Towards solving the hypertriton lifetime puzzle with 
*direct lifetime measurement*:
current status of J-PARC E73 experiment

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Outline

- Introduction & motivation
- J-PARC E73:
  - Experimental method
  - Current status
- Summary
As the lightest hypernucleus, $^3\Lambda\text{H}$ should tell us some important fact of YN interactions just as deuteron for nuclear physics.

A well separated wave function between $\Lambda$ and deuteron implies small modification of $^3\Lambda\text{H}$ lifetime from deuteron and, thus, its lifetime should be presumably determined by free $\Lambda$ decay.

Up to a few years ago, we believe: $\tau \approx 263\text{ ps (}B_\Lambda = 130 \pm 50\text{ keV)}$. $^3\Lambda\text{H} \rightarrow ^3\text{He} + \pi$- decay probability: $\text{kinematics} \times |\text{transition matrix}|^2 \sim \text{phase space} \times \text{wave function overlap} \text{ a small term (separation of } \sim 10\text{ fm})$
Introduction: motivation

As the lightest hypernucleus, $^3_\Lambda$H should tell us some important fact of YN interactions just as deuteron for nuclear physics.

Up to a few years ago, we believe: 
$\tau \approx 263$ ps ($B_\Lambda = 130 \pm 50$ keV);
However, heavy ion experiments suggest $\tau \approx 180$ ps…

Hypertriton lifetime puzzle challenges the very foundation of our knowledge for hypernucleus.

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Experimental method</th>
<th>$^3_\Lambda$H lifetime [ps]</th>
<th>Release date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>Pb collider</td>
<td>$240_{-31}^{+40}$ (stat.)$\pm18$ (syst.)</td>
<td>2019</td>
</tr>
<tr>
<td>STAR</td>
<td>Au collider</td>
<td>$142_{-21}^{+24}$ (stat.)$\pm29$ (syst.)</td>
<td>2018</td>
</tr>
<tr>
<td>HypHI</td>
<td>fixed target</td>
<td>$183_{-32}^{+42}$ (stat.)$\pm37$ (syst.)</td>
<td>2013</td>
</tr>
</tbody>
</table>

Neither fish nor fowl?
**Heavy ion results vs direct lifetime measurement**

**Heavy ion results:**
- Convert decay length to lifetime \( t = L / (\beta \gamma c) \);
- Statistics concentrate in the first few bins.

**Direct lifetime measurement:**
- Lifetime convoluted with time resolution;
- Relatively wide fitting range.

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Methods for *direct lifetime measurement*

- $\pi^- + \text{He}_3 \rightarrow K^0 + \text{Hypertriton}$:
  - proposed by A. Feliciello, INFN, Torino, Italy

- $\gamma + \text{He}_3 \rightarrow K^+ + \text{Hypertriton}$:
  - proposed by S. Nagao, Tohoku University

- $K^- + \text{He}_3 \rightarrow \pi^0 + \text{Hypertriton}$:
  - by J-PARC E73 collaboration

- how to detect $\pi^0$, which decays into 2 gamma almost immediately?
How does E73 work by tagging single $\gamma$-ray?

$^{3}$He(K-, $\pi^{0})^{3}_{\Lambda}H$ strangeness exchange reaction is known for its spin non-flip feature --> helps to pin down the $^{3}_{\Lambda}H$ Q.N.

Input
$\pi^{0}$: 0~1GeV/c; 0~180deg

W/ PbF2 calorimeter cut
$\pi^{0}$: 0.8~1GeV/c; 0~10deg

PbF2 calorimeter selection
$\theta_{\gamma} < 8$deg & $E_{\gamma} > 600$MeV
--> select very forward $\pi^{0}$
--> slowly moving $\Lambda/\Sigma$
--> enhancement of $^{3}_{\Lambda}H$

$\Lambda/\Sigma$: $\sim 200$MeV/c
Experimental setup: $\pi^0$ tagger ($\text{PbF}_2$)

- **$\pi^-$ peak**
- **electron peak**

**Expected performance after one month beam time**
(10 times more resistive than Pb glass)

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Radiation length</th>
<th>Moliere radius</th>
<th>Density</th>
<th>Cost</th>
<th>Resolution</th>
<th>Signal length</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{PbF}_2$</td>
<td>0.93 cm</td>
<td>2.22 cm</td>
<td>7.77 g/cm$^3$</td>
<td>12 USD/cc</td>
<td>5%</td>
<td>2ns</td>
</tr>
</tbody>
</table>

The idea of \textit{direct measurement}: $T_{CDH} - T_0 = t_{beam} + t_{\pi} + \tau$;

1. A complementary measurement for Heavy Ion results
2. Achievable precision: $\sigma/\sqrt{N} \sim 30\text{ps}$
PbF2 calorimeter performance @ELPH

PbF2 calorimeter was installed INTO the beam line

5%/$\sqrt{E}$ resolution measured with positron beam, 2019

pi-/$K$- beam signal on PbF2 calorimeter

electrons mixed in beam line (can be used for calibration)
## Current status of J-PARC E73

