Neutron Lifetime From Beam Experiments

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Outline of Presentation

• A brief introduction to the neutron lifetime
• Status of current beam measurements
  • J-PARC measurement
  • BL2 at NIST
• Future beam measurements
  • BL3 at NIST
• Conclusions
**$V_{ud}$ and the CKM Matrix**

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1\]

Measurements of $\tau_n$ and $\beta$-decay angular correlation coefficients yield $|V_{ud}|$:

\[|V_{ud}|^2 = \frac{4908.7(1.9) \text{ sec}}{\tau_n(1 + 3g_A^2)} \]

\[g_A \equiv \frac{G_A}{G_V}\]

Measurements of $ft$ values for superallowed $0^+ \rightarrow 0^+$ $\beta$-decay also yield $|V_{ud}|$:

\[|V_{ud}|^2 = \frac{2984.48(5) \text{ sec}}{ft(1 + RC)}\]
How to Measure $\tau_n$ ... $N(t) = N_0 e^{-t/\tau_n}$

Direct Observation of Exponential Decay: Observe the decay rate of $N_0$ neutrons and the slope of

$$\ln \left( \frac{\partial N(t)}{\partial t} \right) \text{ is } -1/\tau_n$$

“Bottle” Experiments:
Form two identical ensembles of neutrons and then count how many are left after different times.

$$\frac{N(t_1)}{N(t_2)} = e^{-(t_1-t_2)/\tau_n}$$

Beam Experiments: Decay rates within a fiducial volume are measured for a beam of well known fluence.

$$\frac{\partial N(t)}{\partial t} = - \frac{N}{\tau_n}$$
The State of the Neutron Lifetime

Beam Average
\[ \tau_n = 888.0 \pm 2.1 \, \text{s} \]

Storage Average
\[ \tau_n = 879.6 \pm 0.8 \, \text{s} \]

Note: This average contains result from Yue et al Phys. Rev. Lett. 111, 222501 (2013)
The Present
Precise measurement of neutron lifetime with pulsed neutron beam at J-PARC

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Univ. of Tokyo¹, Nagoya Univ.², KEK³, ICR, Kyoto Univ.⁴, KMI, Nagoya Univ.⁵, Kyoto Univ.⁶, CERN⁷, RCAPP, Kyushu Univ.⁸, RIKEN⁹, RCNP, Osaka Univ.¹⁰, Kyushu Univ.¹¹, GCRC, Univ. of Tokyo¹², ICEPP, Univ. of Tokyo¹³
Principle of our experiment

Cold neutrons are injected into a TPC. The neutron $\beta$-decay and the $^3$He(n,p)$^3$H reaction are measured simultaneously.

Principle (Kossakowski, 1989)

The neutron bunch is shorter than TPC.

Count events during time of bunch in the TPC

$\tau_n = \frac{1}{\rho \sigma_0 v_0} \left( \frac{S_n / \epsilon_n}{S_\beta / \epsilon_\beta} \right)$

$\beta$-decay

$S_\beta = \epsilon_e N \frac{L}{\tau_n v}$

$^3$He(n,p)$^3$H

$S_n = \epsilon_n N \rho \sigma L$

$\sigma v = \sigma_0 v_0$  $\sigma_0=$cross section@$v_0$, $v_0=2200$[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

Our goal is measurement with 1 sec uncertainty.
Setup

Set up of our experiment in “NOP” beam line.

20 cm Iron shield
Spin Flip Chopper
In a Lead Sheald

TPC in
a Vacuum chamber

Gas line
DAQ

Inside of
Lead shielding

Inside of
Cosmic ray Veto

TPC in the
vacuum chamber
Increasing size the Spin Flip Chopper is planned at 2014/2015. Intensity will be 18 times by a designed value. We will start physics run to 1sec at 2016/2017.
The NIST Beam Lifetime Experiment II (BL2)

\[ \tau_n = \frac{G_F^2}{G_V^2 + 3G_A^2} \times 4908.7(1.9) s \]

\[ n = |ddu\rangle \]

\[ p = |duu\rangle \]

\[ e^- \]

\[ W^- \]

\[ \bar{\nu}_e \]
The NIST beam lifetime experiment

\[ \tau_n = -\frac{\bar{N}_n}{\dot{N}_n} \]

- Proton trap electrostatically traps decay protons and directs them to detector via B field
- Neutron monitor measures incident neutron rate by counting \( n + ^6\text{Li} \) reaction products \((\alpha + t)\)

- Precision aperture
- Neutron beam
- Neutron monitor
- \( ^6\text{LiF} \) deposit
- \( \alpha, t \) detector
- Proton trap
- Decay product counting volume
- \( +800 \text{ V} \)

- Beam fluence measurement
- Proton trap electrostatically traps decay protons and directs them to detector via B field
- Neutron monitor measures incident neutron rate by counting \( n + ^6\text{Li} \) reaction products \((\alpha + t)\)
Determining $\tau_n$

$$\tau_n = \dot{N}_{\alpha + t} \left( \frac{L}{\dot{N}_p} \right) \frac{\epsilon_p}{\epsilon_0 \nu_0}$$

$\frac{L}{\dot{N}_p}$ Proton rate measured as function of trap length

$\epsilon_p$ Proton detection efficiency

$\dot{N}_{\alpha + t}$ $n + ^6\text{Li}$ reaction product counting

$\epsilon_0$ Neutron flux monitor efficiency for $\nu_0$
TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

