Hypertriton ($^{3}_{\Lambda}$H) lifetime puzzle

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- Background

  (i) Experimental: from emulsion & bubble chambers to relativistic heavy-ion collisions;

  (ii) Theoretical: from Rayet-Dalitz (1966), Congleton (1992), to Kamada et al. (1998).

- Pion final-state interaction (FSI) effects

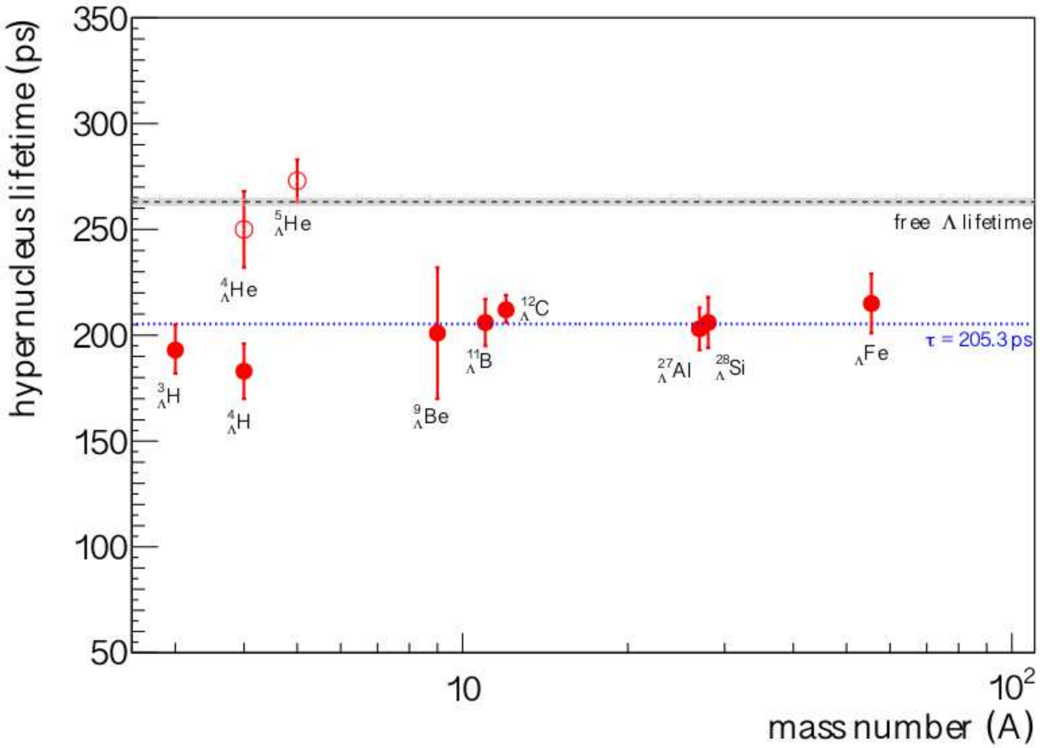
  Gal–Garcilazo, PLB 791 (2019) 48

  Pérez-Obiol–Gazda–Friedman–Gal (ongoing).

- Implications to a stable–$^{3}_{\Lambda}$n lifetime.

