Remarks on $\frac{3}{\Lambda}H$ lifetime puzzle
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- **Background**
  (i) Experimental: from emulsion & bubble chambers to relativistic heavy-ion collisions;


- $\Sigma$ admixtures in $\frac{3}{\Lambda}H$ reduce decay rate: Pérez-Obiol–Gazda–Friedman–Gal (ongoing).

- Lifetimes of $\frac{4}{\Lambda}H$, $\frac{4}{\Lambda}He$ & $\frac{3}{\Lambda}n$, if stable.
Summary of $^A\Lambda Z$ hypernuclear lifetimes

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

- $\Lambda \rightarrow N\pi$, $\approx 99.7\% \Gamma_\Lambda$, replaced for $A \gg 1$ to $\approx 125\% \Gamma_\Lambda$ by $\Lambda N \rightarrow NN$; yet, $\Gamma(^3\Lambda H \rightarrow NNN)$ is only $\sim 1.7\% \Gamma_\Lambda$ as calculated by Golak et al., PRC 56 (1997) 2892.

- **Delayed fission:** $\tau_{A \gg 1}(^A\Lambda Z) \approx 210 \pm 10$ 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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{\textbf{\emph{\textbf{\textit{H}} lifetime puzzle}}}
\end{figure}

World average of measured $\tau(^3\Lambda\text{H})$ is shorter $\sim$30±10% w.r.t. $\tau_\Lambda=263±2$ ps. Note recent UR-HI experiments:

\begin{itemize}
  \item \textbf{STAR}, Au–Au @200 GeV: PRC 97 (2018) 054909, $\tau=142^{+24}_{-21}±29$ ps.
  \item \textbf{ALICE}, Pb-Pb @5 TeV: PLB 797 (2019) 134905, $\tau=242^{+34}_{-38}±17$ ps.
\end{itemize}

Given a tiny $B_\Lambda=0.13±0.05$ MeV, why is $\tau(^3\Lambda\text{H}) \ll \tau_\Lambda$?
Is there a $^3\Lambda \!\!H$ lifetime puzzle?

E. Bartsch for ALICE at Quark Matter 2019

Wuhan, China, Nov. 2019
### $^3\Lambda$H lifetime calculations w/o pion FSI

<table>
<thead>
<tr>
<th>Source</th>
<th>Method</th>
<th>$R_3$</th>
<th>$\Gamma(^3\Lambda\text{H})/\Gamma_\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>$R_3$: He BC</td>
<td>$0.35\pm0.04$</td>
<td>$\sim1.40\pm0.15$</td>
</tr>
<tr>
<td>Rayet-Dalitz (1966)*</td>
<td>closure-$\Lambda pn$</td>
<td>$-$</td>
<td>$1.05$ $1.14$</td>
</tr>
<tr>
<td>Congleton (1992)</td>
<td>closure-$\Lambda d$</td>
<td>$0.33\pm0.02$</td>
<td>$1.14$ $1.15$</td>
</tr>
<tr>
<td>Kamada et al (1998)</td>
<td>full Faddeev</td>
<td>$0.379$</td>
<td>$1.03$ $1.06$</td>
</tr>
<tr>
<td>Gal-Garcilazo (2018)**</td>
<td>closure-$\Lambda pn$</td>
<td>$0.357$</td>
<td>$1.11$ $1.11$</td>
</tr>
</tbody>
</table>

- $R_3=\Gamma(^3\Lambda\text{H}\to\pi^-+^3\text{He})/\Gamma(^3\Lambda\text{H}\to\pi^-+\text{all}) \Rightarrow J = \frac{1}{2}$.

Dalitz (73): $R_3=\sqrt{B_\Lambda}(1.07-0.60\sqrt{B_\Lambda}+0.27B_\Lambda)$, so $R_3=0.35\pm0.04\Rightarrow B_\Lambda(^3\Lambda\text{H})=0.16^{+0.05}_{-0.04} \text{ MeV}$.

- *Closure: $\Gamma(^3\Lambda\text{H})/\Gamma_\Lambda=1+0.14\sqrt{B_\Lambda}$ up to phase space factor boosting decay rate by (5–10)%.

- **PLB 791 (2019) 48, pion FSI effect: $1.11\to1.23$.**
Closure approximation calculations

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

\[ \Gamma_{J=1/2}^{3/2} = \frac{\bar{q}}{1 + \omega_\pi/E_{3N}} \left[ |s_\pi|^2 (1 + \frac{1}{2} \eta(\bar{q})) + |p_\pi|^2 (\frac{\bar{q}}{q_\Lambda})^2 (1 - \frac{5}{6} \eta(\bar{q})) \right] \]

\[ \eta(q) = \int \psi_{3\Lambda H}^*(\Lambda; 2, 3) \exp(i\vec{q} \cdot \vec{r}_{\Lambda 2}) \psi_{3\Lambda H}(2; \Lambda, 3) : \text{exchange.} \]

Gal-Garcilazo: \( \eta(\bar{q}) = 0.14 \pm 0.03, \rightarrow 0 \) upon \( B_\Lambda \rightarrow 0 \).