<table>
<thead>
<tr>
<th>Source of correction</th>
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<th>Uncertainty (s)</th>
<th>Section</th>
</tr>
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<tbody>
<tr>
<td>$^6\text{LiF}$ deposit areal density</td>
<td>2.2</td>
<td></td>
<td>IV A</td>
</tr>
<tr>
<td>$^6\text{Li}$ cross section</td>
<td>1.2</td>
<td></td>
<td>II D</td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
<td>II D 1</td>
</tr>
<tr>
<td>Absorption of neutrons by $^6\text{Li}$</td>
<td>+5.2</td>
<td>0.8</td>
<td>IV A 2</td>
</tr>
<tr>
<td>Neutron beam profile and detector solid angle</td>
<td>+1.3</td>
<td>0.1</td>
<td>IV A 2</td>
</tr>
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<td>Neutron beam profile and $^6\text{Li}$ deposit shape</td>
<td>−1.7</td>
<td>0.1</td>
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</tr>
<tr>
<td>Neutron beam halo</td>
<td>−1.0</td>
<td>1.0</td>
<td>IV B 2</td>
</tr>
<tr>
<td>Absorption of neutrons by Si substrate</td>
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<td>−0.2</td>
<td>0.5</td>
<td>IV A 3</td>
</tr>
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<td>Trap nonlinearity</td>
<td>−5.3</td>
<td>0.8</td>
<td>IV C</td>
</tr>
<tr>
<td>Proton backscatter calculation</td>
<td>0.4</td>
<td></td>
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<td>Neutron counting dead time</td>
<td>+0.1</td>
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**Most significant improvement**

**Other major improvements**

Using AG to calibrate the neutron monitor

\[ \epsilon_0 = \frac{r_{\alpha,t}}{R_n} \frac{\lambda_0}{\lambda_{\text{mono}}} \]

Neutron monitor

HPGe detector

Totally absorbing \( ^{10}\text{B} \) target foil

PIPS detector with aperture

Alpha-Gamma device

Monochromatic neutron beam

HPGe detector
Neutron monitor efficiency uncertainty budget

<table>
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<tr>
<th>Source of uncertainty</th>
<th>Fractional uncertainty</th>
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<tr>
<td>$\alpha$-source calibration of AG $\alpha$-detector</td>
<td>$2.7 \times 10^{-4}$</td>
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<tr>
<td>$\gamma$ attenuation in $\text{B}_4\text{C}$ target</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Neutron beam wavelength</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\gamma$ attenuation in thin $^{10}\text{B}$ target</td>
<td>$1.3 \times 10^{-4}$</td>
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<td>$\lambda/2$ contamination of the beam</td>
<td>$1.0 \times 10^{-4}$</td>
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<tr>
<td>Neutron backscatter in FM substrate</td>
<td>$3.9 \times 10^{-5}$</td>
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<td>Correction to AG $\alpha$-detector efficiency for beam spot</td>
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<td>$6.0 \times 10^{-6}$</td>
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<td>Correction to FM solid angle for beam spot</td>
<td>$4.5 \times 10^{-6}$</td>
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<td>$\gamma$ production in thin $^{10}\text{B}$ target Si substrate</td>
<td>$3.2 \times 10^{-6}$</td>
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<td>FM misalignment w.r.t. beam</td>
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<td><strong>Total</strong></td>
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Most significant improvement

Other major improvements

$\delta \tau_n \approx 1.0$ s

$0.5 s$

$0.1 s$

$0.2 s$

$0.6 s$
ILL PF1b @ 53 MW

- brightness
- capture flux
- capture flux * operating days

* all guide areas are 120 cm² except NG6 (36 cm²)  

NIST NG-C

NIST NG6

SNS FNPB @ 1.2 MW
The Future
BL3
Beam Lifetime 3
The next generation beam neutron lifetime experiment

Two main goals:
1) Cross check, explore, verify all systematic effects in the beam method to the 0.1 s level
2) Reduce the beam neutron lifetime uncertainty to < 0.2 s.
BL3 key features:
- Based on previous Sussex-ILL-NIST apparatus; >30 years experience in this program.
- Larger beam, trap, 2m long magnet: 200x increase in proton trapping rate.
- 10 cm active diameter segmented Si detector (Nab, UCNB).
- $\Delta B/B < 0.001$ in proton trap region: reduces trap end effects.
- Variable field expansion at proton detector: eliminates backscatter extrapolation.
- Dedicated neutron spectral measurement: reduces Li6 self absorption uncertainty.
- Multiple independent absolute neutron flux calibrations.
Nab Si detectors

- 15 cm diameter
- Full thickness: 2 mm
- Dead layer ≤ 100 nm
- 127 pixels
A $^3$He gas scintillation absolute neutron counter
(Tulane, NIST)

Design features:
- absolute neutron counting to 99.95%
- >50 kHz pulse counting rate
- >30 photoelectrons/neutron capture
- $^3$He gas scintillates in XUV (70-90 nm)
- XUV downshifted to visible by TPB
- 1-10 torr $N_2$ quenches long-lived triplet dimers

construction / testing now in progress
Conclusions

• Moving forward the goal is a reliable measurement of the neutron lifetime at the 0.1—0.2 s level

• It is likely that there will be two efforts in the US during the coming decade
  • BL3: a beam experiment designed to achieve an uncertainty of < 0.2 s.
  • UCNtau: a magnetic bottle experiment

• Both experiments will be seeking funding in the next 1—2 years