Neutron lifetime measurement with pulsed neutron beam at J-PARC

Takahito YAMADA (The University of Tokyo)
On behalf of the NOP collaboration
Outline

• Other experiments
• Principle of this experiment
  • In flight $\beta$-decay, $^3\text{He}(n,p)^3\text{H}$ reaction, Cal lifetime
• Neutron source
  • J-PARC, MLF, BL05, Spin Flip Chopper
• TPC
  • High efficiency
    • Define fiducial-volume, Detect low energy $\beta$-decay
  • Low background
    • PEEK, $^6\text{LiF}$ board, Pb&Fe shielding, Cosmic ray veto
• Background subtraction
  • Time-constant, gas scatter
• Other uncertainties
  • Number density of $3\text{He}$, Cross section of $^3\text{He}(n,p)^3\text{H}$, Temperature
• Schedule
• Summary
# Experiments for neutron lifetime

<table>
<thead>
<tr>
<th>Method</th>
<th>Beam</th>
<th>Penning trap</th>
<th>Gravitational trap</th>
<th>Magnetic trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron source</td>
<td>reactor</td>
<td>reactor</td>
<td>reactor</td>
<td>reactor</td>
</tr>
<tr>
<td>Energy</td>
<td>Cold neutron</td>
<td>Cold neutron</td>
<td>UCN</td>
<td>UCN</td>
</tr>
<tr>
<td>Detection particle</td>
<td>Electron</td>
<td>Proton</td>
<td>Neutron</td>
<td>Neutron</td>
</tr>
<tr>
<td>Challenge</td>
<td>high background</td>
<td>flux monitor</td>
<td>wall effect</td>
<td>depolarization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Result</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$878 \pm 27 \pm 14$</td>
<td>$886.6 \pm 1.2 \pm 3.2$</td>
<td>$878.5 \pm 0.7 \pm 0.3$</td>
<td>$878 \pm 1.9$</td>
</tr>
</tbody>
</table>

Neutron lifetime is measured by in-beam and storage methods. Our experiment is in-beam method. We are using pulsed neutrons from separation neutron source.

We are trying for $O(0.1\%)$ with beam method.
In flight $\beta$-decay

Neutron decays into electron, proton and neutrino.

$\beta$-decay is 3-body decay, so energy spectrum has a low energy tail.

99.9% of $\beta$-decay electrons have $>4$ keV energy.

$N_e = \frac{\varepsilon_e t \rho_n}{\tau_n}$

$\sim 10^{-6}$ decay in 1m for cold neutron (1100m/s)

Energy spectrum of electron
The difficulty of in-beam method is determination of the beam flux.

By adding a small amount of $^3$He, we can measure the neutron flux via the $^3$He(n,p)$^3$H reaction.

4mPa of $^3$He gives same event rate with beta decay.

Both of the event rates are proportional to $1/v$, so the velocity dependence is canceled by taking the ratio.
**Principle of our experiment**

Beta decay

\[ N_e = \frac{\varepsilon_e t \rho_n}{\tau_n} \]

10^{-6} decay in 1m

\[ N_p = \varepsilon_p t \rho_n \rho_{^{\text{3He}}} \sigma_{^{\text{3He}}} (v_0) \]

\[ \sigma_{^{\text{3He}}} (v_n) v_n = \sigma_{^{\text{3He}}} (v_0) v_0 \]

Reaction rate is proportional to 1/v

\[ \beta \text{ decay } \sim 3.6 \text{mPa} \text{ } ^{\text{3He}} \]

190 keV

572 keV

\[ v_0 = 2200 \text{ m/s} \]

\[ \sigma_{^{\text{3He}}} (v_0) : \text{Cross section of } ^{\text{3He}}(n,p)^{\text{3H}} \text{ at } 2200 \text{m/s} \]

Neutron Lifetime is given as

\[ \tau_n^{-1} = \frac{N_e / \varepsilon_e}{N_p / \varepsilon_p} \rho_{^{\text{3He}}} \sigma_{^{\text{3He}}} (v_0) v_0 \]

\[ N_e, N_p : \text{Electron and proton counts} \]

\[ \varepsilon_e, \varepsilon_p : \text{Detection efficiencies} \]

\[ \rho_{^{\text{3He}}}, v_0 : \text{Atom density of } ^{\text{3He}} \text{ and velocity} \]

\[ \sigma_{^{\text{3He}}} (v_0) : \text{Cross section of } ^{\text{3He}}(n,p)^{\text{3H}} \]

We use a TPC to detect the electron from the neutron decay and the proton from the \(^{\text{3He}}(n,p)^{\text{3H}}\) reaction, **simultaneously in a same detector**.

