The LiNA experiment:
Development of multi-layered time projection chamber

Naoyuki SUMI / High Energy Accelerator Research Organization
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Introduction: Neutron lifetime

- Free neutrons decay to beta through weak interactions
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]

- Neutron lifetimes have been measured by two different methods.
  - **Beam method:** Counting decay neutrons
    \[ \frac{dN}{dt} = \frac{N}{\tau} \]
  
  - **Storage method:** Counting remaining neutrons
    \[ \frac{N_1}{N_2} = e^{(t_1 - t_2)/\tau} \]

- The cause of the discrepancy between the methods (8.6 s / 4.1σ) has not been understood for a long time.
  \[ \Rightarrow \quad \text{New measurements using beam methods are needed.} \]
J-PARC MLF BL05

Neutron is produced by injecting proton beam to mercury target.

**Beam line property**
- Neutron energy: ~10 meV
- Neutron velocity: ~1000 m/s
- Beta decay rate: 0.1 cps
- \(^3\)He absorption rate: 2.5 cps

Spin Flip Chopper makes short neutron bunches to reduce background.

- \(^6\)LiF shutter: is a 5 mm thick \(^6\)LiF plate to control neutron beam.
- Cosmic veto counters: is plastic scintillators to identify cosmic ray.
Measurement principle

- Using a neutron beam, **beta decay events** and **$^3\text{He}$ absorption events** are measured with a gas detector, Time Projection Chamber.

- The neutron lifetime is derived from the ratio of both signals.

\[
\tau_n = \frac{1}{\rho \sigma v} \left( \frac{S_{\text{He}}}{S_\beta} / \frac{\varepsilon_{\text{He}}}{\varepsilon_\beta} \right)
\]

- **$^3\text{He}$ density** increases, **$^3\text{He}$ cross section $\times$ neutron velocity** also increases.

- Neutron beam

\[
n \rightarrow p + e^- + \bar{\nu}_e
\]

- $n + ^3\text{He} \rightarrow p + ^3\text{H}$

- $< 0.754 \text{ keV}$ or $< 782 \text{ keV}$

- $= 572 \text{ keV}$ $= 191 \text{ keV}$

- TPC detector made of PEEK

- TPC Gas: $^4\text{He}:\text{CO}_2:^3\text{He} = 85 \text{ kPa}:15 \text{ kPa}:100 \text{ mPa}$

- Time Projection Chamber (TPC)
## Measurement results

### Large uncertainty in correction

\[
\tau_n = \frac{1}{\rho \sigma v} \left( \frac{S_{\text{He}}}{S_{\beta}} \frac{\varepsilon_{\text{He}}}{\varepsilon_{\beta}} \right)
\]

- $\rho$ (3He density): $(2.08 \pm 0.01) \times 10^{19}$ #/m$^3$
- $\sigma v$ (3He cross section \times neutron velocity): $5333 \pm 7$ barn \times 2200 m/s
- $S_{\text{He}}$: $202993 \pm 480$ event
- $S_{\beta}$: $8868 \pm 151$ event
- $\varepsilon_{\text{He}}$: $100 - 0.014\%$
- $\varepsilon_{\beta}$: $94.5 \pm 1.0\%$

### Results of the previous experiment

\[
\tau_n = 896 \pm 10 \text{ (stat)} \pm 14/-10 \text{ (syst) sec}
\]

- Beam method: $888.0 \pm 2.0$ sec
- Storage method: $879.4 \pm 0.6$ sec

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Correction</th>
<th>Uncertainty</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$(2.08 \pm 0.01) \times 10^{19}$ #/m$^3$</td>
<td>0</td>
<td>0.5%</td>
<td>Can be improved by the method of introducing $^3$He gas</td>
</tr>
<tr>
<td>$\sigma v$</td>
<td>$5333 \pm 7$ barn \times 2200 m/s</td>
<td>0</td>
<td>0.13%</td>
<td>Alternate measurement required</td>
</tr>
<tr>
<td>$S_{\text{He}}$</td>
<td>$202993 \pm 480$ event</td>
<td>$2672 \pm 351$ event</td>
<td>0.3%</td>
<td>Statistical accuracy dominates</td>
</tr>
<tr>
<td>$S_{\beta}$</td>
<td>$8868 \pm 151$ event</td>
<td>$463 \pm 154$ event</td>
<td>2.6%</td>
<td>Background event contamination 5.2%</td>
</tr>
<tr>
<td>$\varepsilon_{\text{He}}$</td>
<td>$100 - 0.014%$</td>
<td>$0 + 0.014%$</td>
<td>0.014%</td>
<td>Enough accuracy</td>
</tr>
<tr>
<td>$\varepsilon_{\beta}$</td>
<td>$94.5 \pm 1.0%$</td>
<td>$+5.5 \pm 1.0%$</td>
<td>1.0%</td>
<td>Efficiency correction 5.5%</td>
</tr>
</tbody>
</table>
Background contamination