<table>
<thead>
<tr>
<th>Staging:</th>
<th>Stage-0</th>
<th>Stage-1</th>
<th>Stage-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task:</strong></td>
<td>Background study with $^4\text{He}(K^-, \text{pi0})^4\Lambda\text{H}$</td>
<td>First measurement for $^3\text{He}(K^-, \text{pi0})^3\Lambda\text{H}$ reaction</td>
<td>Direct lifetime measurement for $^3\Lambda\text{H}$</td>
</tr>
<tr>
<td><strong>Output:</strong></td>
<td>Established a new method as: $(K^-,\text{pi0}) +$ decay spectrum</td>
<td>Production cross section study for $^3\Lambda\text{H}$ @ 1GeV/c</td>
<td>Pin down Hypertriton lifetime puzzle</td>
</tr>
<tr>
<td><strong>Status:</strong></td>
<td>Cleared by T77 experiment</td>
<td>Fully ready for beam time from now on</td>
<td>Depends on Stage-1 results</td>
</tr>
</tbody>
</table>
Stage-0: feasibility study for E73

\[ K^- + ^4 He \rightarrow ^4 \Lambda H + \pi^0 \]

- T77 refreshes world record for \(^4\Lambda H\) statistics by twice \((1.2k\; events)\);
- New method improves S/N by ~10 times;
- All these happen within 3 days of beam time!

W/ \(\delta E\) correction

132.6 ± 0.1 (stat.) MeV/c
Stage-1: cross section & spin of Hypertriton

- Hypertriton isospin:
  - He\textsubscript{4}: \(T=0\) & He\textsubscript{3}: \(T=1/2\)
  - He\textsubscript{3}(K-, \pi0)\textsubscript{H3L} --> H\textsubscript{3L}: \(T=0\)

- Hypertriton ground state spin is determined by two-body/three-body ratio.
- No direct determination so far...
- E73 stage-1 experiment will shed light on this issue.

https://doi.org/10.1103/PhysRevD.1.66
Stage-1: cross section & spin of Hypertriton

(e, e’K+) reaction @ J-Lab

\(^3\Lambda H/\ ^4\Lambda H \sim 0.26 \pm 0.10\) in average

1.7 deg: 0.25 vs 12 deg: 0.90:
Difficult to interpret, something new?

• (K, pi) reaction is well-known as
spin non-flip feature

• Prof. T. Harada’s calculation:
\(^3\Lambda H/\ ^4\Lambda H \sim 1/3\) for ground state
Summary

- We have established a new method to investigate the isospin mirror Hypernuclei by gamma-ray tagging.
- E73 experiment has been approved as stage-1 and ready for data taking from now on.
  - First counter experiment to determine the Hypertriton ground state spin & cross section --> hint for the 3/2+ state by combining J-Lab results.
- Lifetime measurement is planned around ~2022.
P73/T77 collaborator list

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Backup
Most of the 1.0 GeV/c K- beam in-flight decay background is out of the acceptance of CDS spectrometer.
CDS tracking system works well;
- ~2% momentum resolution for ~100MeV/c pi- signals;
- TOF resolution ~137ps from prompt pi- scattered event
T77 results: pi- spectrum from $^4\Lambda H$

- T77 refreshes world record for $^4\Lambda H$ statistics by twice;
- New method improves S/N by ~ 10 times;
- All these happen within 3 days of beam time!
Physics Motivation

- Recent heavy-ion experiments reported different lifetime of hyper-triton, $^3\Lambda H$:

<table>
<thead>
<tr>
<th>STAR (2018)</th>
<th>ALICE (2018)</th>
<th>free $\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$142^{+24}_{-21} \pm 29$ ps</td>
<td>$237^{+33}_{-36} \pm 17$ ps</td>
<td>$263 \pm 2$ ps</td>
</tr>
</tbody>
</table>

- $\tau(^3\Lambda H) \sim \tau($free $\Lambda)$ is naively expected, because $^3\Lambda H$ is known to be very loosely bound system (~0.13MeV)

$\Rightarrow$ need to clarify the situation using different experimental technique
$^4\Lambda H$ Lifetime @ KEK

- $^4\text{He}(\text{stopped } K^-, \pi^-)^4\Lambda H$ reaction
- The lifetime was obtained from a fitting with a simulated spectrum

For cross-check, we will apply the same procedure to the $^3\Lambda H$ analysis.
Heavy ion experiments: *indirect measurement*

ALICE as an example for the experimental approach.

\[ c\tau = \left( 5.4^{+1.6}_{-1.2} \text{(stat.)} \pm 1.00 \text{(syst.)} \right) \text{ cm} \]

\[ \tau = \left( 181^{+54}_{-39} \text{(stat.)} \pm 33 \text{(syst.)} \right) \text{ ps} \]

Depends on tracking results for decay length and momentum as

\[ t = \frac{L}{\beta \gamma c} \]
Example: stopped K- experiment at KEK:
1. tagging π0 with NaI
2. measuring π- momentum with 300ps delay
3. subtract background from neighboring π- bins
4. fit lifetime with convoluted distribution

Stage-0: feasibility study for E73

- T77 $^4\Lambda$H lifetime fitting: $\sigma < 10$ps (statistical only)
  - preliminary data analysis (T77 finished on June 26th)
- KEK data with stopped K-: $\tau \sim 194^{+24}_{-26}$ ps
  - Improve the precision by a factor of $\sim 3$ (3 days beam time!)
Stage-1: cross section & spin of Hypertriton

(e, e’K+) reaction @ J-Lab

- $^4\Lambda$H contains both 0+ and 1+ states (spin-flip favored) in J-Lab results;
- $^3\Lambda$H is pure 1/2+ or has a virtual 3/2+ state near threshold?
- Can not be distinguished with ~4MeV resolution

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