The ratio of counting rate of electron and proton gives the neutron lifetime.

Comparing with UCN experiment,

There are no systematic uncertainties due to wall interaction or depolarization.
Electrons by beta decay are measured by a gas detector of 1m length.

Neutrons are transported into the detector with a bunch length of 40 cm.

**Good efficiency:** All neutrons are inside of detector in a certain time region.

**Low background:** Background from windows, beam catcher, and chopper can be separated by TOF.
J-PARC at Tokai, Japan

Hadron Beam Facility

Materials and Life Science Experimental Facility

Nuclear Transmutation

MLF

500 m

Neutrino to Kamiokande

Linac (330m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA
### J-PARC Pulsed Neutron source

**BL05, Polarization beam branch**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>25Hz</td>
</tr>
<tr>
<td>Moderator</td>
<td>Coupled (20 K)</td>
</tr>
<tr>
<td>Beam size</td>
<td>10 cm x 4 cm</td>
</tr>
<tr>
<td>Flux</td>
<td>$8.6 \times 10^6$ s$^{-1}$ cm$^{-2}$ (1MW)</td>
</tr>
<tr>
<td>Polarization</td>
<td>96%</td>
</tr>
<tr>
<td>Energy</td>
<td>1 $\sim$ 20 meV</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.2 $\sim$ 1 nm</td>
</tr>
<tr>
<td>Velocity</td>
<td>500 $\sim$ 2000 m/s</td>
</tr>
</tbody>
</table>

→ Experimental apparatus is installed at 20 m distance

![Image of experimental apparatus](image-url)
Resonance flippers flip the neutron spin.
Magnetic supermirror reflects only non-flipped neutrons.

Guide field $B_y$ and oscillating field $B_z \sin(\omega t)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>50 mm</td>
</tr>
<tr>
<td>Length</td>
<td>40 mm</td>
</tr>
<tr>
<td>RF frequency</td>
<td>29 kHz</td>
</tr>
<tr>
<td>RF field $B_z$</td>
<td>0.3 mT</td>
</tr>
<tr>
<td>Guiding field $B_y$</td>
<td>1 mT</td>
</tr>
</tbody>
</table>

Depolarization makes the contrast worse.

Multilayer of Ferromagnetic and Paramagnetic materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromagnetic</td>
<td>Fe</td>
<td></td>
</tr>
<tr>
<td>Paramagnetic</td>
<td>SiGe$_3$</td>
<td></td>
</tr>
<tr>
<td>Magnetizing field</td>
<td></td>
<td>35 mT</td>
</tr>
<tr>
<td>Length</td>
<td>140 mm</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>35 mm</td>
<td></td>
</tr>
<tr>
<td>number of mirrors</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Critical angle</td>
<td>$m=5$</td>
<td></td>
</tr>
</tbody>
</table>

Neutron of 1300 m/s can reflect with 1.5°
**SFC performance**

*With 2 flipper and 3 mirror sets*

- Optimized to give good contrast

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam size</td>
<td>3 cm x 2 cm</td>
</tr>
<tr>
<td>Minimum bunch length</td>
<td>15 cm</td>
</tr>
<tr>
<td>Rising length</td>
<td>5 cm</td>
</tr>
<tr>
<td>Flux (flipper on)</td>
<td>$1.2 \times 10^6$ neutron/sec</td>
</tr>
<tr>
<td>Flux (flipper off)</td>
<td>$0.3 \times 10^4$ neutron/sec</td>
</tr>
<tr>
<td>Contrast</td>
<td>400</td>
</tr>
<tr>
<td>Flux with 5 bunches</td>
<td>$1.7 \times 10^5$ neutron/sec</td>
</tr>
<tr>
<td>Decay rate</td>
<td>0.1 decay/sec</td>
</tr>
<tr>
<td>Fiducial Time</td>
<td>2.8 ms / beam cycle</td>
</tr>
</tbody>
</table>

![Graph with time of flight and neutron counts](image)
### Time Projection Chamber

**Efficiency of cosmic ray is 97 %/wire**

- **Drift cage**
  - Inside of the drift cage was covered by 6LiF/PTFE neutron shield

