The measurement of the properties of hypertriton and anti-hypertriton

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Hypertriton and anti-hypertriton

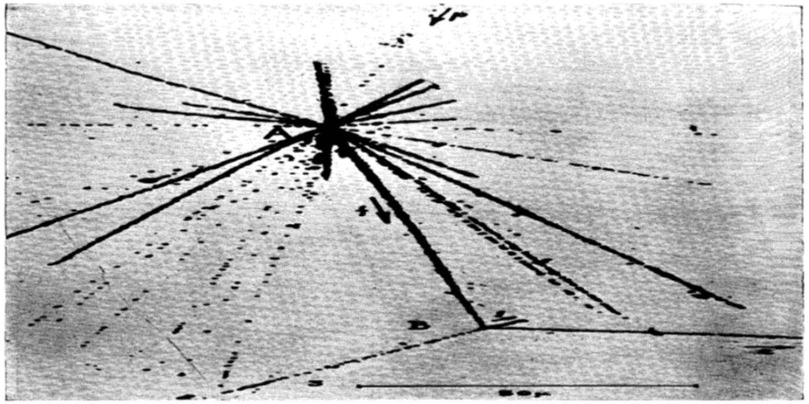
Hypertrion is composed of a proton, neutron and Λ hyperon

In 1953, M. Danysz and J. Pniewski found the first evidence of hypertriton produce by cosmic ray[1]

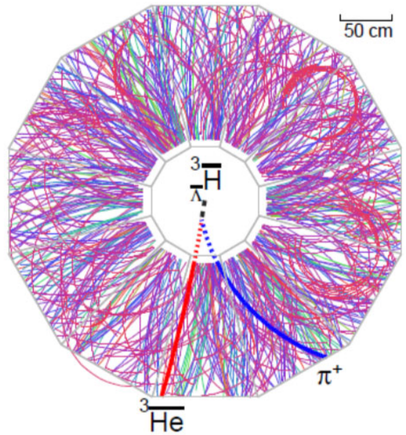
In 2010, the STAR Collaboration found the anti-hypertriton [2]

Hypertriton has been researched for decades and the detectors and measurement have been upgraded

1. M. Danysz, J. Pniewski, Philos. Mag. 44 (1953) 348.
2. Abelev, B. I. *et al.* (STAR Collaboration).. *Science* **328**, 58-62 (2010)



The first observation of hypertriton form cosmic rays [1]



A typical event in the STAR detector that includes the production and decay of an anti-hypertriton candidate [2]

Motivation

Hypertriton are natural hyperon-nucleon correlation systems

- Provide direct access to the hyperon-nucleon (YN) interaction

CPT invariance in YN interaction need to be tested by comparing the binding energy (B_{Λ}) of (anti-) hypertriton

Measuring both ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ can improve the measurement precision of the B_{Λ} and lifetime (τ)

The importance of YN interaction:

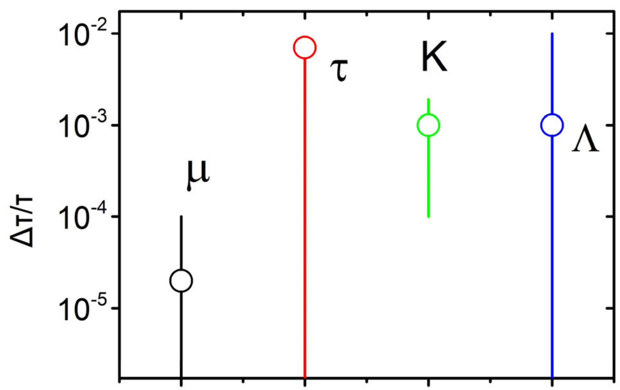
- Introduces the strangeness quantum number in nuclear matter
- The non-perturbative quantum chromodynamics still have some trouble in theory
- Need to be researched on experiment

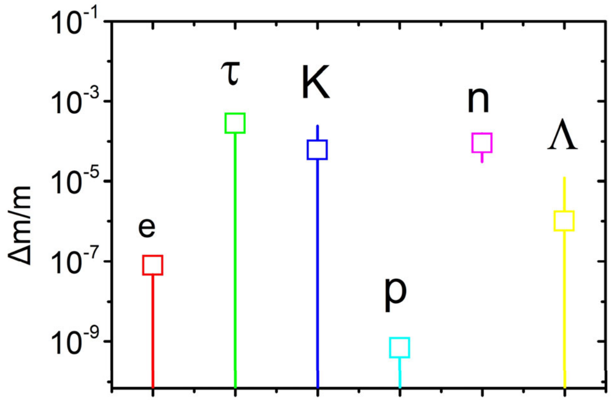
CPT theorem

CPT invariance is a fundamental symmetry of any local field theory, including the standard model