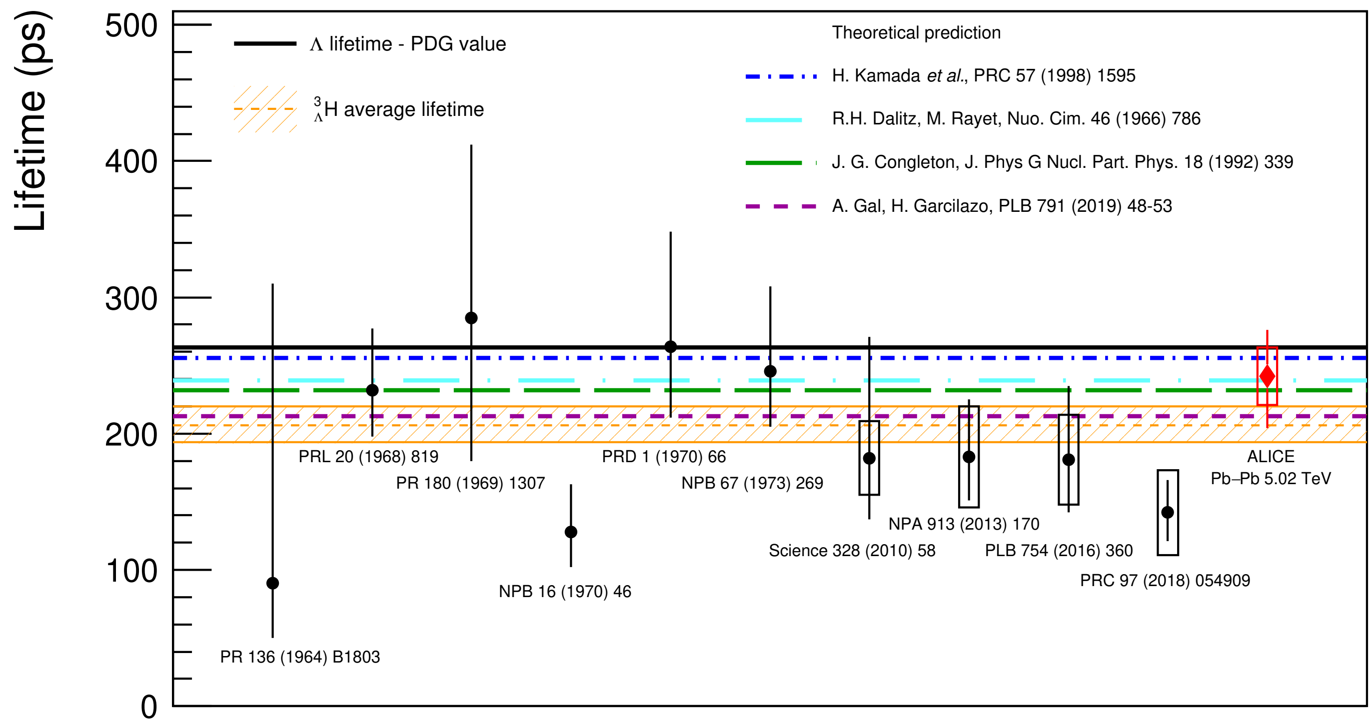
Summary of ${}^{A}_{\Lambda}$Z hypernuclear lifetimes

Agnello-Botta-Bressani-Bufalino-Feliciello, NPA 954 (2016) 176



- $\Lambda \to N\pi$, $\approx$99.7%Γ_Λ, replaced for A$\gg$1 to $\approx$125%Γ_Λ by $\Lambda N \to NN$; yet, $\Gamma({}^{3}_{\Lambda}\mathrm{H} \to \mathrm{NNN})$ is only $\sim$1.7%Γ_Λ [Golak et al. PRC 56 (1997) 2892].
- Delayed fission: $\tau_{A\gg 1}({}^{A}_{\Lambda}\mathrm{Z}) \approx 210 \pm 10$ ps ($\tau_\Lambda = 263 \pm 2$ ps) [Jlab E02-017: X. Qiu, L. Tang, et al. NPA 973 (2018) 116].

${}^{3}_{\Lambda}$H lifetime puzzle



Recent heavy-ion ${}^{3}_{\Lambda}$H production experiments yield lifetimes shorter by $\sim$30% w.r.t. τ_{Λ}=263$\pm$2 ps.

STAR, Au–Au @200 GeV: PRC 97 (2018) 054909, τ=142$^{+24}_{-21}\pm$29 ps.

ALICE, Pb-Pb @5 TeV: PLB 797 (2019) 134905, τ=242$^{+34}_{-38}\pm$17 ps.

Given a tiny B$_{\Lambda}$=0.13$\pm$0.05 MeV, why is $\tau({}^{3}_{\Lambda}\mathrm{H})\ll\tau_{\Lambda}$?

