(anti)hypertriton lifetime puzzle

Yu-Gang Ma
Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Sciences, CHINA

- Why we revisit the lifetime
- New measurement from STAR
  - Signal in separate bins
  - Updated results and world data
  - Discussions
- Concluding remarks
The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate. 

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

**Hypernucleus of lowest \(^3\Lambda H(n + p + \Lambda)\)**

- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to Y-N interactions
- Hypertriton: \(\Delta B = 130 \pm 50\) KeV; \(r \sim 10\) fm
- Production rate via coalescence at RHIC depends on overlapping wave functions of \(n+p+\Lambda\) in final state
- Hypertriton and anti-hypertriton ratios sensitive to matter and anti-matter profiles in heavy-ion collisions
- Important first step for searching for other exotic hypernuclei (double-\(\Lambda\))

Nucleus which contains at least one hyperon in addition to nucleons.

**Hypernucleus**

- \(\Lambda \rightarrow p + \pi^- (64\%); \Lambda \rightarrow n + \pi^0 (36\%)\)
Several possible configurations of **Neutron Stars**
- hyperons, strange quark matter

**Single** and **double** hypernuclei in the laboratory:
- study the **strange sector** of the baryon-baryon interaction
- provide info on EOS of neutron stars
The mesonic decay of hypertriton

Kamada et al., PRC 57, 1595(1998)

TABLE I. Partial and total mesonic and nonmesonic decay rates and corresponding lifetimes.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \Gamma [\text{sec}^{-1}] )</th>
<th>( \Gamma / \Gamma_{\Lambda} )</th>
<th>( \tau = \Gamma^{-1} [\text{sec}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^3\text{He} + \pi^- ) and ( ^3\text{H} + \pi^0 )</td>
<td>( 0.146 \times 10^{10} )</td>
<td>0.384</td>
<td>( 0.684 \times 10^{-9} )</td>
</tr>
<tr>
<td>( d + p + \pi^- ) and ( d + n + \pi^0 )</td>
<td>( 0.235 \times 10^{10} )</td>
<td>0.619</td>
<td>( 0.425 \times 10^{-9} )</td>
</tr>
<tr>
<td>( p + p + n + \pi^- ) and ( p + n + n + \pi^0 )</td>
<td>( 0.368 \times 10^{8} )</td>
<td>0.0097</td>
<td>( 0.271 \times 10^{-7} )</td>
</tr>
<tr>
<td>All mesonic channels</td>
<td>( 0.385 \times 10^{10} )</td>
<td>1.01</td>
<td>( 0.260 \times 10^{-9} )</td>
</tr>
<tr>
<td>( d + n )</td>
<td>( 0.67 \times 10^{7} )</td>
<td>0.0018</td>
<td>( 0.15 \times 10^{-6} )</td>
</tr>
<tr>
<td>( p + n + n )</td>
<td>( 0.57 \times 10^{8} )</td>
<td>0.015</td>
<td>( 0.18 \times 10^{-7} )</td>
</tr>
<tr>
<td>All nonmesonic channels</td>
<td>( 0.64 \times 10^{8} )</td>
<td>0.017</td>
<td>( 0.16 \times 10^{-7} )</td>
</tr>
<tr>
<td>All channels</td>
<td>( 0.391 \times 10^{10} )</td>
<td>1.03</td>
<td>( 2.56 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

Expt. [6]                                    | \( 2.64 + 0.92 - 0.54 \times 10^{-10} \) |
Expt. (averaged) [11]                        | \( 2.44 + 0.26 - 0.22 \times 10^{-10} \) |


\[
\begin{align*}
\Gamma^{3\text{He}} &= \Gamma^{3\text{He} \rightarrow \pi^- + ^3\text{He}}, \\
\Gamma^{p+d} &= \Gamma^{3\text{He} \rightarrow \pi^- + p + d}, \\
\Gamma^{p+p+n} &= \Gamma^{3\text{He} \rightarrow \pi^- + p + p + n}.
\end{align*}
\]

\[
\Gamma = \frac{3}{2}(\Gamma^{3\text{He}} + \Gamma^{p+d} + \Gamma^{p+p+n})
\]

\[
\Gamma^{3\text{He}} = \frac{\Gamma^{3\text{He} \rightarrow \pi^- + ^3\text{He}}}{\Gamma^{3\text{He} \rightarrow \pi^0 + ^3\text{He}}} = 2.
\]
Focus on the hypertriton lifetime (1)

- Though the mesonic decays are Pauli blocked in heavier hypernuclei, they are the dominant channels in hypertriton.
- In experiment, the 2-body helium3 channel and the 3-body deuteron channel are easier to access.

