Towards a 3H/3He Mass-Ratio Measurement with THe-Trap
First IMPRS-PTFS Seminar

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Motivation

Mass of the Electron Antineutrino

- $\beta$-Decay of Tritium

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$$
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  $^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$

- KATRIN: electron kinematics near the endpoint

\[
\begin{align*}
\frac{dN}{dE} & \quad -5 \quad -4 \quad -3 \quad -2 \quad -1 \\
E - E_0 [\text{eV}] & \\
\end{align*}
\]

- $m_{\bar{\nu}_e} = 0$ eV
- $m_{\bar{\nu}_e} = 1$ eV
- $m_{\bar{\nu}_e} = 2$ eV
- $m_{\bar{\nu}_e} = 3$ eV
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Penning Trap Contribution
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**Penning Trap Contribution**

- **Q-value of the decay**: $18\,589.8(1.2)\,\text{eV}$
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- $Q$-value of the decay: 18589.8(1.2) eV
- measurement of the mass-ratio $R$
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### Penning Trap Contribution

- **Q-value of the decay**: 18 589.8(1.2) eV
- Measurement of the mass-ratio \( R \)
- Uncertainty of 30 meV in \( Q \) implies uncertainty of \( 10^{-11} \) in mass-ratio \( R \)
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**Mass of the Electron Antineutrino**

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- **Q-value of the decay**: 18589.8(1.2) eV
- Measurement of the mass-ratio \( R \)
- Uncertainty of 30 meV in \( Q \) → uncertainty of \( 10^{-11} \) in mass-ratio \( R \)

**dedicated** experiment, developed at the University of Washington in Seattle
Charged Particle Confinement

- free-space cyclotron frequency

\[ \omega_c = \frac{qB}{m} \]
A Penning Trap Primer

Charged Particle Confinement

- free-space cyclotron frequency
  \[ \omega_c = \frac{qB}{m} \]
- electrostatic quadrupole field

Invariance Theorem

\[ \omega_{2c}^{2} = \omega_{2c}^{2} + \omega_{2c}^{2} + \omega_{2c}^{2} \]

Mass-Ratio

\[ R = \frac{m_a}{m_b} = \frac{q_a}{q_b} \cdot \omega_c(b) \cdot B_a \cdot B_b \]
A Penning Trap Primer

Charged Particle Confinement

- free-space cyclotron frequency
  \[ \omega_c = \frac{qB}{m} \]
- electrostatic quadrupole field
- three eigenmodes
  - axial \( \omega_z = \sqrt{\frac{qU_0}{md^2}} \)
  - modified cyclotron \( \omega_+ \)
  - magnetron \( \omega_- \)

\[ \omega_{\pm} = \frac{1}{2} \left[ \omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2} \right] \]
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Mass-Ratio
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R = \frac{m_a}{m_b} = \frac{q_a}{q_b} \cdot \frac{\omega_c(b)}{\omega_c(a)} \cdot \frac{B_a}{B_b}
\]
Non-Destructive Ion Detection

Ion Electrode Interaction

- induced image charges \(\Rightarrow\) image currents
- goal: generate and amplify voltage drop

\[
\text{Image Current} + C_t \rightarrow I
\]
Non-Destructive Ion Detection

**Ion Electrode Interaction**
- induced image charges \( \Rightarrow \) image currents
- goal: generate and amplify voltage drop

**Narrow-Band Detection**
- tune out trap capacitance at
  \[ \omega_0 = \frac{1}{\sqrt{LC}} \]
Non-Destructive Ion Detection

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- tune out trap capacitance at \( \omega_0 = \frac{1}{\sqrt{LC}} \)
- resistive cooling
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![Tuned Circuit Diagram]

\[ U(t) \]

Signal Analysis

Frequency Information
Anharmonic Frequency Detection
Anharmonic Frequency Detection

Driven Harmonic Oscillator

- natural motion damped
- oscillation with driven frequency
Anharmonic Frequency Detection

Driven Harmonic Oscillator

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- amplitude and phase determined by
  - natural frequency
  - damping constant
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Coherent Detection
- Error Signal for frequency lock
  ⇒ lock axial mode to the drive
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**Driven Harmonic Oscillator**
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**Radial Modes**
- monitor excitations via higher-order effect on natural axial frequency
The Setup at MPIK
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Complications
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- American standards
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- Lab space: total height
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- lab space: total height
- tritium safety precautions
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Improvements over Predecessor
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#### Improvements over Predecessor

- double-trap assembly
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Improvements over Predecessor
- double-trap assembly
- external ion source
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■ double-trap assembly
■ external ion source
■ novel cascaded Zener-diode voltage-reference voltage-source
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The Control Room
The Magnet Room

External Influences

- room temperature
- external magnetic field changes
- vibration isolation

Cold-Bore Magnet

Temperature-dependent magnetic susceptibility

⇒ stabilize:

- liquid helium pressure
⇒ constant boiling point
- liquid helium level
⇒ constant temperature distribution
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The Traps of The-Trap

Inside Vacuum Envelope

- two hyperbolic traps with correction electrodes
The Traps of THe-Trap

Inside Vacuum Envelope

- two hyperbolic traps with correction electrodes
- transfer section
- capture section
Inside Vacuum Envelope

- two hyperbolic traps with correction electrodes
- transfer section
- capture section
- Field Emission Point
RF Ion Work

The Road to Ions

- load a cloud of ions
RF Ion Work

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- load a cloud of ions
- kick the contaminants
RF Ion Work

The Road to Ions
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- kick the contaminants
- work with one species ($^{12}\text{C}^4+$)
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Triggered Sweeps
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- establish lock
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- establish lock
- run triggered sweeps
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Triggered Sweeps
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Summary and Outlook

Personnel

Klaus Blaum:
MPIK/UW-PTMS → THe-Trap

David Pinegar
Christoph Diehl
Martin Höcker
Sebastian Streubel
Marius Tremer

Robert Van Dyck, Jr.:
UW-PTMS

Achievements
experiment moved to MPIK
dedicated lab
commissioning experiments
single ion sensitivity

Challenges
systematic studies
external loading and ion transfer

Long-term Goal

$^{3}\text{H}/^{3}\text{He}$ Mass-Ratio Measurement
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