Measurement of the Neutron Lifetime with Magnetically Levitated Ultracold Neutrons

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Neutron Lifetime

- Tests for BSM physics
  - CKM unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
  - $\delta \tau_n = 0.4 \text{ s}$ would match the present (conservative) uncertainty of radiative corrections (w/anticipated improvements to $\lambda$ measurements).

- Input to models of BBN
  - $^4\text{He}$ abundance prediction
  - Need $\delta \tau_n \approx 1 \text{ s}$ or better.

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

Marciano and Sirlin, PRL 96 (2006), 032002.

Neutron Decay Master Relation

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

Figure from Brown et al. [UCNA collab.], PRC 97, 035505 (2018)
Two* techniques are used to measure $\tau_n$

*Plus VCN storage ring by Paul et al.

Cold Neutron Beam

Thin neutron detector

Neutron decay product counter (for $p$, $e^-$, or both)

$N_{\text{decay}} = N_{\text{beam}} \frac{\Delta t}{\tau_n}$

Traversal time $\Delta t = L / v_n$

Ultracold Neutron (UCN) Bottle

Fill Store Count

Could also detect decay products...

Number Observed

Time
Ultracold Neutron Properties

Ultracold Neutrons (UCN) are neutrons with energies on the order of 100 neV:
- Material reflections for any angle of incidence
- Energy comparable to $n$ gravitational potential
- Classical motion is that of a projectile
- Energy comparable to $n$ potential energy in 1 T
- Polarized and trapped via Stern-Gerlach

UCN behave like a gas: “Think Density”

Magnetic Interaction

Gravitational Interaction

\[
U = - \left[ - |\gamma_n| \vec{S} \right] \cdot \vec{B} \sim \pm 60 \ \text{neV/T}
\]

\[
U/h = mg \sim 100 \ \text{neV/m}
\]

Nuclear Interaction

\[
U_F(\vec{r}) = \frac{2\pi \hbar^2 a}{\mu} \delta^{(3)}(\vec{r})
\]

Materials:
- Be: 252
- SS: 180
- Cu: 168
- Al: 54

Be
SS
Cu
Al

A. Holley
UCN sources around the world

- TRIUMF (Canada)
  - LHe, spallation
- NCSU (USA)
  - SD2, reactor
- LANL* (USA)
  - SD2, spallation
- ILL* (France)
  - Turbine, reactor
  - LHe, reactor
- PSI (Switzerland)
  - SD2, spallation
- Mainz* (Germany)
  - SD2, reactor
- TUM (Germany)
  - SD2, reactor
- PNPI (Russia)
  - LHe, reactor
- J-Parc (Japan)
  - SD2, spallation
- RCNP (Japan)
  - LHe, spallation (moved to TRIUMF)

Operating sources (*Multi-experiment facilities)
Sources under construction
Ultracold Neutron Bottle to Measure $\tau_n$

Video: Pouring UCN from a stainless steel bottle into a 3He counter, [https://youtu.be/JtN1whSiMSA](https://youtu.be/JtN1whSiMSA)
UCN Storage in Material Bottles

\[ N(\Delta t) = N_0 e^{-\Delta t/\tau_s} \]

\[ \tau_s^{-1} = \tau_{\beta}^{-1} + \tau_{w}^{-1} + \tau_{O}^{-1} \]

Nomenclature (for this talk):
“Storage time” \( \equiv \tau_s \)
“Holding time” \( \equiv \Delta t \)

Wall interaction loss contribution for process \( i \):
\[ \tau_i^{-1} = \gamma(v)\mu_i(v) \text{, where } \gamma = \text{wall collision rate.} \]
Vary $\gamma(v)$ to enable extrapolation to $\tau_{w}^{-1} = 0$

$$\tau_{s}^{-1}(v) = \tau_{\beta}^{-1} + \tau_{w}^{-1}(v) = \tau_{\beta}^{-1} + \mu(v)v/\lambda$$

- Energy spectrum evolves over storage time
- Different approaches have been used to vary wall collision rate, typically by changing bottle surface-to-volume ratio

**Diagram**

- "MAMBO 1"
- Neutron valves
- UCN detectors to detect wall upscattering
- Fomblin pump
- Vacuum vessel
- Kurchatov group experiment
- UCN guide for filling bottle and emptying into UCN detector
Mambo I

- Fomblin-coated bottle of variable size
- Corrections applied to original result for energy spectral evolution did not include surface waves in liquid-Fomblin coating
- Steyerl et al. calculated this effect for Mambo 1 (extended previous calculations by others):

  Steyerl et al., PRC 85, 065503 (2012)

- The effect becomes important for UCN energies near the Fomblin Fermi potential

\[
\frac{\tilde{\mu}(k)}{\tilde{\mu}(k_0)}
\]

- 887.6 ± 3 s (1989)
- 882.5 ± 2.1 s (2012)
Gravitrap I

Serebrov et al., PHYSICAL REVIEW C 78, 035505 (2008)
Gravitrap I

Serebrov et al., PHYSICAL REVIEW C 78, 035505 (2008)

![Diagram of Gravitrap I]

