Neutron Lifetime Measurements: Much Ado About 1 second

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The History of Neutron Lifetime: PDG compilation

PDG average

Experiments

Solid circle: beam
Open square: bottle

PDG 2004-2010: 885.7 ± 0.8 s
PDG 2011: 881.0 ± 1.5 s
PDG 2013: 880.0 ± 0.9 s
PDG 2014: 880.3 ± 1.1 s
Discrepancy: Beam vs Bottle

\[ \tau_n(\text{beam}) = 888.0 \pm 2.0 \text{ s} \]

\[ \tau_n(\text{bottle}) = 879.78 \pm 0.56 \text{ s} \]

The discrepancy between beam and bottle experiments is about 4 standard deviations.

courtesy: Scott Dewey
Outline

• How do we use neutrons to test the Standard Model of particle physics?

• How to measure the neutron lifetime?
  – The beam method: NIST BL experiments.
  – The bottle method (material, magnetic): the UCNtau experiment at LANL

• Broader Impact
  – Big-Bang Nucleosynthesis
If the electrons were to feel the strong force, there would be no chemistry or crystallography or biology -- only nuclear physics.  

S. Weinberg

\[ n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV} \]
**$V_{ud}$ for CKM Unitarity Test**

$f$: Phase space factor $= 1.6886$

(Fermi function, nuclear mass, size, recoil)

$$\frac{1}{\tau_n} = f G_F^2 |V_{ud}|^2 m_e^5 (1 + 3 g_A^2)(1 + RC)/2\pi^3$$

From $\mu$-decay: 0.6 ppm (MuLan 2011)

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9s}{\tau_n (g_V + 3 g_A^2)}$$


To be comparable to the theoretical uncertainty: $4 \times 10^{-4}$, requires experimental uncertainty: $\Delta A/A = 4\Delta \lambda/\lambda < 2 \times 10^{-3}$ and $\Delta \tau/\tau = 4 \times 10^{-4}$. 
$V_{ud}$

$V_{ud} : \tau_n \& G_A/G_V$

$0^+ \rightarrow 0^+$ nuclear decays:

$V_{ud} = 0.97425(8)_{\exp(10)}^{nucl(18)}_{RC}$

Neutron:

$\tau_n = 880.0(0.9) \text{ s}$

$g_A = 1.2701(25)$

$\rightarrow V_{ud} = 0.9774(5)_{\tau_n(16)}^{g_A(2)}_{RC}$

This is $2 \sigma$ discrepancy between the neutron and super-allowed decays.

To bring these two into agreement, we need

- Shift $g_A = 1.275$
- Or a longer $\tau_n = 886 \text{ s}$
The Two Pillars: Beam and Bottle Experiments

NIST beam experiment: $\tau_n = (887.7 \pm 1.2 \pm 1.9) \, s$

- Counts protons from beta-decays in flight
- Absolute neutron flux must be measured very accurately

Gravitrap: $\tau_n = (878.5 \pm 0.7 \pm 0.3) \, s$

- Material trap w/frozen Fomblin coating gives a long storage time.
- Some dependence on Monte Carlo to extrapolate to zero-wall-loss storage time.
The Beam Method

\[ R_p = \varepsilon_p \frac{A_{beam}}{\tau_n} \frac{L_{det}}{\varphi(v)} dv \]

\[ R_n = \varepsilon_{th} A_{beam} v_{th} \int \frac{\varphi(v)}{v} dv \]

\[ \tau_n = \frac{R_n \varepsilon_p L_{det}}{R_p \varepsilon_{th} v_{th}} \]
The NIST Beam Lifetime Experiment (BL1, BL2)

- A quasi-penning trap electrostatically traps decay protons, which are guided to detector via a B field, when the door electrodes are lowered to the ground potential.
- Neutron monitor measures incident neutron rate by counting $n + ^6\text{Li} \rightarrow \alpha + t$. 
\[ \dot{N}_p = \dot{N}_{\alpha+t} \left( \frac{L}{\tau_n} \right) \frac{\epsilon_p}{\epsilon_0 \nu_0} \]
$R_n$ determined by absolute $\gamma$ counting from $^{10}\text{B}(n,\gamma)^{7}\text{Li}$ reaction
1. Measure the absolute activity of an alpha source
2. Use this source to determine solid angle of alpha detector
3. Use an $(n, \alpha \gamma)$ reaction to transfer the calibration to the gamma detectors
4 Measure neutron rate

Thin foil replaced with thick $^{10}$B foil
- all neutrons absorbed
- observed gamma rate and established gamma efficiency determine incident neutron rate

886.3 ± 1.2 [stat] ± 3.4 [sys] seconds  Nico et al 2005
887.7 ± 1.2 [stat] ± 1.9 [sys] seconds  Yue et al 2013
The Bottle Method: fill-store-count

\[ \tau_n = \frac{-(t_2 - t_1)}{\log\left(\frac{N_2}{N_1}\right)} \]

Measures the Storage Time

\[ \frac{1}{\tau_{\text{mea}}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{\text{heat}}} + \frac{1}{\tau_{qb}} + \ldots \]
Material Bottle Experiments


Dubbers & Schmidt, Rev. Mod. Phys., 83, 1111 (2011)
Neutron Lifetime Measurement and the Three Bears
Baby Bear: “Someone has been eating my porridge,...
and it is ALL GONE.”