- Any evidence of CPT violation would be evidence of local Lorentz violation and a sign of physics beyond the standard model
- One implication is that every particle should have a mass and lifetime identical to those of its antiparticle
- No CPT violation has ever been observed

The measurement of the properties of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ can prove the CPT theorem in YN interaction





The mass and lifetime difference between some particles and its antiparticles[1]

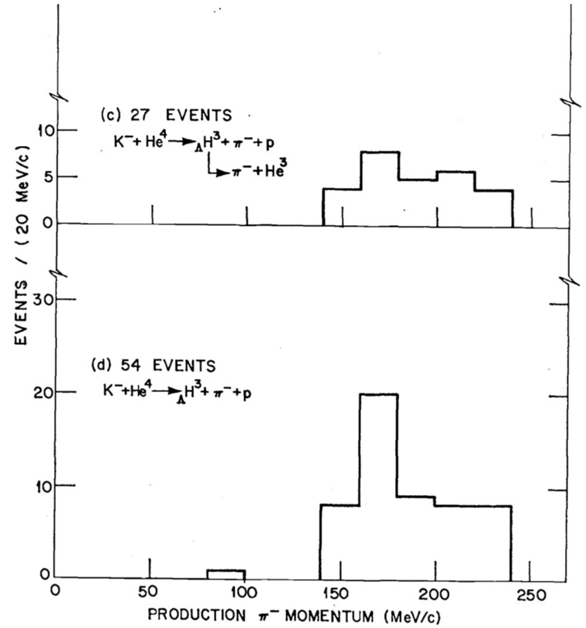
1. Date from PDG

The production of hypertriton and anti-hypertriton

In the early research, the experiments are performed on emulsion or bubble chamber exposed to a beam of K^- mesons:

$$K^- + {}^4He \rightarrow {}^3_\Lambda H + p + \pi^-$$

Nowadays, the experiments are performed on heavy ion collisions, like RICH and LHC, where produce not only ${}^3_\Lambda H$ but also ${}^3_\Lambda \overline{H}$



The production of hypertriton by Kaon beam [1]

1. Keyes, G. *et al*. *Phys. Rev. D* **1**, 66–77 (1970).

The reconstruction in early research

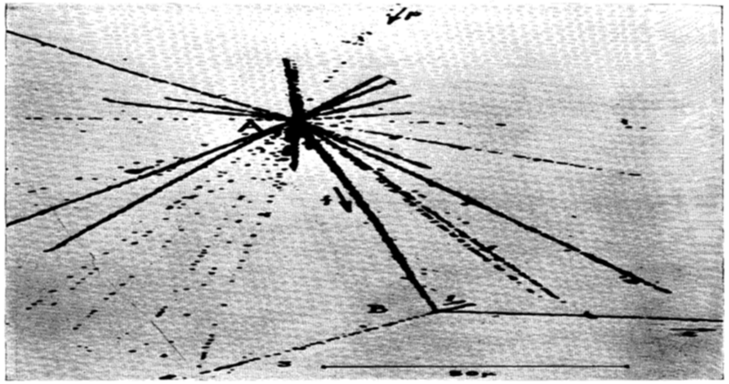
The decays of ${}^{3}_{\Lambda}H$

$$
\begin{aligned}
{}^{3}_{\Lambda}H &\rightarrow \pi^{-} + {}^{3}He \\
&\rightarrow \pi^{-} + d + p \\
&\rightarrow \pi^{-} + p + p + n
\end{aligned}
$$

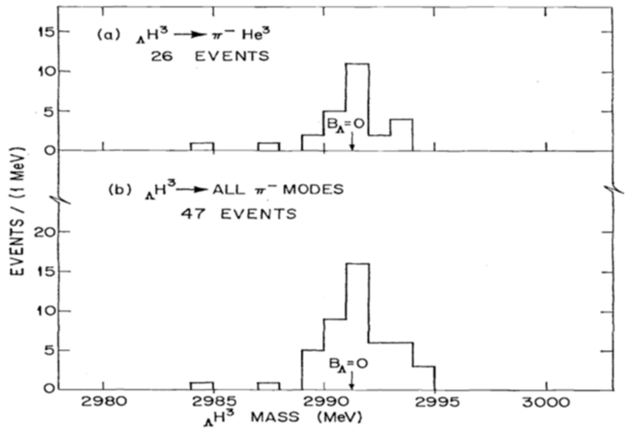
Reconstructing ${}^{3}_{\Lambda}H$ from these decays