**FIG. 12.** Result of extrapolation to the neutron lifetime when combined energy and size extrapolations are used. The open circles represent the results of measurements for a quasispherical trap, and the full circles the results of measurements for a cylindrical trap.
Gravitrap II

Fig.1. Gravitational spectrometer with service platforms

Content from A. Serebrov, PPNS2018
Gravitrap II
\[ \tau_n = 881.5 \pm 0.7 \pm 0.6 \text{ s} \]

Gravitrap I
\[ \tau_n = 878.5 \pm 0.7 \pm 0.3 \text{ s} \]
UCNτ Overview

- UCN trap with very low intrinsic losses
  - Magneto-gravitational trap
  - Superposed holding field to eliminate B-field zeros (no depolarization losses)
  - Fast removal of quasi-bound UCNs possible through trap asymmetry and field ripple

- High statistics are achievable
  - Large volume
  - In situ UCN detector
  - High overall efficiency
  - Also: Less sensitive to phase-space evolution than draining

Based on original concept: P.L. Walstrom, J.D. Bowman, S.I. Penttila, C. Morris, A. Saunders, NIMA 599 (2009) 82-92
LANL UCN Source at LANSCE

Flapper valve

2L SD2 volume (5K) - 58Ni coated guide

Cooled Poly Moderator

He-cooled W spallation target

Graphite

Be

T. M. Ito et al., Phys. Rev. C 97, 012501(R) – 29 January 2018
LANL UCN Facility

- UCN source
- New nEDM experiment
- UCNA/B experiment
- UCNτ experiment
Halbach Array + Holding Field

\[ |\mathbf{B}| = B_{\text{rem}} (1 - e^{-kd}) e^{-k\zeta} \]

(if continuous rotation of M)

Holding field eliminates field zeros
Reflection of UCNs by the UCN$\tau$ Magnetic Field

**UCN$\tau$ Example:**
- $\mu \cdot B$ for neutron $\approx 60$ neV/Tesla
- Gravitational potential $\approx 100$ neV/m
- 50 cm drop (from rest) $\rightarrow$ closest approach to surface about 2 mm
Removal of Quasi-bound UCNs

- Trap asymmetry + field ripple from the array induces phase-space mixing.

- An absorber placed near the top of the trap quickly removes the superbarrier UCNs.

Simulation of trap cleaning

\[ h_{\text{clean}} = 44 \text{ cm} \]

\[ h_{\text{clean}} = 42 \text{ cm} \]

[Walstrom et al., NIMA 599 (2009) 82-92.]
View of the Halbach Array and Lowered UCN Detector
The *in-situ* Neutron Detector

- Vacuum compatible: low outgassing
- Realtime neutron counting (scintillation light)
- (Relatively) fast neutron counting: detection time is 8-10 s
- High neutron efficiency: each trapped neutron has multiple interactions until absorbed.

\[
n + ^{10}\text{B} \rightarrow ^7\text{Li} + \alpha
\]
Measurement Cycle

1. Load the trap
2. Close the trap door
3. Remove quasi-bound UCNs (lower absorber, wait, raise absorber)
4. Hold UCNs in the trap for time $t$
5. Count the surviving UCN population $N$

Using two different cycles with holding times $t_1$ and $t_2$,

$$\tau_n = -(t_2 - t_1)/\log\left(\frac{N_2}{N_1}\right)$$
Flux Monitoring

All monitors is $^{10}$B/Zns scintillators *
- No 3He
- Use ratio of the Mon to SP to correct for spectral effects
Multi-step UCN detection

Example with an insufficiently-cleaned UCN population

(Before we installed the “Giant Cleaner”)

![Graph showing multi-step UCN detection process](image)

- Count Total Uncleaned UCN
- Subtract From Total Population

Position 1
Position 2
Position 3
Position 4
Trap cleaned to $10^{-4}$

Dagger lowered in successive steps

Dagger lowered in one step
Global fit into a single exponential function

After unblinding: $877.7 \pm 0.7$ (stat) $+0.4/-0.2$ (sys) s

*Science* 06 May 2018, DOI: 10.1126/science.aan8895
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Effect</th>
<th>Upper bound (s)</th>
<th>Direction</th>
<th>Method of evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depolarization</td>
<td>0.07</td>
<td>+</td>
<td>Varied external holding field</td>
</tr>
<tr>
<td>Microphonic heating</td>
<td>0.24</td>
<td>+</td>
<td>Detector for heated neutrons</td>
</tr>
<tr>
<td>Insufficient cleaning</td>
<td>0.07</td>
<td>+</td>
<td>Detector for uncleaned neutrons</td>
</tr>
<tr>
<td>Dead time/pileup</td>
<td>0.04</td>
<td>±</td>
<td>Known hardware dead time</td>
</tr>
<tr>
<td>Phase space evolution</td>
<td>0.10</td>
<td>±</td>
<td>Measured neutron arrival time</td>
</tr>
<tr>
<td>Residual gas interactions</td>
<td>0.03</td>
<td>±</td>
<td>Measured gas cross sections and pressure</td>
</tr>
<tr>
<td>Background variations</td>
<td>&lt;0.01</td>
<td>±</td>
<td>Measured background as function of detector position</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.28</strong></td>
<td></td>
<td>(uncorrelated sum)</td>
</tr>
</tbody>
</table>

### Heating
- Limit established by long holding time excess

### Insufficient Cleaning
- Limit established by short holding time excess

![Diagram](https://via.placeholder.com/150)

**Fit curve from Steyerl et al. 2016**
The 2017-18 data is under analysis

2017-2018 Beam Cycle:

\[ \sigma_T \approx \pm 0.3 \text{ s (stat)} \pm 0.12 \text{ s (sys)} \]

Goal: unblind by end of 2019 for new physics result with overall uncertainty < 0.5 s.

