_w(H→2n)∼10^5 s, by far too short to make H dark-matter candidate.**

A. Gal, PLB 857 (2024) 138973 [arXiv:2404.12801]

The elusive H dibaryon

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

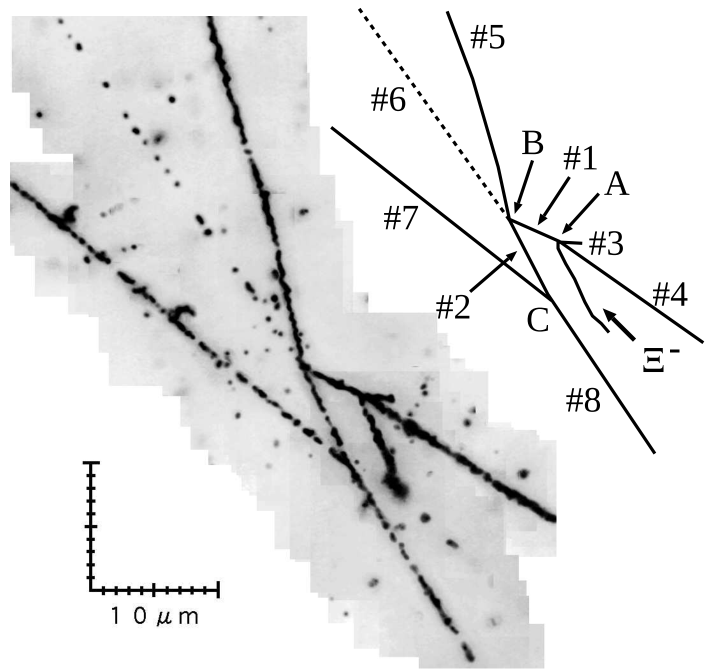
$$\mathbf{H} \sim \mathcal{A}[\sqrt{\mathbf{1/8}}\ \Lambda\Lambda + \sqrt{\mathbf{1/2}}\ N\Xi - \sqrt{\mathbf{3/8}}\ \Sigma\Sigma,]_{I=S=0}$$

- **No H signal in past (K^-, K^+) experiments at AGS-BNL & PS-KEK. Awaiting J-PARC E42.**
- **Bound H above $\Lambda p\pi^-$, ∼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$2.05 GeV, ruled out in BaBar's Υ(2S,3S)$\to$H$\bar{\Lambda}\bar{\Lambda}$ search [PRL 122 (2019) 072002].**

- **Bound H in LQCD calculations:**
  S.R. Beane et al (NPLQCD) PRL 106 (2011) 162001,
  T. Inoue et al. (HALQCD) PRL 106 (2011) 162002,
  Green-Hanlon-Junnarkar-Wittig, PRL 127 (2021) 242003, **bound by just 4.6±1.3 MeV w.r.t. ΛΛ.**
- **But unbound by 13±14 MeV when chirally extrapolated to physical quark masses:**
  Shanahan-Thomas-Young, PRL 107 (2011) 092004.

- **$SU(3)_f$ breaking might push it to ≈26 MeV in the ΛΛ 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 ${}_{\Lambda\Lambda}^{A}$**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**$\rightarrow H + {}^4$**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 $\hbar/\Gamma$.

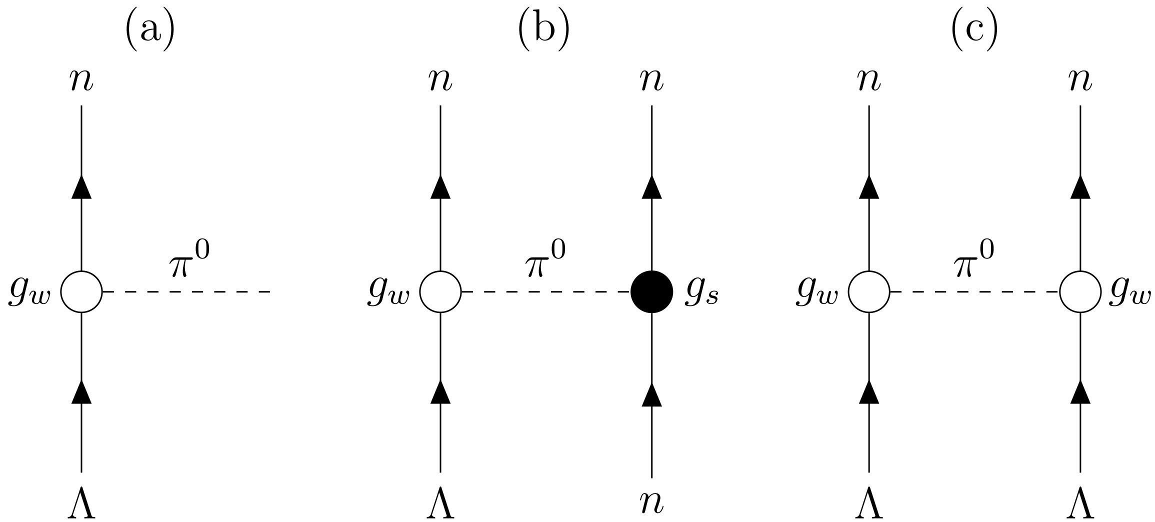
$B_{\Lambda\Lambda}$ (MeV)	k_H (fm^{-1})	Γ (eV)	τ (s)
100	**2.547**	$0.782 \cdot 10^{-2}$	$0.841 \cdot 10^{-13}$
200	**3.612**	$0.501 \cdot 10^{-8}$	$1.315 \cdot 10^{-7}$
300	**4.377**	$0.679 \cdot 10^{-14}$	$0.970 \cdot 10^{-1}$
400	**4.980**	$2.436 \cdot 10^{-20}$	$2.703 \cdot 10^{4}$
176	**3.393**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

