The Hypertriton ($^3_\Lambda$H) Lifetime Puzzle

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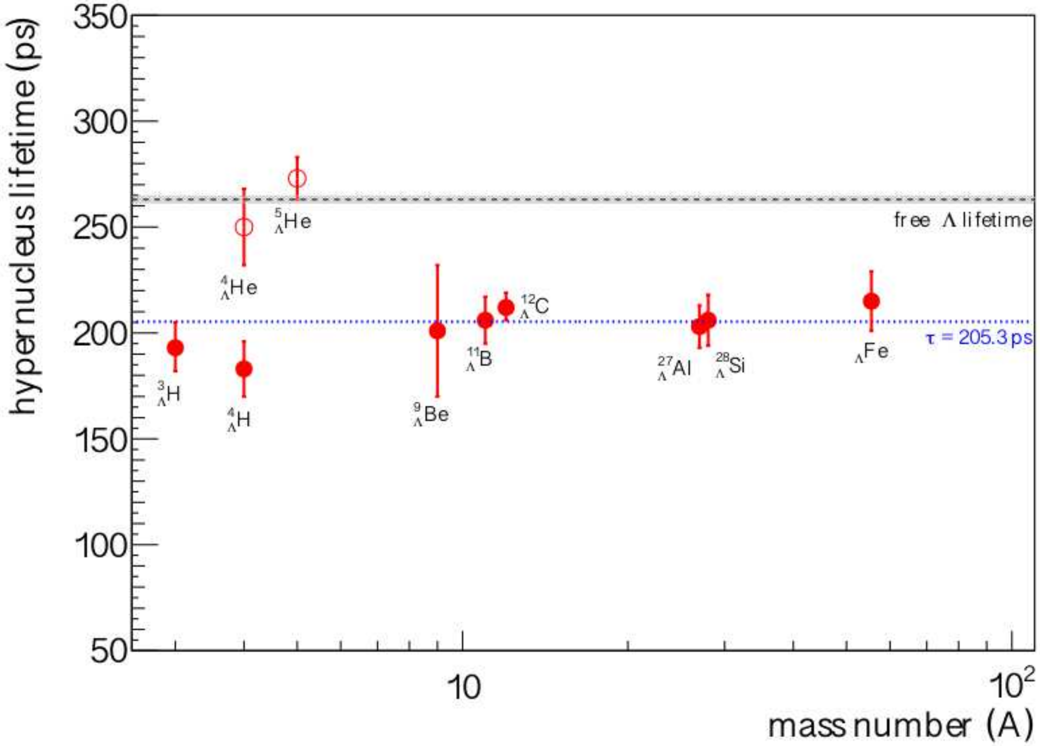
- Background
  (i) Experimental: from emulsion & bubble chambers to relativistic heavy-ion collisions;
  (ii) Theoretical: from Rayet-Dalitz (1966), Congleton (1992), to Kamada et al. (1998).
- Pion final-state interaction (FSI) enhances decay rate: Gal–Garcilazo, PLB 791 (2019) 48.
- Σ admixtures in $^3_\Lambda$H reduce decay rate: Pérez-Obiol–Gazda–Friedman–Gal (ongoing).
- Lifetimes of $^4_\Lambda$H, $^4_\Lambda$He & $^3_\Lambda$n, if stable.