Several refinements are in progress to the apparatus. Ultimate goal: \( \sim 0.2 \) s.
The UCN\(\tau\) experiment uses only a small fraction of the UCNs produced by the LANSCE source.

Simulations suggest that a bigger, deeper (necessarily superconducting) trap could use 10x as many neutrons per run, allowing 3x the sensitivity in this statistics-limited technique. Goal is \(\delta \tau = 0.06\) s at a price of \(~$1e7\).
World data on $\tau_n$

- **Beam average**
  - $888.0 \pm 2.0 \text{ s}$
  - $\chi^2/1 = 0.08$

- **Bottle average**
  - $879.2 \pm 0.6 \text{ s}$
  - $\chi^2/8 = 2.49$
Interpretation of $\tau_n$ Measurements: Recent change in a radiative correction term

PRL 121, 241804 (2018)

Reduced Hadronic Uncertainty in the Determination of $V_{ud}$

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$$|V_{ud}|^2 = \frac{2984.432(3)}{\mathcal{F} t (1 + \Delta^V_R)}$$

$$\Delta^V_R = 0.02361(38)$$


$$\Delta^V_R = 0.02467(22)$$

Seng et al., PRL 121, 241804 (2018)
New Experimental Result for $\lambda = g_A/g_V$


Measurement of the weak axial-vector coupling constant in the decay of free neutrons using a pulsed cold neutron beam


Accepted 10 May 2019

ABSTRACT

We present a precision measurement of the axial-vector coupling constant $g_A$ in the decay of polarized free neutrons. For the first time, a pulsed cold neutron beam was used for this purpose. By this method, leading sources of systematic uncertainty are suppressed. From the electron spectra we obtain $\lambda = g_A/g_V = -1.27641(45)_{stat}(33)_{sys}$ which confirms recent measurements with improved precision. This corresponds to a value of the parity violating beta asymmetry parameter of $A_0 = -0.11985(17)_{stat}(12)_{sys}$. We discuss implications on the CKM matrix element $V_{ud}$ and derive a limit on left-handed tensor interaction.
Updated Experimental Results

- Seng et al. radiative correction calculation for neutron beta decay
- New PERKEO III result for $\lambda$ included in $\lambda_{\text{Post2002}}$

2019: no longer includes beam measurements. Expands error bar by x1.6 due to tension in UCN results.
Updated Experimental Results

- Seng et al. radiative correction calculation for neutron beta decay
- New PERKEO III result for $\lambda$ included in $\lambda_{\text{Post2002}}$
Is the neutron $\beta$-decay branching ratio $<100\%$?

Dark Matter Interpretation of the Neutron Decay Anomaly

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There is a long-standing discrepancy between the neutron lifetime measured in beam and bottle experiments. We propose to explain this anomaly by a dark decay channel for the neutron, involving one or more dark sector particles in the final state. If any of these particles are stable, they can be the dark matter. We construct representative particle physics models consistent with all experimental constraints.

DOI: 10.1103/PhysRevLett.120.191801
Decay into dark matter with associated $\gamma$ or $e^+/e^-$

Sun, X et al., “Search for dark matter decay of the free neutron from the UCNA experiment: $n \rightarrow \chi + e^+e^-$,” PHYSICAL REVIEW C 97, 052501(R) (2018).

Tang, ZT et al., “Search for the Neutron Decay $n \rightarrow X + \gamma$ where $X$ is a dark matter particle,” PRL 121, 022505 (2018).

A buffer volume installed (2018) to smooth out the pulse response for more stable normalization.
Ultra-Cold Neutron Experiment for Proton Branching Ratio in Neutron Beta Decay (UCNProBe)

New idea to check the Beam vs. Bottle discrepancy

• Requires absolute measurements similar to the beam experiment:
  • Number of neutrons in the trap
  • Number of decay products
  • Needs precision <<1% for each quantity
• Now in early R&D stage to determine feasibility
Summary

• Magneto-gravitational traps avoid the wall-interaction uncertainties of material bottles.
• However, new loss mechanisms could be introduced: depolarization and quasi-trapped orbits.
• The UCN$_\tau$ design addresses these losses, greatly suppressing them (and monitoring for them).
• We anticipate improving our n lifetime measurement a factor of 2-3 soon.
• Superallowed beta decay and new RCs do not agree with first-row CKM unitarity.
• The beam vs. bottle puzzle persists. New experiments are needed.
UCNτ Collaboration

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