$B_{\Lambda\Lambda}$=176 MeV corresponds to m_H=m_Λ+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_Λ+m_n, where decay of H requires a $\Delta\mathcal{S} = 2$ weak decay H→nn, assuming H is above nn.**

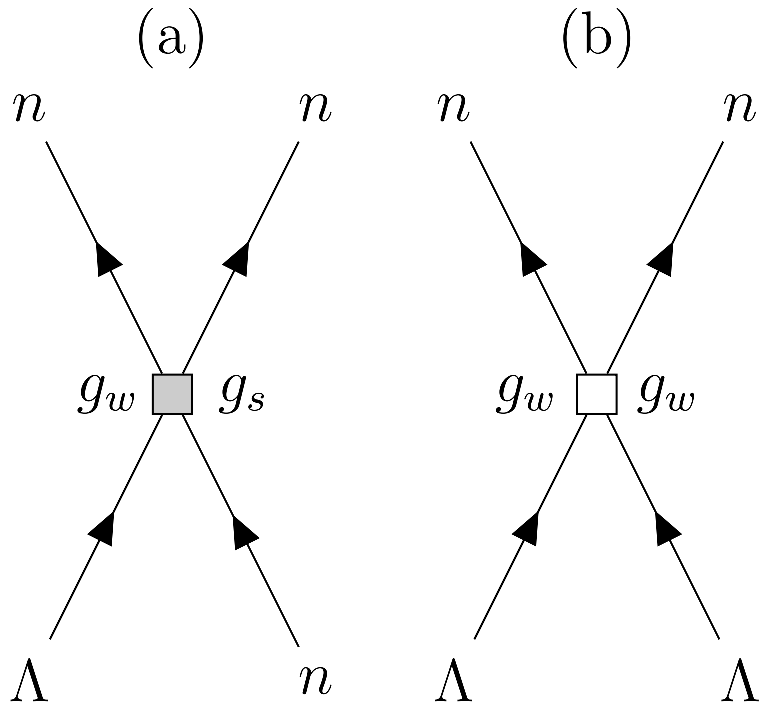
- **A lower-mass H would be in conflict with nuclear stability limits, e.g. ^{16}O.**

$\Lambda n \to nn$ 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 $^1S_0 \to {}^1S_0$ transitions, OPE contributes little at the large momentum transfers involved; K exchange interferes destructively with OPE in $\Lambda n \to nn$, so a contact term is sufficient. $^1S_0 \to {}^3P_0$ appears suppressed w.r.t. $^1S_0 \to {}^1S_0$.**

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



- **Use low-energy constants (LECs) $C_{\Delta S}^{(\lambda)}$ 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 $g_s(\mathrm{OPE}) \approx 13.6$ 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 (10^{-20} eV)	τ_H (10^5 s)
176	2.109	1.57±0.19	0.78±0.09
200	1.955	1.44±0.17	0.83±0.10
300	1.130	0.86±0.10	1.35±0.16

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

- **Extract $C_1^{(\lambda)}$ for a given λ by evaluating $\Gamma_n(C_1)$,** $\Gamma_n = v_{\Lambda n}\,\sigma_{\Lambda n \to nn}\,\frac{1}{4}\rho_n$, **requiring** $\Gamma_n = (0.35 \pm 0.04)\Gamma_\Lambda$ **where** $\Gamma_\Lambda = \hbar/(\tau_\Lambda = 263\,\mathrm{ps})$.
- **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 $\Gamma({}_{\Lambda\Lambda}^{6}He \to H + {}^4He)$.**

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!