Future Precision Measurements of the Hypertriton Mass

motivation, ideas, concepts, experimental limitations, …

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**The 5 Ws (and an H)**

Who, what, and where, by what helpe, and by whose: Why, how and when, doe many things disclose.

Thomas Wilson: *The Arte of Rhetorique* (1560)

**what:**
- ordinary matter
- strange matter
- dark photons

**who:**
- P Achenbach, U Mainz

**where:**
- established high-precision experiments at Mainz Microtron MAMI
- beyond MAMI: new infrastructure available > 2020
  - energy recovering superconducting accelerator MESA
  - new research buildings: Center for Fundamental Physics

Future precision measurements of the hypertriton mass
Future precision measurements of the hypertriton mass

A hypernuclear halo system

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The $\Lambda$-hypernuclear three-body system

- **the hypertriton**
  - simplest system in which $\Lambda$ particle interacts with nucleons at low energy
  - $\Lambda$ separation = binding energy
    \[ B_\Lambda = 130 \pm 50 \text{ (stat.) } \pm 50 \text{ (syst.)} \text{ keV} \]
  - short ranges of NN and $\Lambda N$ interactions & small total binding energy ($\sim 2.3$ MeV) imply $S$ states for relative motions and very loose structure
  - lightest hypernuclear bound state
    - $S = -1$, $J^P = \frac{1}{2}^+$, $T = 0$
  - mesonic weak decay (MWD) is expected to dominate over non-MWD

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Hypertriton as a halo system

- 1n and 2n halos known for small n separation energies near dripline
- universal scaling relations derived for nuclear systems with low binding
- hypertriton effective two-body $d\Lambda$ system (?)
- in hypertriton no centrifugal barrier, no Coulomb repulsion
- pair of particles is close $\Rightarrow$ third particle far away
- for a spatially extended nuclear state
  $\Rightarrow$ most of wave function in classically forbidden region

$$R = \sqrt{\langle r_{\Lambda-d}^2 \rangle} = \sqrt{\frac{\hbar^2}{(4\mu B_{\Lambda})}}$$

[Riisager et al., Europhys. Lett. 49 (2000)]
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The puzzle of hypertriton lifetime vs $B_\Lambda$
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- only ~ 10 hypernuclear lifetimes known
- theoretical predictions scattered over a large range
- predicted lifetime reduction for hyperhydrogen no more than 10%
- observed lifetime reduction for light light ($A \leq 4$) hypernuclei significant
- lifetime of $^4_\Lambda H$ ~ 20% smaller with respect to $^4_\Lambda He$

[Image: Graph showing hypernuclear lifetimes vs. mass number (A) with data points and labels for different isotopes.]


Scaled lifetime $\tau/\tau_\Lambda$
if $\Lambda$ in the hypernucleus is weakly bound

$\Rightarrow$ lifetimes of light ($A \leq 4$) hypernuclei expected to be similar to free $\Lambda$

- world average of $^3_\Lambda H$ lifetime measurements $\tau = 215^{+18}_{-16}$ ps
- comparison with $\tau = 263.2 \pm 2$ ps

values from heavy ion experiments demonstrate small lifetime

[ALICE Collab. PLB 754 (2016)]
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- lifetime puzzle depends on validity and accuracy of $B_\Lambda$ measurement
- unique location of $^3_\Lambda H$ compared to all other known hypernuclei
- binding energy of $^4_\Lambda H \sim 15\%$ smaller with respect to $^4_\Lambda He$
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Emulsion data limitations
The emulsion data for $^3\Lambda$H

only about 200 analyzed events from emulsion:

these data (from 2 decay modes): only source of binding energy information

\[
\begin{align*}
^3\Lambda_{^3H} &\rightarrow \pi^- + ^3\text{He}: \quad B_{\Lambda} = 70 \pm 60 \text{ keV} \\
^3\Lambda_{^3H} &\rightarrow \pi^- + ^1\text{H} + ^2\text{H}: \quad B_{\Lambda} = 120 \pm 80 \text{ keV} \\
\text{Total:} \quad B_{\Lambda} & = 130 \pm 50 \text{ keV}
\end{align*}
\]

\[50 \text{ keV difference}\] [M. Juric et al. NP B52 (1973)]
Need for new precision measurements
Errors on binding energy by method

- goal of calibrations is syst. error comparable to stat. error < 20 keV
- decay-pion spectroscopy will be the most precise method of all

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High-precision mass measurements at MAMI

requirements: calibration and beam energy with $O(10^{-4})$ precision

projected error compared to emulsion errors:

binding energies of light hyperisotopes could be measured with improved precision by decay-pion spectroscopy
Decay-pion spectroscopy at MAMI
Hyperfragment decay-pion spectroscopy with electron beams

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Hypernuclear experiments at MAMI done in Collaboration with Tohoku University (S.N.N. Nakamura et al.)