\[ \Gamma_{J=3/2}^{3/2} = \frac{\bar{q}}{1 + \omega_\pi/E_{3N}} \left[ |s_\pi|^2 (1 - \eta(\bar{q})) + |p_\pi|^2 (\frac{\bar{q}}{q_\Lambda})^2 (1 - \frac{1}{3} \eta(\bar{q})) \right] \]

\[ \Gamma_{J=1/2}^{3/2} \approx \frac{q_\Lambda}{1 + \omega_\pi/E_{3N}} \ 0.641 \ (|s_\pi|^2 + |p_\pi|^2) \]

\[ \Gamma_{3\Lambda n}/\Gamma_\Lambda \approx 1.114 \times 0.641 = 0.714, \ \tau(3\Lambda n) \approx 368 \ \text{ps}, \]

compared to \( 181^{+30}_{-24} \pm 25 \ \text{ps} \) or \( 190^{+47}_{-35} \pm 36 \ \text{ps} \) 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, w & w/o 3N FSI, and their sum with FSI (solid curve). Most events in [96-104] MeV/c $k_\pi$ interval, resulting in $\delta\Gamma/\Gamma \approx \pm 4\%$, mostly from closure momentum $\bar{q}$. 
**Pion FSI: s-wave $\pi N$ (Gal-Garcilazo)**

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

$\pi^-$ atoms fits: $b_0 \approx -0.02 \text{ m}^{-1}$, $b_1 \approx -0.12 \text{ m}^{-1}$

- Repulsive for $N \geq Z$, not in $\pi^- {^1H}$ & $\pi^- {^3He}$ as confirmed by attractive 1s level shifts.
- Repulsive FSI in the $\pi^0 {^3H}$ decay channel.
  Summed FSI in total $\Lambda {^3H}$ decay rate nearly zero.
- $\Delta I = 1/2$ rule: coherent $I = 1/2$ ($\pi^- {^3He} - \pi^0 {^3H}$), so isovector term gives attractive $-2b_1$.
- $\Gamma(\Lambda {^3H})/\Gamma_\Lambda$: 1.11 (no FSI) $\Rightarrow$ 1.23 (pion FSI); with pion FSI: $\tau(\Lambda {^3H}) = 214 \pm 8 \text{ ps}$.
- World average: $\tau(\Lambda {^3H}) = 206^{+15}_{-13} \text{ ps}$. 
Pion FSI: adding p waves (ongoing)

\[ \delta V_{\text{opt}} \propto \left( \vec{\nabla} \cdot [c_0(\rho_n + \rho_p) + c_1(\rho_n - \rho_p)]\vec{\nabla} \right) / (\text{EELL renorm.}) \]

\(\pi^–\) atoms fits: \(c_0 = 0.23 \, m_\pi^{-3}\), \(c_1 = 0.16 \, m_\pi^{-3}\) (\(\pi N\) values)

- Attractive for \(N \geq Z\), but in \(^3\Lambda H \rightarrow \pi^- + ^3\text{He}\), for \(p_\pi \sim 100\) 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 that enhances \(\Gamma(^3\Lambda H)\) by \((10–20)\%\).

- Ongoing: Pérez-Obiol, Gazda, Friedman, Gal, where, furthermore, \(\Sigma\) admixtures of less than \(1\%\) reduce \(\Gamma(^3\Lambda H)\) by \(~10\%\).
Addendum: $^4_A$H & $^4_A$He lifetimes

\[
\frac{\Gamma(^4_AH)}{\Gamma_A} \approx \frac{3}{2} \times \left( \frac{2}{3} \times 0.7 + 1 \times 0.3 \right) + 0.25 = 1.40
\]

\[
\frac{\Gamma(^4_AHe)}{\Gamma_A} \approx \frac{3}{2} \times \left( \frac{1}{3} \times 0.7 + 1 \times 0.3 \right) + 0.25 = 1.05
\]

Input: $\frac{3}{2}$ for nuclear structure, $R_4=0.7$
$\frac{2}{3}$ & $\frac{1}{3}$ for $\pi^-$ or $\pi^0$ and $^4$He, $\Gamma_{n.m.}/\Gamma_A \approx 0.25$

$\Rightarrow \tau(^4_AH) \approx 190$ ps, $\tau(^4_AHe) \approx 250$ ps

in rough agreement with measured lifetimes.

Looks like Lifetime Puzzle is limited to $^3_A$H.

- For $A \geq 12$, $\tau(^A_AZ) \sim 200$ ps, from KEK and very recently from HKS JLab E02-E017: NPA 973 (2018) 116. Lifetime is due to $\Lambda N \to NN$. 


Summary & Outlook

• Pion FSI makes $^3\Lambda$H decay faster by (10–20)%.  
• $\Sigma$ admixtures in $^3\Lambda$H reduce $\Gamma(\Lambda H)$ by $\sim$10%. 
• Provided these contributions cancel largely each other, one remains with a (5–10)% enhanced $\Gamma(\Lambda H)$ w.r.t. $\Gamma_\Lambda$ from phase-space and exchange factors.

• Future UR-HI experiments in both LHC and RHIC should resolve the discrepancy between ALICE and STAR $\tau(\Lambda H)$ determinations; need to lower measurement uncertainties, as just reported in QM2019 by ALICE.

• Rule out $^3\Lambda n$ in forthcoming HI experiments.
• New proposed experiments at J-PARC on $^3$He:
  (i) P73: $^3$He($K^-$, $\pi^0$)$_\Lambda(^3H$, Ma et al.
  (ii) P74: $^3$He($\pi^-$, $K^0$)$_\Lambda(^3H$, Feliciello et al.
  Could be done also on $^4$He to study $^4\Lambda$H decay.

• Establish resonance nature, if so, of $^3\Lambda n$ at Jlab
  on $^3$H target: $^3$H(e, e$'K^+$)$_\Lambda(^3H$, as proposed and
done by L. Tang et al. This might provide
  constraints on $\Lambda n$–$\Lambda p$ 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!