H dibaryon is not a DM candidate

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Avraham Gal, Hebrew University, Jerusalem, Israel

- 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 $\tau_s({}^{6}_{\Lambda\Lambda}\mathrm{He}\rightarrow\mathrm{H}+{}^{4}\mathrm{He})\gg\tau_w$ 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, PLB 857 (2024) 138973 [arXiv:2404.12801]

The elusive H dibaryon

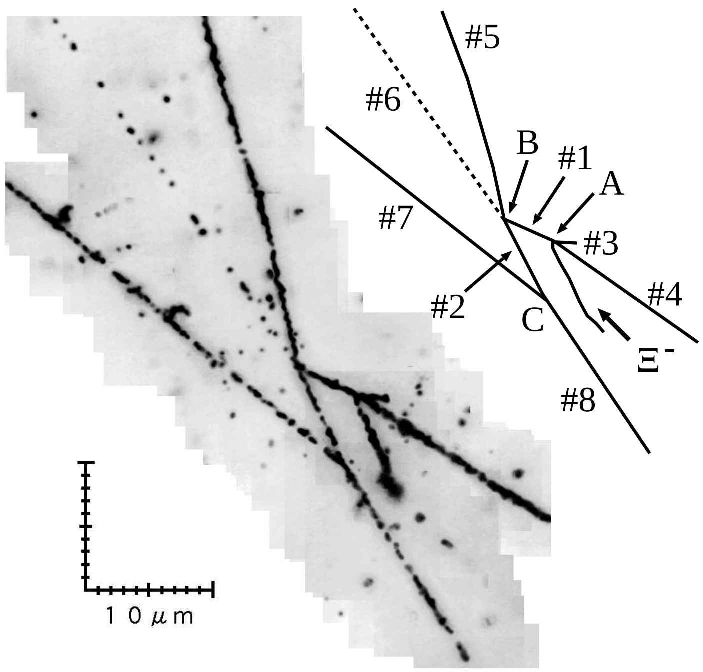
A stable H(uuddss) predicted by Jaffe PRL 38 (1977) 195

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

- **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 $\Upsilon(2S,3S) \to H\bar{\Lambda}\bar{\Lambda}$ 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. $\Lambda\Lambda$.**
- **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 $\Lambda\Lambda$ continuum, near $N\Xi$ threshold:**
  HALQCD Collaboration [NPA 881 (2012) 28]
  & Haidenbauer-Meißner [NPA 881 (2012) 44].
  Consistent with J-PARC E42 final results?

Hypernuclear Constraints: Nagara event



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

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

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

Few other weakly decaying ${}^{\ A}_{\Lambda\Lambda}\mathrm{Z}$ **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.**
- $< r^2_{B_a} >=< r^2_{B_b} >=< r^2_{B_a B_b} >= \frac{9}{8\nu}\,, \quad < r^2_H >= \frac{5}{8\nu}\,.$

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

${}_{\Lambda\Lambda}^{\;\;6}$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

- $\Gamma({}_{\Lambda\Lambda}^{6}\text{He} \rightarrow H + {}^4\text{He}) = \frac{\mu_{H\alpha}\, k_H}{(2\pi\hbar c)^2} \int |<\Psi_f|V_{\Lambda\Lambda}|\Psi_i>|^2\, \mathrm{d}\hat{\vec{k}}_H$, 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 $\mathrm{B}_{\Lambda\Lambda}$ 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.