Calculating the momentum, which can be measured by the length or radii of tracks, and using kinetics equation to get the mass distribution of ${}^{3}_{\Lambda}H$ and binding energy

Due to the low production tracks are clear on emulsion and bubble chamber



The track of ${}^{3}_{\Lambda}H$ decay on emulsion [1]



The mass distribution of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}H$ decays [2]

1. M. Danysz, J. Pniewski, Philos. Mag. 44 (1953) 348.
2. Keyes, G. *et al. Phys. Rev. D* **1**, 66–77 (1970).

The detectors and PID

In heavy-ion collision, the tracks are more complex

Particle identification (PID) is important

Take STAR for example:

- Time projection chamber (TPC):

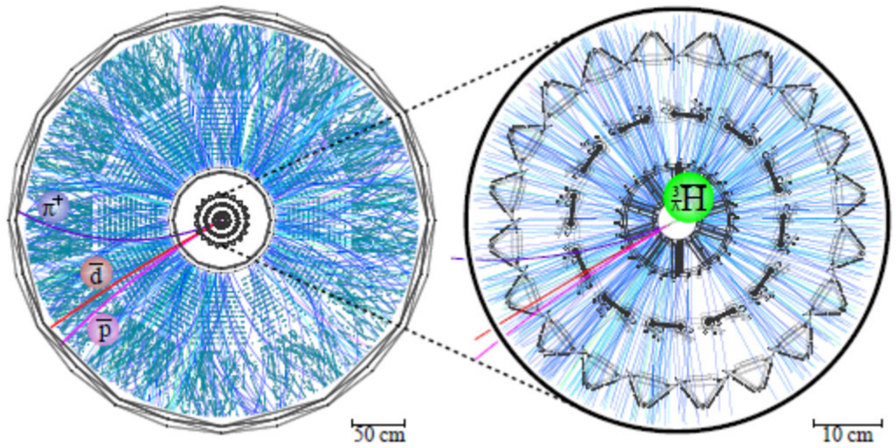
  Measure energy loss ($\langle dE/dx \rangle$) of charged particles produced in heavy-ion collisions

- Heavy flavor tracker (HFT)

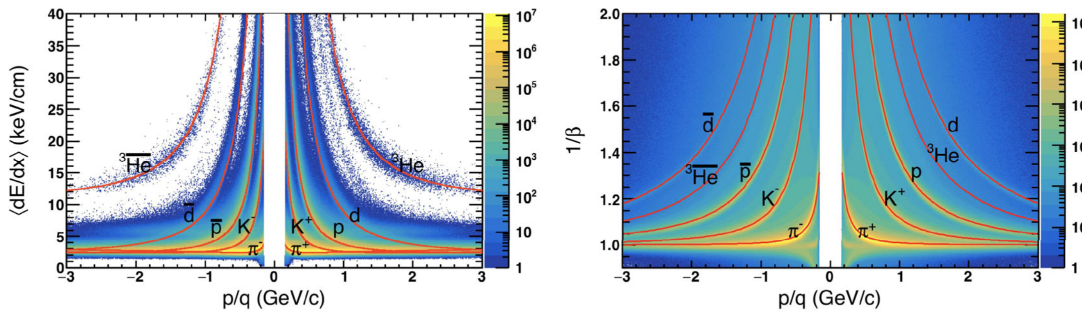
  High-precision tracking located at the center of the TPC

- Time of flight detector (TOF)

  Measure the speed (β = v/c) of charged particles



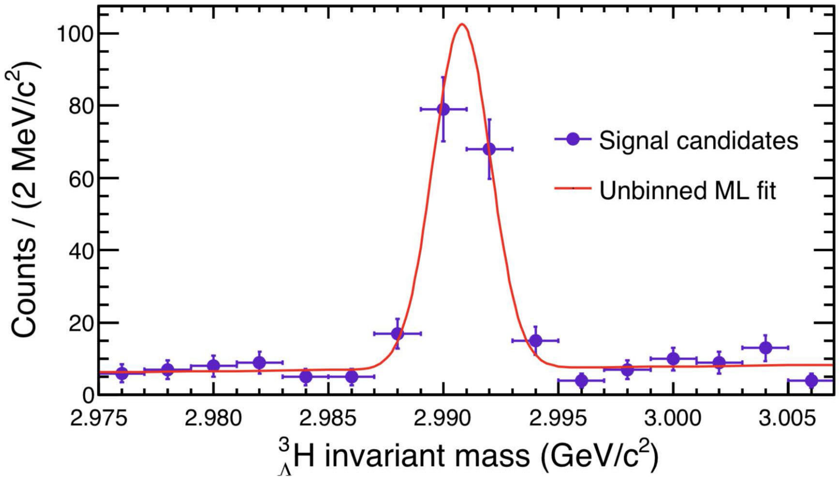
Tracks on the STAR TPC (left) and HFT (right) detectors[1]