\[ M_{HYP} = \sqrt{M_{ncl}^2 + p_{\pi}^2} + \sqrt{M_{\pi}^2 + p_{\pi}^2} \]
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Decay-pion spectrum

emulsion

MAMI

Decays of quasi-free produced hyperon

Accidental background reactions

Mono-energetic pions
World data on $^4_\Lambda$H mass

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**World data on $^4_\Lambda$H mass**

*Outer error bars correlated from calibration*

**MAMI**

**emulsion**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>MAMI 2014 (SpekA, 250 μm Be)</th>
<th>MAMI 2014 (SpekA, 125 μm Be)</th>
<th>MAMI 2014 (SpekC, 250 μm Be)</th>
<th>MAMI 2014 (SpekC, 125 μm Be)</th>
<th>MAMI 2012 (SpekC, 125 μm Be)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^- + ^4$He</td>
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</tbody>
</table>

**emulsion**

- $B_\Lambda (^4_\Lambda$H) (stat.) (syst.)
- emulsion: $2.04 \pm 0.04 \pm 0.05$ MeV [M. Juric et al. NP B52 (1973)]
- MAMI 2012: $2.12 \pm 0.01 \pm 0.09$ MeV [A. Esser et al., PRL 114 (2015)]
- MAMI 2014: $2.16 \pm 0.01 \pm 0.08$ MeV [F. Schulz et al., NPA (2016)]
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Limitation by absolute beam energy precision
Future precision measurements of the hypertriton mass

Absolutoe momentum calibration

scattering off thin tantalum foil

\[ \hat{p} = 209.888 \text{ MeV/c} \]

- spectrometer FWHM of 53 keV/c $\rightarrow \delta p/p \sim 2 \cdot 10^{-4}$
- repeated calibrations at different momenta reveal $\delta p_{\text{calib}} \sim 5$ keV/c

\[ ^{181}\text{Ta}(e,e')^{181}\text{Ta}, \ 17 \text{ mg/cm}^2 \]

$E_0 = 210.17 \text{ MeV}$

$\theta_{\text{cent}} = 93.5^\circ, \Delta \Omega = 28 \text{ msr}$

$p_{\text{cent}} = 210.282 \text{ MeV/c}$

$E'_{\text{elastic}} = 209.886 \text{ MeV}$

\[ 53 \text{ keV/c} \]

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Simulation of scattering process and spectrometer

comparison of simulation vs. data reveals highest precision

Monte Carlo code for
...energy-loss of incoming beam,
...reaction vertex distribution,
...reaction kinematics, and
...energy-loss of outgoing particle
→ shape & width well reproduced

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Future precision measurements of the hypertriton mass

**Absolute beam energy**

- Beam energy absolute accuracy $\delta_{p_{\text{beam}}} \pm 160 \text{ keV/c} \rightarrow \delta E/E \sim 7 \cdot 10^{-4}$

- Ebeam
  - Entries: 111
  - Mean: 727.678
  - RMS: 0.037
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Interferometry of optical undulator radiation
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- two spatially separated sources of coherent synchrotron light
- two separated wave trains show interference in optical detector
- monochromator serves as Fourier analyzer of wave trains
- intensity for a selected wavelength shows a periodical variation
- intensity oscillation length directly related to beam energy

\[ \gamma_{\text{beam}}^2 = \frac{\lambda_{\text{osc}}}{2\lambda_{\text{rad}}} \]
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Pioneering run with undulator setup at MAMI

- two 50 cm long undulators
- variable distance of 500 mm
- monochromator and CCD system
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Evolution of synchrotron spectrum with distance

- clean spectra observed at center of radiation cone
- intensity at one wavelength varies periodically
- low counting noise ⇒ high statistical precision

proof of principle demonstrated with this measurement
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Highest-precision beam energy measurement achieved

Intensity oscillation for one selected wavelength:

Simultaneous measurement for 2328 wavelengths in CCD:

gamma_{beam} = 382.2 \pm 0.002 \text{ (stat.)} \pm 1.3 \text{ (syst.} \delta \Theta \text{)} \pm 0.1 \text{ (syst.} \delta \lambda \text{)}

E_{beam} = 194.8 \pm 0.001 \text{ (stat.)} \pm 0.7 \text{ (syst.} \delta \Theta \text{)} \pm 0.05 \text{ (syst.} \delta \lambda \text{)} \text{ MeV}
Limitation by luminosity
Li: an ideal target for $^3_\Lambda$H production

Future precision measurements of the hypertriton mass

- $^3_\Lambda$H production 3–11 x lower compared to $^4_\Lambda$H
- order of magnitude increase in target thickness
The story from hypernuclear halos to optical interferences

- a hypernuclear halo system
- the puzzle of hypertriton lifetime vs $B_{Λ}$
- limitation of emulsion data
- need for new precision measurements
- decay-pion spectroscopy at MAMI
- limitation by absolute beam energy precision
- limitation by luminosity

a hypertriton decay-pion experiment could be performed by ~ 2019