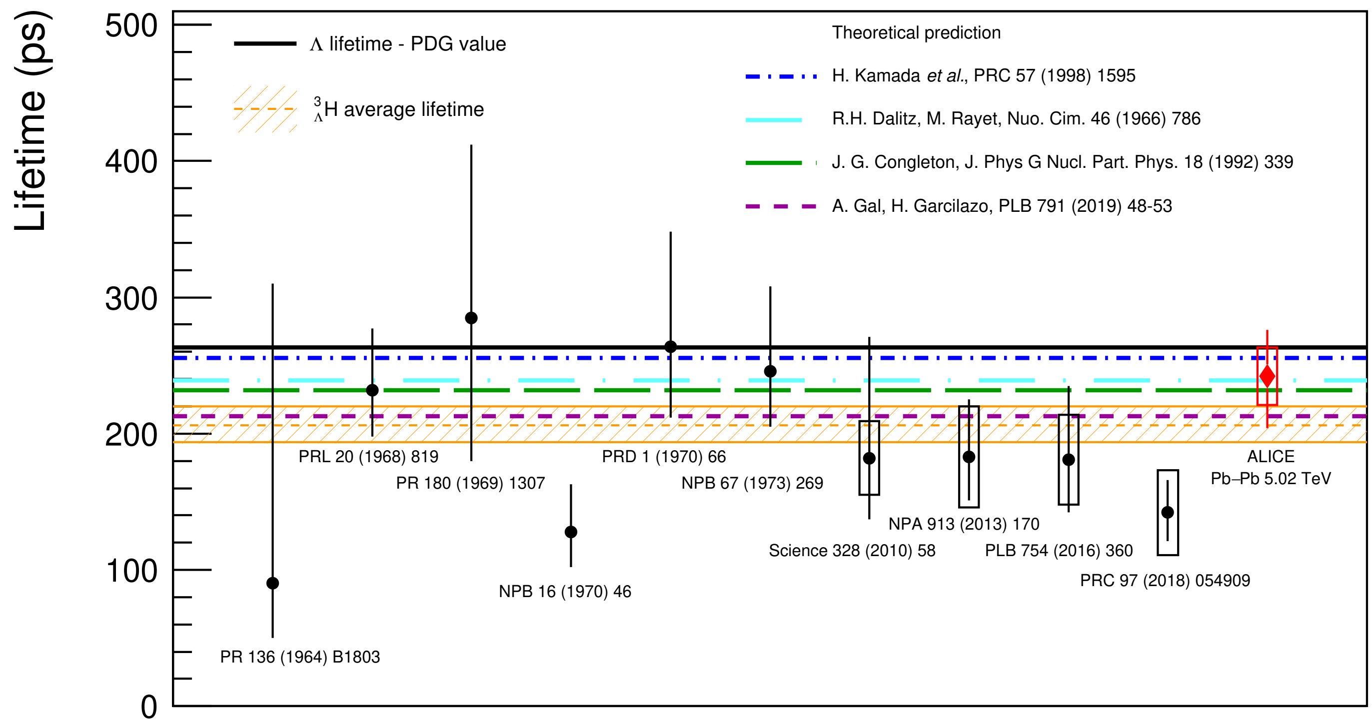
Summary of ${}^{A}_{\Lambda}$Z hypernuclear lifetimes

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



- $\Lambda \to N\pi$, $\approx 99.7\%\Gamma_\Lambda$, replaced for $A \gg 1$ to $\approx 125\%\Gamma_\Lambda$ by $\Lambda N \to NN$; yet, $\Gamma({}^{3}_{\Lambda}\mathrm{H} \to \mathrm{NNN})$ is only $\sim 1.7\%\Gamma_\Lambda$ as calculated by Golak et al., PRC 56 (1997) 2892.
- Delayed fission: $\tau_{A\gg 1}({}^{A}_{\Lambda}\mathrm{Z}) \approx 210 \pm 10$ 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