Brief review of ${}^{3}_{\Lambda}$H lifetime calculations

Source	Method	R_3	$\Gamma({}^{3}_{\Lambda}\mathrm{H})/\Gamma_{\Lambda}$
Experiment	R_3: He BC	0.35±0.04	~1.40±0.15
Rayet-Dalitz (1966)*	closure-Λpn	–	1.05
Congleton (1992)	closure-Λd	0.33±0.02	1.14
Kamada et al (1998)	full Faddeev	0.379	1.03
Gal-Garcilazo (2018)**	closure-Λpn	0.357	1.23±0.03

- $R_3 = \Gamma({}^{3}_{\Lambda}\mathrm{H}\to\pi^- + {}^{3}\mathrm{He})/\Gamma({}^{3}_{\Lambda}\mathrm{H}\to\pi^- + \mathrm{all}) \Rightarrow J = \frac{1}{2}$. Dalitz (73): $R_3 = \sqrt{B_\Lambda}(1.07\text{-}0.60\sqrt{B_\Lambda} + 0.27 B_\Lambda)$, so $R_3 = 0.35\pm0.04 \Rightarrow B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) = 0.16^{+0.05}_{-0.04}$ MeV.
- *Closure: $\Gamma({}^{3}_{\Lambda}\mathrm{H})/\Gamma_\Lambda = 1 + 0.14\sqrt{B_\Lambda}$ up to phase space factor boosting decay rate by (5–10)%.
- **PLB 791 (2019) 48, pion FSI effect: 1.09→1.23.

Closure approximation calculations

$$\Gamma_\Lambda(q) = \frac{q}{1+\omega_\pi(q)/E_N(q)}(|s_\pi|^2+|p_\pi|^2\frac{q^2}{q_\Lambda^2}), \quad \left|\frac{p_\pi}{s_\pi}\right|^2 \approx 0.132(0.203)$$

$$\Gamma^{J=1/2}_{{}^3_\Lambda\mathrm{H}} = \frac{\bar{q}}{1+\omega_\pi(\bar{q})/E_{3N}(\bar{q})}[|s_\pi|^2(1+\frac{1}{2}\eta(\bar{q}))+|p_\pi|^2(\frac{\bar{q}}{q_\Lambda})^2(1-\frac{5}{6}\eta(\bar{q}))]$$

$\eta(q) = \int \psi_{{}^3_\Lambda\mathrm{H}}(\Lambda;2,3)\exp(i\vec{q}\cdot\vec{r}_{\Lambda 2})\psi^*_{{}^3_\Lambda\mathrm{H}}(2;\Lambda,3)$: **exchange integral,**

roughly 0.2±0.1, vanishing upon $B_\Lambda \to 0$.