The Culprit

Experimentalists
The most recent result from a material bottle experiment

2008-2010 at ILL
\[ \tau_n = 880.2 \pm 1.2 \text{ s} \]
Ultra-Cold Neutrons (UCN)

- What are UCN?
  - Very slow neutrons
    \( v < 8 \text{ m/s} \rightarrow \lambda > 500 \text{ Å} \)
    that cannot penetrate into certain material.

- Long storage time
- Low radiation background
- 100% polarization

→ Precision measurements
Ultracold Neutrons

- Nuclear force (max: 350neV)
- Magnetic force (60neV/T)
- Gravitational force (100neV/m)

High field seeker

Low field seeker

Low field seekers

magnetic quadruple trap
NEtron STOrage Ring (NESTOR)

R ~ 0.5 m, Bmax = 3.5 T, current density: 250 A/mm

W. Paul et al (1970)

1989: $\tau_n = (877.0 \pm 10) \text{ s}$

Problem: betatron motions mix with the cyclotron motion
UCN Lifetime Experiment at Institut Laue-Langevin

Neutrons from the ILL turbine.
Trapped with permanent magnets and gravity.
Surviving neutrons counted.

V. Ezhov et al., NIMA, 611, 167 (2009)

\[ \tau_n = 878.3 \pm 1.9 \text{ s}, \quad \text{arXiv:1412.7434 (2014)} \]
Dr. Who & a captured Dalek
Main Features of the UCNτ Experiment

1. An intrinsically low loss rate and long trap lifetime
   → confinement with *magnetic fields & gravity*; no material interaction.

2. Rapid evolution and mixing of the phase space
   → fast removal of quasi-bound neutrons; The neutron population quickly reach a stochastic distribution.

3. Phase-space insensitive detection scheme.
   → Negligible bias on neutron detection efficiency even if the neutron distribution could evolve between the short and long storage times.

4. A large neutron statistics for sub-1 sec precision (1 s statistical uncertainty every few days)
   → enable data-driven study of systematic effects: needs a large volume, high UCN density, and high neutron detection efficiency.
UCNτ: Magneto-Gravitational Trap

- **Magnetic trapping**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding $\mathbf{B}$ field throughout the trap (perpendicular to the Halbach array field).

Walstrom et al, NIMA, 599, 82 (2009)
Asymmetric Trap induces ``Phase Space Mixing’’

**Low symmetry**, together with **field ripples**, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

→ **quick cleaning** (~ 10s of seconds) of the ‘quasi-bound’ UCN.

Adjacent Magnetization $\pi/2$ out of phase

PMs in a given row share same $\mathbf{M}$ alignment

$R_1=1\text{m}$

$R_2=0.5\text{m}$

Two torus patches of different curvatures join along middle row

- **Rows**: 141
- **PMs**: 5310
Quasi-bound Neutrons

If the QB neutrons are not sufficiently cleaned, they will leak out of the trap with its own characteristic time constant $\tau_{qb}$. The resulting correction time is:

$$\Delta \tau = \frac{\tau^2_\beta}{(t_2 - t_1)} \varepsilon \left[ \exp\left(-t_1/\tau_{qb}\right) - \exp\left(-t_2/\tau_{qb}\right) \right]$$

$t_2 = 2000$ s
$t_1 = 200$ s
$\varepsilon = 0.01$

To limit $\Delta t < 0.1$ s for all $\tau_{qb}$, need $\varepsilon < 3e^{-4}$

$\Delta t = 0.1$ s
UCN Spectrum Cleaning

\[ E_{\text{max}} = E_0 + 6 \text{ neV} \]

\[ E_0 = 50 \text{ neV: trap threshold} \]
Halbach Array Completion: Dec 2012
Trap Door Actuation

Gap size ~ 0.003”.

Continuous B fields prevent the UCN from leaking through the gaps.
UCNtau apparatus installed at the LANSCE UCN facility: Feb. 2013
The UCN\(\tau\) Experiment at LANSCE

UCN SD\(_2\) Source
Spallation driven by LANSCE
800 MeV proton accelerator

UCN\(\tau\) Magneto-Gravitational Trap

UCNA Spectrometer (1 UCN/c.c.)