- Beta decay and background events get mixed up.
  - **β decay**: Radial distribution from beam axis
  - **Background**: Intrusion into beam axis
Solution using magnetic field

- Separating beta decay from background events
  - **β decay**: Focus on beam axis
  - **Background**: No intrusion into beam axis

![Diagram](image)

**Beta decay tracks at 600 mT**

- **β decay**

![Beta decay tracks graph](image)

**Neutron-induced background tracks at 600 mT**

- **Background**

![Background tracks graph](image)
Superconducting magnet

- Using a spare superconducting magnet from the BESS experiment
  - Solenoid coil 920 mT @580 A
  - Coil $\Phi 1000 \text{ mm} \times 1300 \text{ mm}$
  - Superconducting wire NbTi:Cu:Al
Detector Design

- **Using 3D CAD to design detectors**
  - Three-layer detector area
  - Select non-magnetic materials for components.
Integration test with superconducting magnet

- Transport of fabricated detectors to KEK
  - Integration test of superconducting magnet and detector was carried out.
    - Detectors and amplifiers can operate in magnetic fields?
    - Performance evaluation of detectors using cosmic rays and sources

- Detector calibration using X-rays from a $^{55}$Fe source
  - Sufficient gain and energy resolution at Anode HV +1.8 kV
    - No variation with or without magnetic field
Pseudo neutron beam measurement

- We want to place the beta source on the beam axis to simulate a neutron beam.
  - Intensity of checking source is too high and saturates the detector
  - Difficult to get permission to use in a magnetic or electric field
  - We decided to use the natural isotope $^{40}$K in KCl.

- KCl powder (6.2 g) is needed to make 100 Bq
  - Wrapped in Kapton sheet and placed in the center of the detector with a jig made with a 3D printer
Pseudo background event measurement

- The gamma source is placed next to the detector to simulate a background event.
  - **Without magnetic field**: Electrons generated on the wall enter the signal region.
  - **With magnetic field**: The electrons can't get to the signal field.

  $\Rightarrow$ **Background events suppressed to 2.9%**.
Estimation of measurement accuracy

- The measurement accuracy was estimated using Geant4 simulation.
- A magnet and a detector are placed to inject a neutron beam.
- Calibrate detector response with cosmic ray and source data

⇒ *Create the same waveform as the experimental data,*

and calculate the lifetime

*using the same analysis as the experimental data.*

\[ \tau_n(MC) = 887.0 \pm 3.3 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ sec} = 887.0 \pm 3.5 \text{ sec} \]
Estimation of accuracy

Decrease in indeterminacy as correction amount decreases

\[ T_n = \frac{1}{\rho \sigma v} \left( \frac{S_{\text{He}}}{S_{\beta}} \left/ \frac{\varepsilon_{\text{He}}}{\varepsilon_{\beta}} \right. \right) \]

- \( ^3\text{He} \) density \( \uparrow \)
- \( ^3\text{He} \) cross section \( \times \) neutron velocity

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<tr>
<td>( \rho )</td>
<td>(2.3927 ± 0.002) ( \times 10^{19} ) #/m(^3)</td>
<td>0</td>
<td>0.1% Can be improved by the method of introducing ( ^3\text{He} )</td>
</tr>
<tr>
<td>( \sigma v )</td>
<td>5333 ± 7 barn ( \times 2200 ) m/s</td>
<td>0</td>
<td>0.13% Alternate measurement required</td>
</tr>
<tr>
<td>( S_{\text{He}} )</td>
<td>1915609 ± 1384 event</td>
<td>9578 ± 575 event</td>
<td>0.3% Statistical accuracy dominates</td>
</tr>
<tr>
<td>( S_{\beta} )</td>
<td>76611 ± 276 event</td>
<td>163 ± 12 event</td>
<td>0.4% Correction 5.2%→0.21%</td>
</tr>
<tr>
<td>( \varepsilon_{\text{He}} )</td>
<td>100 - 0.01%</td>
<td>0 + 0.01%</td>
<td>0.01% Enough accuracy</td>
</tr>
<tr>
<td>( \varepsilon_{\beta} )</td>
<td>99.90 ± 0.01%</td>
<td>+0.10 ± 0.01%</td>
<td>0.01% Correction 5.5%→0.10%</td>
</tr>
</tbody>
</table>
Summary

- Discrepancies exist between the two neutron lifetime measurement methods, the beam method and the storage method.

- The previous experiment has large indefiniteness associated with the correction.
  ⇒ Proposed measures to reduce corrections and developed a new measurement system
  - Developed a detector and evaluated its performance in a magnetic field.

- Precise neutron lifetime measurement with reduced correction using this system