- **MWPC**
  - Voltage of MWPC (12 mm pitch)

- **Beam catcher**
  - Drift direction
  - Beam Entrance

### Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode wire</td>
<td>29 of W-Au wires (+1780V)</td>
</tr>
<tr>
<td>Field wire</td>
<td>28 of Be-Cu (0V)</td>
</tr>
<tr>
<td>Cathode wire</td>
<td>120 of Be-Cu (0V)</td>
</tr>
<tr>
<td>Drift length</td>
<td>30 cm (-9000V)</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>He:CO2=85kPa:15kPa</td>
</tr>
<tr>
<td>TPC size(mm)</td>
<td>300,300,970</td>
</tr>
</tbody>
</table>
Low background TPC (inside)

**PEEK** (Poly-Ether-Ether-Ketone): used in gas detector for the first time

**Feature**: Chemically made from organic materials → small impurity

**Pros**:
- Easily machinable, weldable,
- 1m material can be made to accuracy of 100μm

**Cons**:
- Small elasticity, need pre-tension to set up wires

**Backgrounds caused by prompt γ rays from capture reactions of scattered neutrons by gas**

**6LiF board**: sintered 95% enriched **6LiF and PTFE**

(LiF : PTFE = 30wt% : 70wt%)

**All inner surface covered with 6LiF board**
- Relative permittivity is $\varepsilon = 3.0$
- Position of electrodes were optimized by simulation.
- Uniformity of the drift velocities was less than 1%

$^{6}$Li + neutron $\rightarrow \alpha + ^3$H

Absorption length is 500μm
Low background TPC (outside)

- **Lead shielding and Cosmic ray Veto**

![Lead shielding image]

- **Event Selection**
  - Energy cut: Energy deposit over 1.4keV
  - Fiducial cut: Hit on Beam region

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No shielding or veto</td>
<td>123.7</td>
<td>100.1</td>
<td>30.7</td>
</tr>
<tr>
<td>+With Lead</td>
<td>58.4</td>
<td>44.2</td>
<td>13.9</td>
</tr>
<tr>
<td>+With Veto</td>
<td>7.7</td>
<td>4.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

- **Environmental radiation**: 0.8 cps
- **Cosmic ray**: 0.5 cps
- **Radioactives in TPC**: 0.1 cps

*S/N achieved to 0.9*
Background subtraction
Time-constant /outside of TPC

- **Time constant background can be subtracted by TOF**
  - Environmental background
  - Cosmic rays
  - Radiation inside/outside of TPC
- **Open/Closed of $^6\text{Li}$ shutter**
  - Prompt-$\gamma$ from outside of TPC

Only remaining background is from TPC gas
Background subtraction

**Scattered neutron by TPC gas**

Scattered neutron are

1) captured by TPC gas $\rightarrow$ prompt-$\gamma$
2) Scattered by gas $\rightarrow$ captured by $^6$Li board $\rightarrow$ prompt-$\gamma$
3) Scattered by gas $\rightarrow$ decay on off-axis

*These BGs are proportional to the TPC gas pressure*

Measurements with different gas pressure can evaluate the BGs

We can subtract all BGs by data-driven method.

**BG rate**

$\sim 1\%$ of beta decay

1) Captured by gas $\rightarrow$ prompt-$\gamma$

2) Scattered by gas $\rightarrow$ captured by $^6$Li $\rightarrow$ prompt-$\gamma$
• Define \(^3\text{He}(n,p)^3\text{H}\) reaction as a High energy event at low gain spectrum for primitive event selection.

• Compare between turning beam on/off by Front Shutter’s Open/Close, to extract neutron signal.
Time of Flight (Experiment)

- Plot of background estimate which compares beam on/off.
  
  Red : beam on  
  Blue : beam off  
  Black : Red – Blue

- The subtraction seems working for $\beta$–decay candidates, but not $^3$He events.
Time of Flight (Experiment)

- The reaction points on z-axis of TPC and ToF for $^3\text{He}(n,p)^3\text{H}$ reaction.
- Reaction points move to downstream as time. The slope corresponds to neutron velocity. Later bunches are slower.
- Velocities can be determined with $O(1\%)$ uncertainty by the slopes. This results are consistent with Flipper timing.
The decay rate is $0.1 \text{cps}$ for beam power of 220 kW. S/N of 0.9 achieved in present condition.