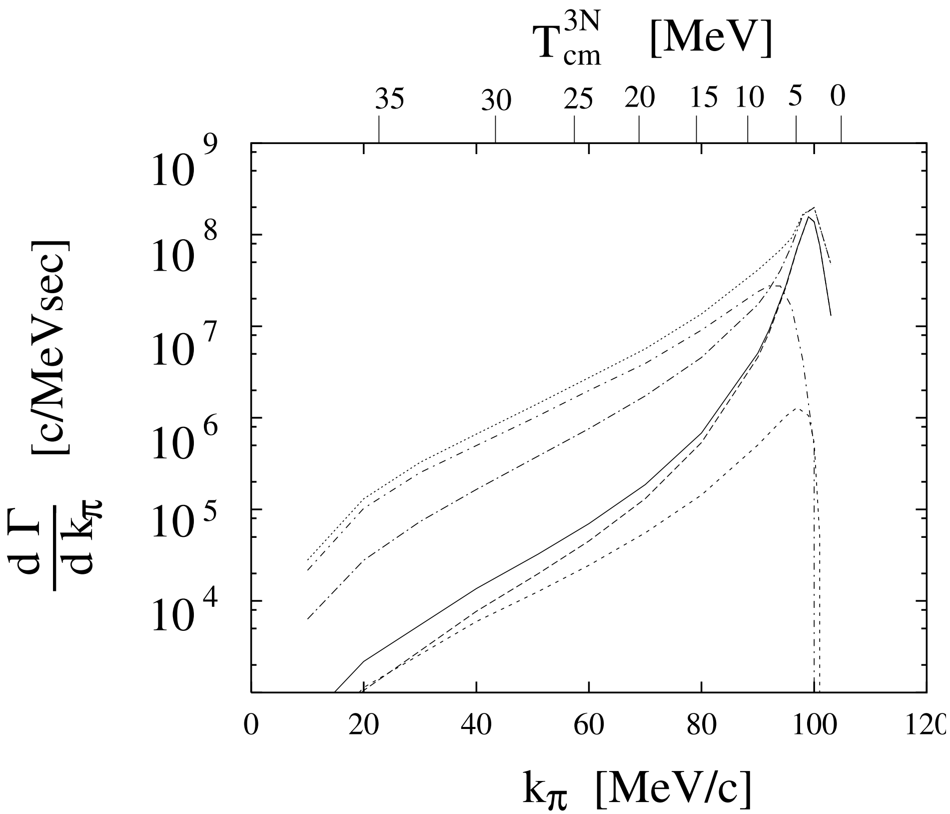
$$\Gamma^{J=3/2}_{{}^3_\Lambda\mathrm{H}} = \frac{\bar{q}}{1+\omega_\pi(\bar{q})/E_{3N}(\bar{q})}[|s_\pi|^2(1-\eta(\bar{q}))+|p_\pi|^2(\frac{\bar{q}}{q_\Lambda})^2(1-\frac{1}{3}\eta(\bar{q}))]$$

$$\Gamma^{J=1/2}_{{}^3_\Lambda\mathrm{n}} \approx \frac{\bar{q}}{1+\omega_\pi(\bar{q})/E_{3N}(\bar{q})}\,0.641\left(|s_\pi|^2+|p_\pi|^2(\frac{\bar{q}}{q_\Lambda})^2\right)$$

$$\Gamma({}^3_\Lambda\mathrm{n})/\Gamma_\Lambda \approx 1.114\times 0.641 = 0.714, \quad \tau({}^3_\Lambda\mathrm{n}) \approx 368 \text{ ps},$$

compared to $181^{+30}_{-24}\pm 25$ ps or $190^{+47}_{-35}\pm 36$ ps from HypHI.

Does closure make sense?



Kamada et al. PRC 57 (1998) 1595

$^3_\Lambda$H differential decay rates to p+d &p+p+n, with and without 3N FSI, and their sum with FSI (solid curve).

Most events in [96-104] MeV/c k_π interval, $\Rightarrow \pm 4\%$ Γ_{closure} uncertainty, mostly from phase space factor $\bar{q}$.

Pion FSI: s-wave πN (Gal-Garcilazo)

$$V_{\rm opt}^{\pi^-} = -\frac{4\pi}{2\mu_{\pi N}}\left(b_0[\rho_n(r)+\rho_p(r)] + b_1[\rho_n(r)-\rho_p(r)]\right)$$

π^- **atoms fits:** $b_0 \approx -0.02\, m_\pi^{-1}$, $b_1 \approx -0.12\, m_\pi^{-1}$

- **Repulsive for $N \geq Z$, not in $\pi^-\ {}^1$H & $\pi^-\ {}^3$He as confirmed by attractive 1s level shifts.**
- **Repulsive FSI in the $\pi^0\ {}^3$H decay channel. Summed FSI in total ${}^3_\Lambda$H decay rate nearly zero.**
- **ΔI=1/2 rule: coherent I=1/2 ($\pi^-\ {}^3$He—$\pi^0\ {}^3$H), so isovector term gives attractive $-2b_1$.**
- **$\Gamma({}^3_\Lambda\text{H})/\Gamma_\Lambda$: 1.09 (no FSI) $\Rightarrow$ 1.23 (pion FSI); with pion FSI: $\tau({}^3_\Lambda\text{H})$=214$\pm$8 ps.**
- **World average: $\tau({}^3_\Lambda\text{H})$=$206^{+15}_{-13}$ ps.**