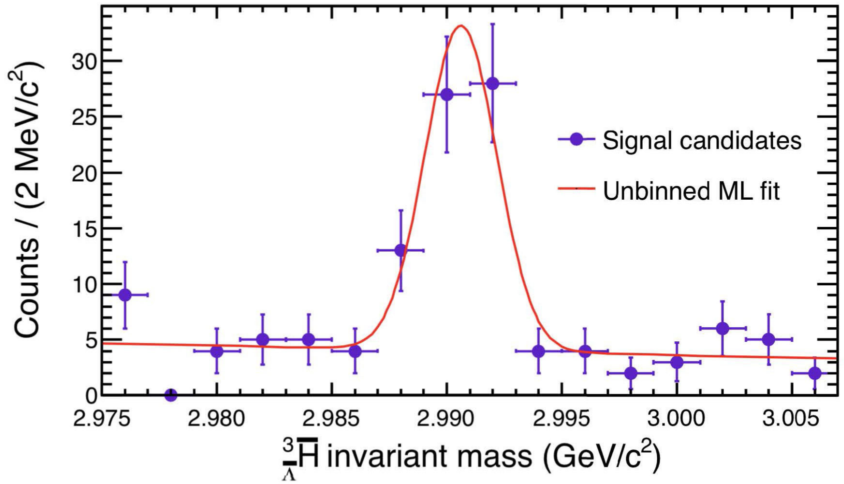


Particle identification using TPC and TOF in STAR [1]

1. Adam, J., Adamczyk, L., Adams, J.R. et al. Nat. Phys. 16, 409–412 (2020).

The test of CPT [1]





$m_{^{3}_{\Lambda}\mathrm{H}} = 2990.95 \pm 0.13(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}/c^2$

$m_{^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}} = 2990.60 \pm 0.28(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}/c^2$

$$\frac{\Delta m}{m} = \frac{m_{^{3}_{\Lambda}\mathrm{H}} - m_{^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}}}{m} = [\,1.1 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})] \times 10^{-4}$$

CPT invariance with high precision in YN interaction is not violated

The mass for $^{3}_{\Lambda}H$ and $^{3}_{\bar{\Lambda}}\overline{H}$ combined

$$m = 2990.89 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}/c^2 \qquad B_{\Lambda} = 0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}$$

1. Adam, J., Adamczyk, L., Adams, J.R. et al. Nat. Phys. 16, 409–412 (2020).

The measurement of lifetime

The lifetime can be calculated using events that decay in flight

The lifetime is determined by the length of tracks of ${}^3_\Lambda H$

Two method to measured the lifetime:

- Likelihood method, using:

$$L(\tau) = \prod_{i=1}^{N} \frac{1}{\tau} \frac{e^{t_i/T}}{e^{-t_{min-i}/\tau} - e^{-t_{max-i}/\tau}}$$