Radiation Shielding

7T Polarizer Field

Zr Vacuum Separation Foil

Gate Valve (80 UCN/c.c.)

UCN\(\tau\) 10\(^{\text{B}}\) UCN Detector

Gate Valve

\(^{3}\)He UCN Detector

6T Pre-Polarizer Magnet (PPM)

Gate Valve
Operation of the $^{10}$B UCN$\tau$ Experiment

“Fill-Store-Count” cycle
1. Fill polarized UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Count UCN

Detector R&D:
2013: External UCN detector
2014-2015: V-foil in-situ UCN detector
2015-2016: $^{10}$B/ZnS in-situ UCN detector

$^{3}$He Drift Tubes (not pictured)

AFP Spin Flipper in 130G (370 kHz)

UCN Spectrum Cleaner (Polyethylene sheet)
**Fill-Store-Count:** UCN dumped into an external detector

200 s storage run, followed by a 2000 second storage run

\[ \tau_n = \frac{-(t_2 - t_1)}{\log\left(\frac{N_2}{N_1}\right)} \]

Example Fill-and-Empty Run

**Fill-Store-Count:** neutron hit and activate a V foil

1. V foil lowered into trap from above (~1s)
2. Remaining UCN are absorbed (~20s for current small foil)
3. V foil raised and activity is measured

---

**Neutron scattering lengths and cross sections**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>conc</th>
<th>Coh b</th>
<th>Inc b</th>
<th>Coh xs</th>
<th>Inc xs</th>
<th>Scatt xs</th>
<th>Abs xs</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>---</td>
<td>-0.3824</td>
<td>---</td>
<td>0.0184</td>
<td>5.08</td>
<td>5.1</td>
<td>5.08</td>
</tr>
<tr>
<td>50V</td>
<td>0.25</td>
<td>7.6</td>
<td>---</td>
<td>7.3(1.1)</td>
<td>0.5</td>
<td>7.8(1.0)</td>
<td>60(40)</td>
</tr>
<tr>
<td>51V</td>
<td>99.75</td>
<td>0.402</td>
<td>6.35</td>
<td>0.0203</td>
<td>5.07</td>
<td>5.09</td>
<td>4.9</td>
</tr>
</tbody>
</table>

- Negative Material Potential
- Good n Absorber

\[ T_{1/2} = 3.7 \text{ min.} \]

\[ {^{51}_{\text{V}}} + \text{n} \rightarrow {^{52}_{\text{V}}} \]

\[ {^{52}_{\text{V}}} \rightarrow {^{52}_{\text{Cr}}} + \beta^- (0 -- 2.54 \text{ MeV}) + \gamma (1.43 \text{ MeV}) \]
Cut Criteria:
1. Beta event is not coincident with a beta event in the other detector
2. Beta event pulse-height (460~8000).
3. Beta event is coincident with a NaI event
4. NaI event a pulse-height (2500~3500)

Beam On
Beam Off

\[ S/N = 2.28 \]
\[ \varepsilon_\beta = 0.8 \]
\[ \varepsilon_\gamma = 0.3 \]

\[ S/N = 10 \]
\[ \varepsilon_\beta = 0.8 \]
\[ \varepsilon_\gamma = 0.21 \]
Data Analysis on 2014-2015 Dataset

The probability to observe a dataset, \((x_i, y_i)\), is

\[
P(y_i; f(x_i)) = \prod_{i=1}^{N} \frac{f(x_i)^{y_i}}{y_i!} e^{-f(x_i)}
\]

Maximum likelihood function:

\[
M = \sum_{i=1}^{N} [y_i \ln R(t_i) - R(t_i)]
\]

\[52^V \rightarrow 52^Cr + \beta^- + \gamma\]

\[\tau_V = 324.6\ s\]

\[52^V \rightarrow 52^Cr + \beta^- + \gamma\]

\[\tau_V = 324.6\ s\]

\[R(t) = \begin{cases} 
  a \exp(-t/324.6) + c & \text{if } t < t_{\text{count}} \\
  a \exp(-t/324.6) + c + \left(\frac{d}{324.6}\right) \exp\left(-\frac{(t - t_{\text{count}})}{324.6}\right) & \text{if } t > t_{\text{count}}
\end{cases}\]

- Background
- UCN signal

\(N_1\) or \(N_2\)
Energy cut on gamma events

Load 300 s
Clean 200 s
Absorb 30 s
Count 1000s

β×NaI (photopeak)
ε=15%

β×NaI (>750 keV)
2000 s holding time
ε=30%

β×NaI (>200 keV)
ε=60%

Fit Background to this region

Load
Clean
Absorb
Count

ε=15%
ε=30%
ε=60%

Before coincidence
Eγ (keV)