Pion FSI: adding p waves (ongoing)

$$\delta V^{\pi^-}_{\rm opt} \propto \left(\vec{\nabla}\cdot[c_0(\rho_n+\rho_p)+c_1(\rho_n-\rho_p)]\vec{\nabla}\right) / \,(\text{EELL renorm.})$$

π^- **atoms fits:** $c_0 = 0.23\,m_\pi^{-3}$, $c_1 = 0.16\,m_\pi^{-3}$ **(πN values)**

- **Attractive for $N \geq Z$, but in ${}^3_\Lambda$H $\rightarrow \pi^- + {}^3$He, for p$_\pi$~100 MeV/c, c_1 yields repulsion that cancels out most of the attraction from b_1.**
- **The attractive c_0 overcomes the repulsive b_0, producing robust attractive pion FSI of order (10–20)%.**
- **Ongoing: Pérez-Obiol, Gazda, Friedman, Gal.**

${}^4_\Lambda$H & ${}^4_\Lambda$He lifetimes

$$\Gamma({}^4_\Lambda\mathrm{H})/\Gamma_\Lambda \approx \frac{3}{2} \times (\frac{2}{3} \times 0.7 + 1 \times 0.3) + 0.25 = 1.40$$

$$\Gamma({}^4_\Lambda\mathrm{He})/\Gamma_\Lambda \approx \frac{3}{2} \times (\frac{1}{3} \times 0.7 + 1 \times 0.3) + 0.25 = 1.05$$

Input: $\frac{3}{2}$ for nuclear structure, R_4=0.7

$\frac{2}{3}$ & $\frac{1}{3}$ for π^- or π^0 and ^{4}He, $\Gamma_{\mathrm{n.m.}}/\Gamma_\Lambda \approx$ 0.25

$\Rightarrow \tau({}^4_\Lambda\mathrm{H}) \approx$ **190 ps,** $\tau({}^4_\Lambda\mathrm{He}) \approx$ **250 ps**

in rough agreement with measured lifetimes.

Looks like Lifetime Puzzle is limited to ${}^3_\Lambda$H.

- **For A≥12, $\tau({}^A_\Lambda\mathrm{Z})\sim$200 ps, from KEK and very recently from HKS JLab E02-E017: NPA 973 (2018) 116. Lifetime is due to ΛN→NN.**

Summary & Outlook

- **Pion FSI makes ${}^{3}_{\Lambda}$H decay faster by (10–20)%. Values $\Gamma({}^{3}_{\Lambda}\mathrm{H})/\Gamma_{\Lambda}\approx$1.2-1.3 are not unreasonable.**
- **Future Relativistic HIC experiments in both LHC and RHIC should resolve the discrepancy between the latest ALICE and STAR $\tau({}^{3}_{\Lambda}\mathrm{H})$ determinations; 1st challenge is to lower the measurement uncertainties.**
- **New prposed experiments at J-PARC on ^{3}He:**
  (i) ${}^{3}\mathrm{He}(\pi^-, K^0){}^{3}_{\Lambda}\mathrm{H}$, Agnello et al.;
  (ii) ${}^{3}\mathrm{He}(K^-, \pi^0){}^{3}_{\Lambda}\mathrm{H}$, Ma et al.
  Could be done also on ^{4}He to study ${}^{4}_{\Lambda}$H decay.
- **Rule out ${}^{3}_{\Lambda}$n in forthcoming HIC experiments.**

- **Establish resonance nature, if so, of $^{3}_{\Lambda}$n at Jlab on ^{3}H target: ^{3}H(e, e'K^{+})$^{3}_{\Lambda}$n, as proposed and done by L. Tang et al. This might provide constraints on Λn–Λp CSB.**
- **Re-measure the $^{4}_{\Lambda}$H–$^{4}_{\Lambda}$He complex (E13→E63) for refining future input to CSB calculations, and their consequences for p-shell hypernuclei.**

Thanks for your attention!