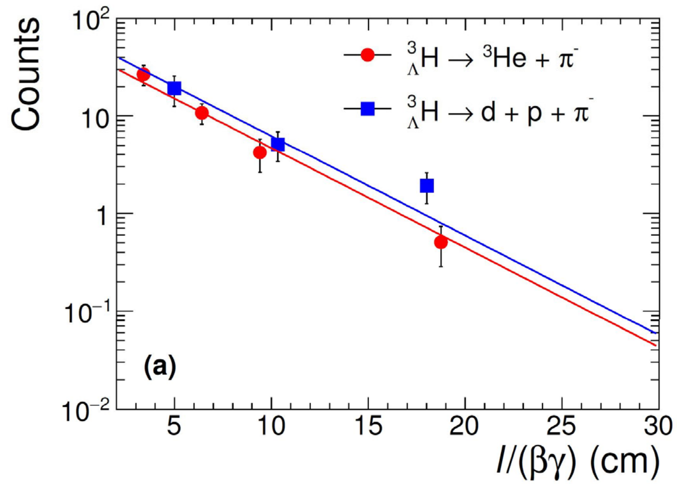
$$t_i = lm/pc$$

- The ${}^3_\Lambda H$ decays obey

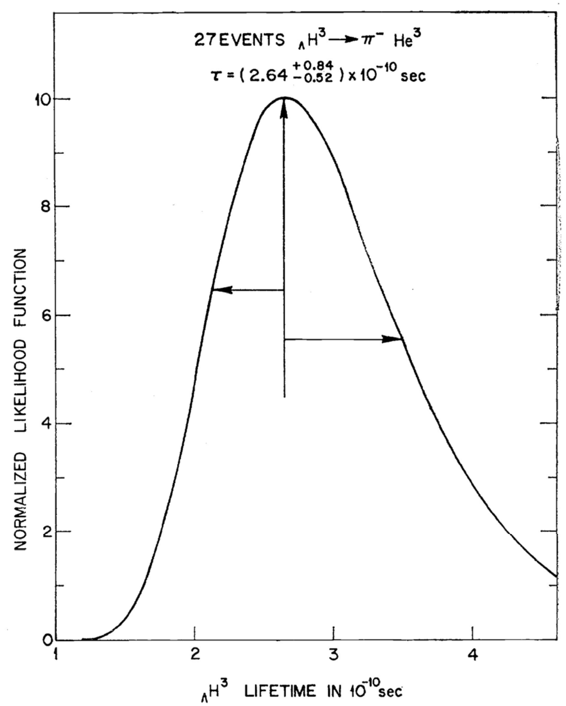
$$N = N_0 e^{-t/\tau} = N_0 e^{-l/\beta\gamma c\tau}$$

$$\ln(N) = -\frac{1}{c\tau}\left(\frac{l}{\beta\gamma}\right) + C$$

choose the minimum χ^2 fit of $c\tau$



Fit to the $l/\beta\gamma$ distribution [2]



Likelihood method [1]

1. Keyes, G. *et al. Phys. Rev. D* **1**, 66–77 (1970).
2. Adamczyk, L. *et al. Phys. Rev. C* **97**, (2018).

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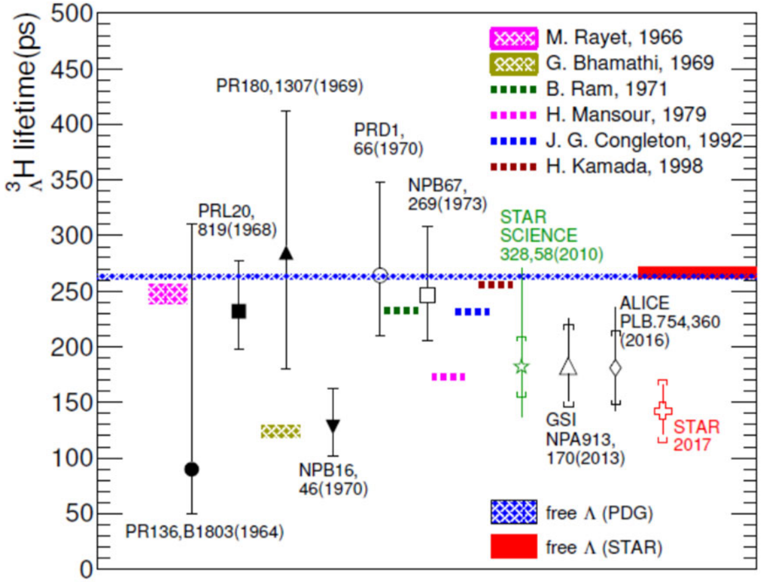


The measured lifetime through the decades [2]