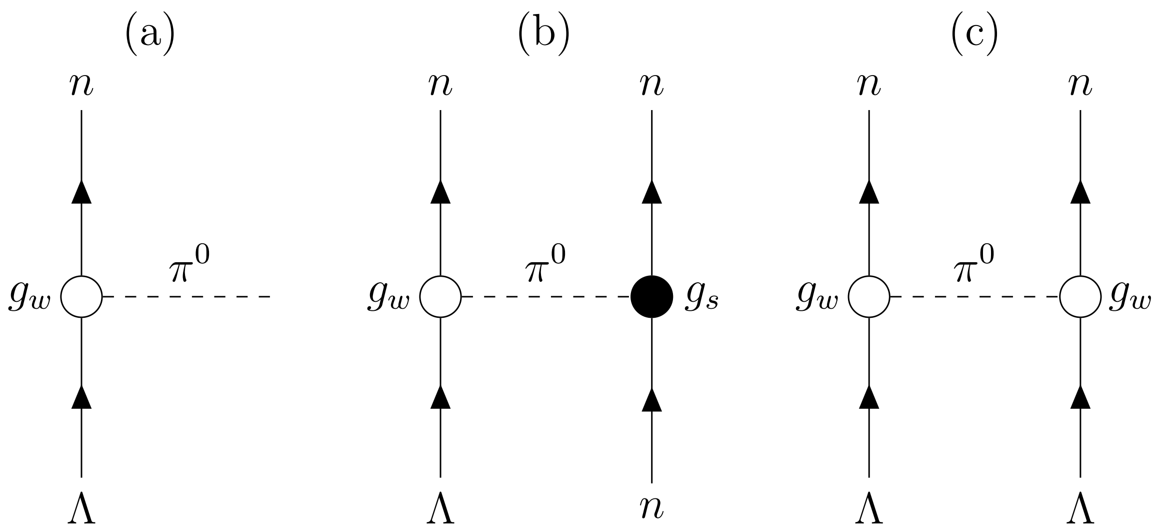
${}_{\Lambda\Lambda}^{6}$He $\rightarrow H + {}^{4}$He decay rate Γ and decay time $\hbar/\Gamma$.

$B_{\Lambda\Lambda}$ (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$\rightarrow$nn, assuming H is above nn.**
- **A lower-mass H would be in conflict with nuclear stability limits, e.g. ^{16}O.**

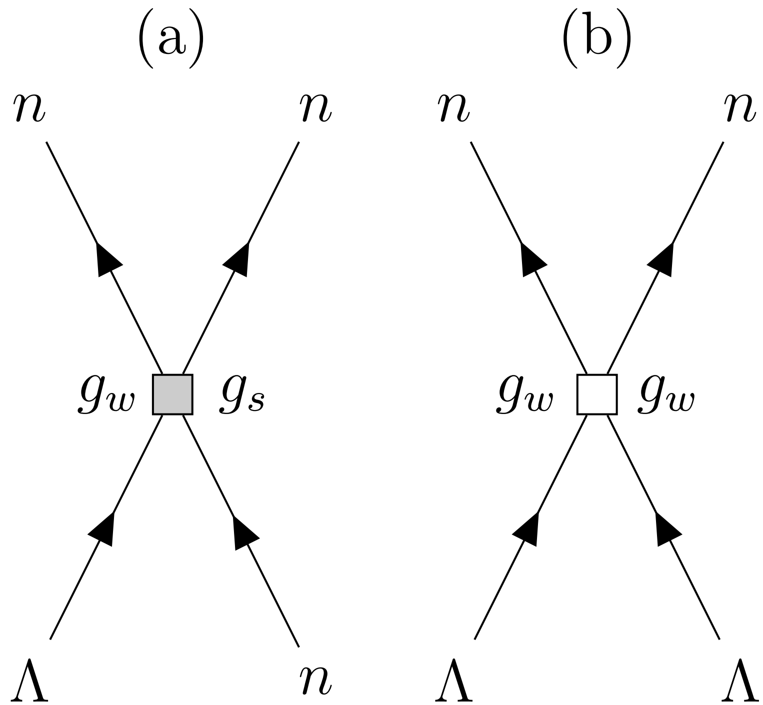
$\Lambda n \to nn$ and $\Lambda\Lambda \to nn$ weak decays



- **$\Lambda \to n\pi^0$ weak decay vertex (a) embedded in nonmesonic weak decay OPE diagrams:** **$\Delta\mathcal{S} = 1$ $\Lambda n \to nn$ (b), $\Delta\mathcal{S} = 2$ $\Lambda\Lambda \to nn$ (c).**

- **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(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** $C_2^{(\lambda)} = g_w\,C_1^{(\lambda)} = (G_F\,m_\pi^2)\,C_1^{(\lambda)} = (2.21\times 10^{-7})\,C_1^{(\lambda)}$.
- $\Gamma(H\to nn) = \frac{\mu_{nn}\,k_n}{(2\pi\hbar c)^2}\int |<\exp(i\vec{k}_n\cdot\vec{r})|C_2^{(\lambda)}\delta_\lambda(\vec{r})|\tilde{\psi}_{\Lambda\Lambda}(r)>|^2\,\mathrm{d}\hat{\vec{k}}_n$.
- **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!