The lifetime measurements are interesting especially in view of the short values from early experiments:

The 1\textsuperscript{st} measurements is $(0.95^{+0.19}_{-0.15}) \times 10^{-10}$s from helium bubble chamber, by Block et al., presented in the proceeding of Conference on Hyperfragments at St, Cergue, 1963, p.62

Results from AGS nuclear-emulsion experiments: $(0.9^{+2.2}_{-0.4}) \times 10^{-10}$s, Phys. Rev.136 (1964) B1803,
- from Bevatron and AGS Phys. Rev. 139(1965) B401
  - 2-body (3 in flight, 4 at rest) $(0.8^{+1.9}_{-0.3}) \times 10^{-10}$s
  - 2-body combined with 3-body (5 in flight, 18 at rest) $(3.4^{+8.2}_{-1.4}) \times 10^{-10}$s

Nuclear-emulsion with maximum likelihood procedure, Nucl. Phys. B 16 (1970) 46, $(1.28^{+0.35}_{-0.26}) \times 10^{-10}$s,
But other measurements gave different values:

Helium bubble chamber from Argonne ZGS:
- \((2.32^{+0.45}_{-0.34}) \times 10^{-10}\text{s}\), PRL 20 (1968)819
- \((2.64^{+0.84}_{-0.52}) \times 10^{-10}\text{s}\), PRD 1(1970)66
- \((2.46^{+0.62}_{-0.41}) \times 10^{-10}\text{s}\), NPB 67(1973)269

Nuclear-emulsion from Bevatron:
- 2-body is \((2.00^{+1.10}_{-0.64}) \times 10^{-10}\text{s}\) and 3-body \((3.84^{+2.40}_{-1.32}) \times 10^{-10}\text{s}\),
- and a combined of \((2.74^{+1.10}_{-0.72}) \times 10^{-10}\text{s}\)

How about the theoretical understanding of these experimental results?
The hypertriton being a loosely-bound nuclear system, its mean lifetime should not be significantly different from that of the free Lambda.

Theoretical calculations from Dalitz et al., initially gave a short value and updated later on a larger value close to the free Lambda’s, Phys. Lett. 1 (1962) 58 and Nuovo Cimento A 46,786 (1986).

The calculations based on modern 3-body interaction force, the total lifetime is predicted to be $2.56 \times 10^{-10}$s, Phys. Rev. C 57 (1998) 1595.

The hypertriton lifetime data are not sufficiently accurate to distinguish between models, more precise measurements are needed.
Results from RHIC-STAR Col.

Previous measurement (before 1973)
Use nuclear emulsion or bubble chamber.
Accepted events: less than 80

STAR 2010 measurement
- Run4 200GeV MB 22M
- Run4 200GeV Central 23M
- Run7 200GeV MB 68M

STAR 2012 measurement
- Run10 200GeV MB ~223M
- Run10 200GeV Central ~199M
- Run10&11 low energies MB ~213M

It is promising to obtain an improved lifetime measurement using the new data
Relativistic heavy-ion collisions

Initial condition of collisions

New state of matter: QGP

Hadronization and hadronic interaction

RHIC creates hot and dense matter, containing dozens of hyperons in central events: ideal source of hypernuclei studies.

RHIC white paper: Nucl. Phys. A 757
The STAR Detector

- **TPC**: effectively 3-D ionization camera with over 50 million pixels.
- **STAR**: a complex set of various detectors, a wide range of measurements and a broad coverage of different physics topics.

**STAR-TPC**: NIMA 499 (2003) 659

**STAR-detector**: NIMA 499 (2003) 624
A beautiful event in the STAR TPC that includes the production and decay of an antihypertriton candidate. (Data taken from Run4 Au+Au 200GeV MB collision)
Datasets and event statistics

<table>
<thead>
<tr>
<th>Run</th>
<th>Energy (GeV)</th>
<th>MB</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run10</td>
<td>7.7</td>
<td>MB</td>
<td>~4M</td>
</tr>
<tr>
<td>Run10</td>
<td>11.5</td>
<td>MB</td>
<td>~11M</td>
</tr>
<tr>
<td>Run11</td>
<td>19.6</td>
<td>MB</td>
<td>~31M</td>
</tr>
<tr>
<td>Run11</td>
<td>27</td>
<td>MB</td>
<td>~49M</td>
</tr>
<tr>
<td>Run10</td>
<td>39</td>
<td>MB</td>
<td>~118M</td>
</tr>
<tr>
<td>Run10</td>
<td>200</td>
<td>MB</td>
<td>~223M</td>
</tr>
<tr>
<td>Run10</td>
<td>200</td>
<td>Central</td>
<td>~199M</td>
</tr>
<tr>
<td>Run7</td>
<td>200</td>
<td>MB</td>
<td>~56M</td>
</tr>
</tbody>
</table>

Analysis method: secondary vertex finding technique

- Identify $^3\text{He}$ and $\pi$ candidate
- Find the V0 position from daughters pairing
- Plot the invariant mass dis. of daughters
- Combinatorial background analysis
The largest Hypertriton sample

Statistics: Run7+Run10+Run11 MB+Central, ~610M events

Signal observed from the data (bin-by-bin counting [2.986,2.996]GeV): 602±63, which is the largest hypertriton sample ever created.