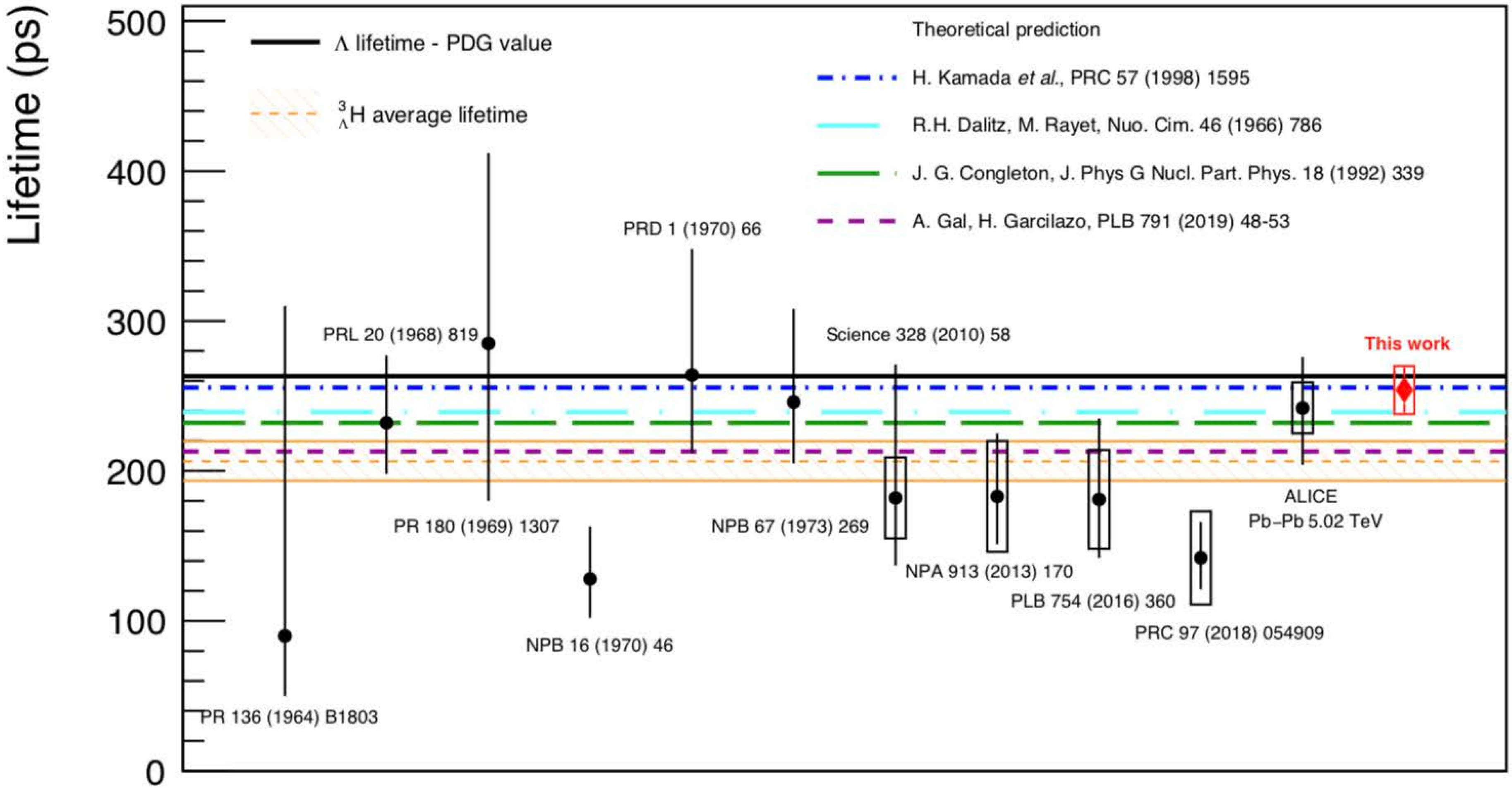
World average of measured $\tau({}^{3}_{\Lambda}\mathrm{H})$ is shorter ∼30±10% w.r.t. τ_Λ=263±2 ps. **Note recent UR-HI experiments:**

STAR, Au–Au @200 GeV: PRC 97 (2018) 054909, $\tau=142^{+24}_{-21}\pm29$ ps.

ALICE, Pb-Pb @5 TeV: PLB 797 (2019) 134905, $\tau=242^{+34}_{-38}\pm17$ ps.

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

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

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 1.14
Congleton (1992)	closure-Λd	0.33±0.02	1.14 1.15
Kamada et al (1998)	full Faddeev	0.379	1.03 1.06
Gal-Garcilazo (2018)**	closure-Λpn	0.357	1.11 1.11

- 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$_3$=$\sqrt{B_\Lambda}(1.07\text{-}0.60\sqrt{B_\Lambda}+0.27B_\Lambda)$,
  so R$_3$=0.35±0.04⇒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: 1.11→1.23.

Closure approximation calculations

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

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

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

Gal-Garcilazo: $\eta(\bar{q})$=0.14±0.03, →0 upon $\mathbf{B}_\Lambda$→0.