- **J–PARC beam power**
  - will be $400 \text{ kW (about twice)}$ at 2014

- **Spin flip chopper**
  - The intensity is limited by mirror size.
  - Present beam size is $3 \times 2 \text{ cm}$.
  - Large mirrors make the beam size to $10 \times 4 \text{ cm}$.
  - Beam Intensity will be $16 \text{ times}$

Beam intensity will be 32 times at 2014. Statistical error is estimated to achieve 0.1 % in 150 days.
Uncertainties

\[ \tau_n^{-1} = \frac{N_e / \varepsilon_e}{N_p / \varepsilon_p} \rho_{3\text{He}} \sigma_{np} \left( v_0 \right) v_0 \]

- Statistical uncertainty: \( \sim 0.1\% \) by measurement of 150 days.
- Determination of \( N_e \) and \( N_p \): \( \varepsilon_e > 99.9\%(4\text{keV}), \varepsilon_p = 100\% \)

Background of

- \( \sim 1\% \) of simultaneous background
- \( \sim 35\% \) of time dependent background (Comparing \( \beta \) events)
- \( \sim 110\% \) of time independent background

Should be subtracted correctly.

- **Density of \( ^3\text{He} \) atoms**
- **\( ^3\text{He}(n,p)^3\text{H} \) cross section**
Number density of $^3$He atoms

TPC gas is prepared by mixing natural He and $^3$He($>99.9\%$)
We determine

1) Absolute pressure of mixed He $\sim 80$ kPa
2) $^3$He/$^4$He for abundance of $10^{-6}$ with accuracy of $10^{-3}$

- Pressure can be measured to $10^{-4}$ precision at $100$ kPa with a piezo-drive transducer.
- Partial pressure of $^3$He dopant is controlled by a baratron gauge and volume expansion method. It provide $\Delta P(^3$He)/$P \sim 0.2\%$.
- Temperature can be measured with $\Delta T \sim 0.1$ K.
- Natural He contents $^3$He of $\sim 0.1$ ppm. It will be determined by a mass spectroscopy. Present limit is $1\%$.

Present uncertainty of $^3$He density is $\sim 0.2\%$
Cross section of $^3$He($n,p)^3$H

Transmission of $^3$He was measured.

Present $\sigma_{np}$ is $5333 \pm 7$ barn (0.13%)

More precise measurement can be done at J-PARC (e.g. 100m beamline).
Uncertainties

\[ \tau_n^{-1} = \frac{N_e / \varepsilon_e}{N_p / \varepsilon_p} \rho_{\text{He}} \sigma_{np} (v_0) v_0 \]

- Statistical uncertainty: \( \sim 0.1\% \) by measurement of 150 days.

- Determination of \( N_e \) and \( N_p \): \( \varepsilon_\beta > 99.9\% (4\text{keV}), \varepsilon_p = 100\% \)

  Background of

  \( \sim 1\% \) of simultaneous background

  \( \sim 35\% \) of time dependent background

  \( \sim 110\% \) of time independent background

  Should be subtracted correctly.

- Density of 3He atoms \( \rightarrow \sim 0.2\% \)

- 3He(n,p)3H cross section \( \rightarrow 0.13\% \).
### Timeline of this experiment

<table>
<thead>
<tr>
<th>Year</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>3 4 5 6 7 8 9 10 11 12</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>J-PARC Beam operation</td>
<td><strong>200kW</strong></td>
<td><strong>300kW</strong></td>
<td><strong>400kW</strong></td>
</tr>
<tr>
<td>Measurements</td>
<td><strong>Commissioning</strong></td>
<td><strong>Systematic study</strong></td>
<td><strong>Physics run</strong></td>
</tr>
<tr>
<td>SFC</td>
<td></td>
<td><strong>Increasing size of SFC (16 times)</strong></td>
<td></td>
</tr>
<tr>
<td>TPC</td>
<td></td>
<td></td>
<td><strong>Increasing size of aperture of TPC</strong></td>
</tr>
</tbody>
</table>
Summary

• We aim to measure the neutron lifetime to O(0.1%)

• Features of our experiment are
  – We use pulsed neutron from J-PARC (BL05).
  – Neutron bunches by Spin Flip choppers.
  – Electrons are detected by TPC.
  – Neutron flux is measured by $^3$He(n,p)$^3$H

• The physics run will start from the next year.