Background estimation: rotated background

Background: form:

\[ f(x) \propto \exp\left(-\frac{x}{p_1}\right) - \exp\left(-\frac{x}{p_2}\right) \]
Hypertriton signal from STAR BES at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 200 GeV

Run10 7.7 GeV minbias
$\chi^2$/ndf 25.8/32
Yield 45.57 ± 17.35
Mean 2.991 ± 0.001

Run10 11 GeV minbias
$\chi^2$/ndf 130.1/34
Yield 44.29 ± 16.46
Mean 2.991 ± 0.001

Run11 19 GeV minbias
$\chi^2$/ndf 60.7/34
Yield 42.11 ± 14.06
Mean 2.991 ± 0.001

Run11 27 GeV minbias
$\chi^2$/ndf 64.2/34
Yield 46.43 ± 16.34
Mean 2.991 ± 0.001

Run10 39 GeV minbias
$\chi^2$/ndf 41.1/32
Yield 88.12 ± 20.98
Mean 2.992 ± 0.002

Run10 200 GeV minbias
$\chi^2$/ndf 75.3/34
Yield 82.91 ± 20.32
Mean 2.991 ± 0.000

STAR preliminary
Signal in separated decay length bins

\[ N(t) = N(0) \times e^{-t/\tau} = N(0) \times e^{-L/\beta\gamma c\tau} \]

- Measure the hypertriton signal in different \( L/\beta\gamma \) bins: 2-5-8-11-41cm
- Combined dataset
  - run10: 7.7, 11.5, 39, 200GeV MiniBias,
  - run10: 200GeV central; run11: 19.6, 27GeV MB
The 12th International Conference on Nucleus-Nucleus Collisions (NN2015), Italy, 6/2015

New hypertriton lifetime result

STAR Preliminary result:

\[ \tau = 260 \pm 1 \text{ps} \]

STAR 2010+2012 combined fit:

\[ \tau = 123 \pm 26 \pm 10 \text{ps} \]

\[ \tau = 138 \pm 23 \text{ps} \]

As a further cross-check, \( \Lambda \) is reconstructed via the \( \Lambda \rightarrow p + \pi^- \) decay channel. We use exactly the same method to obtain the \( \Lambda \) lifetime and the result is \( 260 \pm 1 \) ps which is consistent with the \( \tau = 263 \pm 2 \) ps compiled by the Particle Data Group [10].

Measurement from HpyHI project

Hypernuclear spectroscopy at GSI: $^6$Li projectiles on $^{12}$C target at 2 A GeV presents the hypertriton lifetime measurement from 2-body channel:

$\tau = 183 \pm 32 \pm 37 \text{ps}$

• The combined analysis of the world data for the lifetime of $^{3}\Lambda H$ and $^{4}\Lambda H$ gave the average of $^{3}\Lambda H$ and $^{4}\Lambda H$ lifetime was respectively $216^{+19-16}$ ps and $192^{+20-18}$ ps.

• With these studies, it has been revealed that the measured lifetime of $^{3}\Lambda H$ and $^{4}\Lambda H$ can be significantly shorter than that of the $\Lambda$–hyperon.
The physics for short lifetime?

★ Revisit the previous theoretical calculation:

A statistical combination analysis of the experimental lifetime data give average of $216^{+19}_{-18}$ ps for hypertriton, indicated that the lifetime of light hypernuclei is significantly shorter than the free Lambda’s.

★ Revisit binding energy (130 ± 50 kev), STAR exp. 3-body analysis have significant progress.

★ Physics implications:
(1) Loose Lambda inside hypernucleus, hypernuclear lifetime ~ free Labmda
(2) Stronger lambda-n interaction, hypernuclear lifetime < free Labmda

………
(nnΛ) signal in HI reaction?

HypHI exp. observed a signal in the invariant mass distribution of \( d+\pi \) and \( t+\pi \) channel.