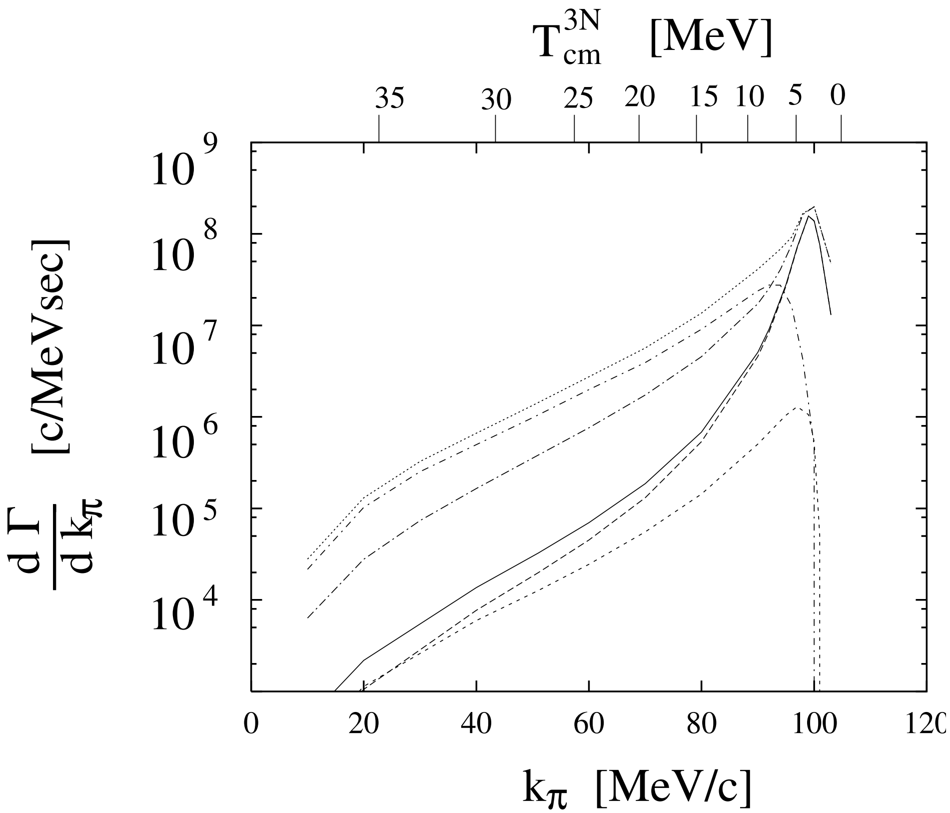
$$\Gamma^{J=3/2}_{{}^3_\Lambda\mathrm{H}} = \frac{\bar{q}}{1+\omega_\pi/E_{3N}}[|s_\pi|^2(1-\eta(\bar{q}))+|p_\pi|^2(\frac{\bar{q}}{q_\Lambda})^2(1-\frac{1}{3}\eta(\bar{q}))]$$

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

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

compared to 181^{+30}_{-24}±25 ps or 190^{+47}_{-35}±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, w & w/o 3N FSI, and their sum with FSI (solid curve).

Most events in [96-104] MeV/c k_π interval, resulting in $\delta\Gamma/\Gamma \approx \pm 4\%$, mostly from closure momentum $\bar{q}$.

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 $-2b_1$.**
- **$\Gamma({}^3_\Lambda$H$)/\Gamma_\Lambda$: 1.11 (no FSI) $\Rightarrow$ 1.23 (pion FSI); with pion FSI: $\tau({}^3_\Lambda$H$)$=214$\pm$8 ps.**
- **World average: $\tau({}^3_\Lambda$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\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, Σ admixtures of less than 1% reduce $\Gamma({}^3_\Lambda$H) by $\sim$10%.**

Addendum: ${}^4_\Lambda$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, $\tau({}^A_\Lambda\mathrm{Z})$~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)%.**
- **Σ admixtures in ${}^{3}_{\Lambda}$H reduce $\Gamma({}^{3}_{\Lambda}$H) by ~10%.**
- **Provided these contributions cancel largely each other, one remains with a (5–10)% enhanced $\Gamma({}^{3}_{\Lambda}$H) w.r.t. Γ_{Λ} from phase-space and exchange factors.**
- **Future UR-HI experiments in both LHC and RHIC should resolve the discrepancy between ALICE and STAR $\tau({}^{3}_{\Lambda}$H) determinations; need to lower measurement uncertainties, as just reported in QM2019 by ALICE.**
- **Rule out ${}^{3}_{\Lambda}$n in forthcoming HI experiments.**

- **New prposed experiments at J-PARC on ^{3}He:**
  (i) P73: $^{3}\mathrm{He}(K^{-},\pi^{0})^{3}_{\Lambda}\mathrm{H}$, Ma et al.
  (ii) P74: $^{3}\mathrm{He}(\pi^{-},K^{0})^{3}_{\Lambda}\mathrm{H}$, 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: $^{3}\mathrm{H}(\mathrm{e},\mathrm{e'}K^{+})^{3}_{\Lambda}\mathrm{n}$, 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!