After coincidence
Eγ (keV)
Neutron Lifetime vs $E_{\gamma}^{\text{low}}; E_{\gamma}^{\text{high}} = 1550$ keV

- Sandwich background subtraction
- Trace Sum (200ns–500ns coinc. window)
- Trace Sum (1µs–1µs coinc. window)

Clean(s)-store(s)

- 100–1200
- 200–1200
- 200–2000
- 200–2000
- 300–2000
### Estimate of Systematic Effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Upper Bound</th>
<th>Direction</th>
<th>Current Eval.</th>
<th>Method of Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>residual gas</td>
<td>$&lt; 1 \times 10^{-4}$</td>
<td>+</td>
<td>meas</td>
<td>RGA/cross-section measurements</td>
</tr>
<tr>
<td>depolarization</td>
<td>$&lt; 1 \times 10^{-4}$</td>
<td>+</td>
<td>calc</td>
<td>field map, <em>in situ</em> detection</td>
</tr>
<tr>
<td>material loss</td>
<td>$&lt; 4 \times 10^{-4}$</td>
<td>+</td>
<td>calc</td>
<td>measure Cu tape loss-per-bounce</td>
</tr>
<tr>
<td>cleaning</td>
<td>$&lt; 6 \times 10^{-4}$</td>
<td>+</td>
<td>sim</td>
<td>vary cleaning time/depth, active cleaner</td>
</tr>
<tr>
<td>cleaner reliability</td>
<td>$&lt; 5 \times 10^{-4}$</td>
<td>±</td>
<td>sim</td>
<td>verify position reproducibility</td>
</tr>
<tr>
<td>microphonic heating</td>
<td>$&lt; 1 \times 10^{-4}$</td>
<td>+</td>
<td>sim</td>
<td>accelerometer measurements</td>
</tr>
<tr>
<td>dead time/pileup</td>
<td>$&lt; 1 \times 10^{-4}$</td>
<td>±</td>
<td>calc</td>
<td>pileup ID/artificial dead time</td>
</tr>
<tr>
<td>gain drifts</td>
<td>$&lt; 2 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>spectral monitoring/gain monitoring</td>
</tr>
<tr>
<td>time-dep. background</td>
<td>$&lt; 5 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>background data analysis</td>
</tr>
<tr>
<td>phase space evolution</td>
<td>$&lt; 5 \times 10^{-4}$</td>
<td>±</td>
<td>sim</td>
<td>vanadium time studies, active detector</td>
</tr>
<tr>
<td>UCN monitoring</td>
<td>$&lt; 3 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>measure monitor response/source stability</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>$&lt; 1.2 \times 10^{-3}$</td>
<td>±</td>
<td></td>
<td>(uncorrelated sum)</td>
</tr>
</tbody>
</table>
2015 upgrade: Active *in-situ* UCN Detectors

V-foil replaced with a $^{10}$B/ZnS detector, which allows:

- Counting UCNs *as they are absorbed* (in real time) rather than the delayed decays of the absorption product.
- Measuring the timing spectrum of UCN absorption, to monitor the possible phase-space evolution of UCN in the trap.

Z. Wang et al., NIMA 798, 30 (2015).
The new detector works great!

Neutron capture to $^{10}\text{B}$ in real time.

Normalized to the total counts in each distribution.

Delayed counting on number of UCN.
Big-Bang Nucleosynthesis

\[ n + \nu_e \leftrightarrow p + e^- \]
\[ n + e^+ \leftrightarrow p + \bar{\nu} \]

0.1 MeV (entropy-delayed nucleosynthesis)

Neutrinos decouple from thermal bath
BBN: $\tau_n$ and $Y_p$ (primordial $^4$He abundance)

BBN: $\tau_n$ & $Y_p$


- L. Salvati et al. arXiv:1507.07243
Summary

• The 2014-2015 data set, measured using the V-foil in-situ neutron detector, yields a preliminary neutron lifetime between
  – 884.7 ± 3.5 s (narrow E cut) to
  – 878.6 ± 3.5 s (wide E cut).
  – UCN statistics: ~20,000 UCN per load (210 cycles of measurements)
  – Monte-Carlo studies on neutron activated background are underway.

• The systematics appear to be under control to one second level.
  – New $^{10}$B/ZnS detector eliminates systematic dependence on NaI gamma ray detector energy cuts. New 2015 data hints at phase space insensitivity.
  – First pass of B field mapping finds no zero-field crossing. Improved mapping planned.
  – Testing the new detector this beam cycle for a 1 s measurement.