1. Keyes, G. *et al. Phys. Rev. D* **1**, 66–77 (1970).

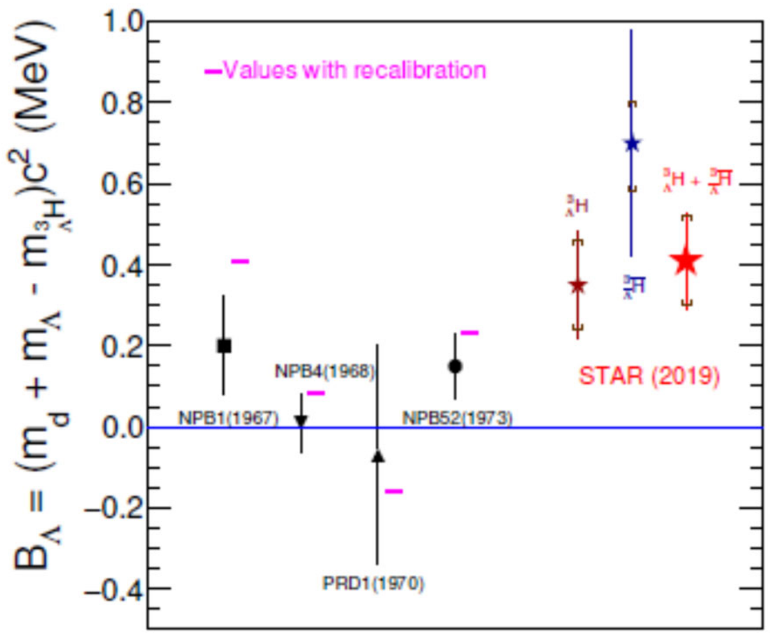
2. Adamczyk, L. *et al. Phys. Rev. C* **97**, (2018).

The measurement of binding energy

The (anti)$^{3}_{\Lambda}H$ invariant mass distributions is usually reconstructed through 2-body and 3-body decay channels

Two methods of fit:

- Kinematically fitting all events for various values of the $^{3}_{\Lambda}H$ mass and observing the χ^2 goodness of fit (early experiments)
- Fitted with a Gaussian function plus a straight line, using the unbinned maximum likelihood method (modern experiments)



The measured mass through the decades [1]

1. Adam, J., Adamczyk, L., Adams, J.R. et al. Nat. Phys. 16, 409–412 (2020).

Summary

The meaning of the measurement of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$:

- Study the YN interaction
- Test the CPT theorem in YN interaction
- Improve the precision of the lifetime and binding energy of ${}^{3}_{\Lambda}H$

Conclusion:

- The CPT invariance with high precision in YN interaction is not violated
- The experiments on heavy-ion collision improve the precision of the measurement of the the lifetime and binding energy of ${}^{3}_{\Lambda}H$ which gives a deeper understanding of the YN interaction

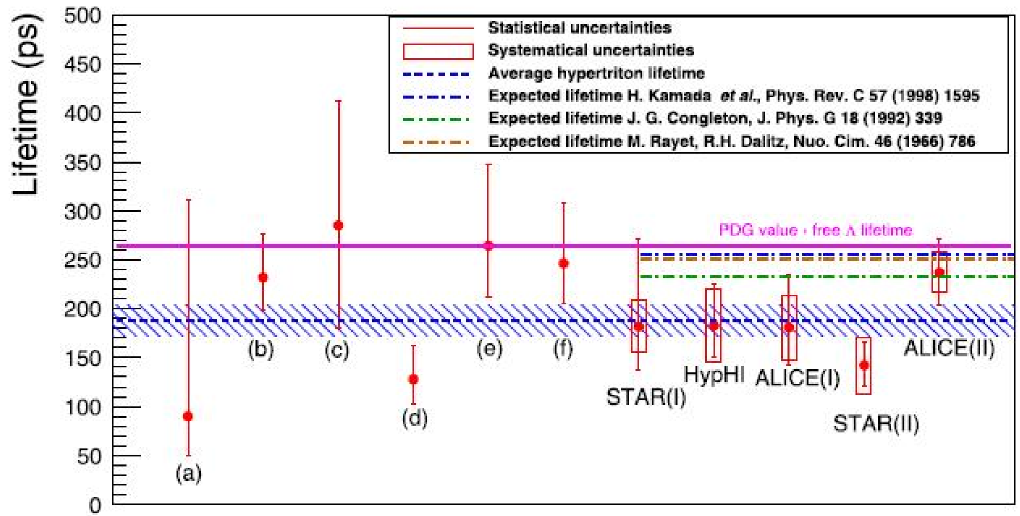
Lifetime puzzle

The binding energy of hypertriton is small

Assuming that Λ hyperon and deuteron are weakly bound in ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}H$ decay by Coulomb dissociation

The lifetime of ${}^{3}_{\Lambda}H$ will approximate the Λ

The lifetime of Λ is longer than the experimental result of ${}^{3}_{\Lambda}H$



${}^{3}_{\Lambda}H$ Measured lifetime values in chronological order, and (a)–(f) from emulsion and bubble-chamber measurements[1]

1. Gal, A. & Garcilazo, H. *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.* **791**, 48–53 (2019).