PRC 88,041001R(2013)

Data from HIRES Col.
Excluded the (Lp) candidates

PLB 687, 31(2010)
PRD 84, 032002(2011)

A possible interpretation might be the two- and three-body decays of an unknown bound state of 2 neutrons associated with a Lambda:

\[ \Lambda n \rightarrow t + \pi^- \] and \[ \Lambda n \rightarrow t^* + \pi^- \rightarrow d + n + \pi^- \],
STAR preliminary

Yifei Xu (SINAP&BNL)

Two Bodies:

\[ \Lambda H \rightarrow ^3\text{He} + \pi^- \]

\[ \Lambda H \rightarrow ^3\text{He} + \pi^+ \]

Three Bodies:

\[ \Lambda H \rightarrow d + P + \pi^- \]

\[ \Lambda H \rightarrow d + P + \pi^+ \]

---

<table>
<thead>
<tr>
<th>Run</th>
<th>Energy</th>
<th>Vertex-R</th>
<th>Vertex-Z</th>
<th>Ref-Mult</th>
<th>Trigger Type</th>
<th>Trigger ID</th>
<th>Event Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run11</td>
<td>27GeV</td>
<td>\leq 2.0</td>
<td>\leq 50</td>
<td>All</td>
<td>Min-Bias</td>
<td>360001, 360002</td>
<td>53.31 M</td>
</tr>
<tr>
<td>Run10</td>
<td>39GeV</td>
<td>\leq 2.0</td>
<td>\leq 40</td>
<td>All</td>
<td>Min-Bias</td>
<td>280001</td>
<td>134.41 M</td>
</tr>
<tr>
<td>Run10</td>
<td>62.4GeV</td>
<td>\leq 2.0</td>
<td>\leq 40</td>
<td>All</td>
<td>Min-Bias</td>
<td>270001, 270011, 270021</td>
<td>70.23 M</td>
</tr>
<tr>
<td>Run11</td>
<td>200GeV</td>
<td>\leq 2.0</td>
<td>\leq 30</td>
<td>All</td>
<td>Min-Bias</td>
<td>350003, 350013, 350023, 350033, 350043</td>
<td>516.87 M</td>
</tr>
</tbody>
</table>
Topologic cuts

\[ ^3_H \Lambda \rightarrow d + P + \pi^- \]

- v012 : Mid-point of DCA 1 to 2
- v023 : Mid-point of DCA 2 to 3
- v013 : Mid-point of DCA 1 to 3

We assume the three points above to be the three vertexes of a triangle, then:

- v0123 : Centre of gravity of the triangle

Then we have:

dca1, dca2, dca3, Decay Length
dca1to2, dca2to3, dca1to3........
Preliminary 3-body analysis also shows a short lifetime. Detailed results will be shown in HYP2015, Sept. 2015 by Mr. Yifei Xu.
Concluding Remarks

Measurements of hypertriton lifetime are an interesting project in the field. Independent exp. present different results.

Several theoretical interpretations have achieved in the field and tend to conclude a value close to the free Lambda’s

New and precise measurements (>600 signals) from STAR Col. in the Relativistic Heavy-Ion Collider give a short value:

$$\tau = 123 \pm \frac{26}{22} \pm 10$$

Data from HypHI from GSI fixed target exp. Also show a short lifetime value:

$$\tau = 183 \pm \frac{42}{32} \pm 37\, ps$$

The discrepancy among different exp. is still there, the hypertriton lifetime is still a puzzle. New measurements from STAR Col., esp. for 3-body decay channel should shed new light on the puzzle.
The shortened lifetimes of hyper-3H and hyper-4H are due to the Pauli blocking effects which will suppress one pole amplitude but unaffected the other. As a consequence, the “perfect cancelation” between those two pole terms will be violated and the increased amplitude will broaden the width and then shorten the lifetime of the hypernuclei.
Systematic Study on Lifetime

Absorption

Hypertriton interacts with air and detector structure material

\[
\frac{\sigma_{^3H+\text{material}}}{\sigma_{p+\text{material}}} \frac{l}{\lambda_T/\rho} \sim e^{\frac{\sigma_{^3H+p}}{\sigma_{p+p}} \frac{l}{\lambda_T/\rho}} < e^{\frac{\sigma_{pd}+\sigma_{p\Lambda}}{\sigma_{pp}} \frac{l}{\lambda_T/\rho}}
\]

Absorption effect is less than 1.5% and can be neglected

Bin Width

Present is 4MeV bin, \( \tau \) fit result is \( 123 \pm 24 \)ps

For 2MeV bin, \( \tau \) fit result is \( 116 \pm 23 \)ps

Systematic error due to binning is 5.7%

Different Cuts

Change cuts 1): \( \tau : 120 \pm 30 \)ps  
Change cuts 2): \( \tau : 130 \pm 28 \)ps

Systematic error due to cuts is 6.2%

Total Systematic Error: \( \sim 8.4\% \)