Neutron Lifetime Measurements

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2009 Neutron Physics Summer School
Outline

• History of the lifetime
  (short - only about 15 minutes)

• Physics highlights (not previously covered)

• Measurements that constitute the world average

• Measurements either in progress or under development
Measuring the Lifetime: The Early Years

It took many years from the discovery of the neutron by Chadwick in 1932 and the conjecture of its instability by Chadwick & Goldhaber in 1935 until its radioactive decay was observed in 1948.
Why is it so Difficult?

- Long lifetime -> low decay rate
- Limited numbers of neutrons
- Difficult to obtain a “well-defined” sample
- Many ways to either lose neutrons from your container or miss counting them
The early years


A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a \(2\frac{1}{2} \times 1\frac{1}{2}\) inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the aperture. Readings are taken (1) with and without a thin B\(^{10}\) shutter in the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample (\(4 \times 10^4\)) give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincidences are presently being sought between the disintegration betas and the collected protons.

Proton counter

n lifetime between 13 and 26 minutes
First “precise” lifetime experiment
Robson et al., 1951

Chalk River reactor; 3 cm diameter beam
thermal beam with $2 \times 10^9$ n/cm$^2$/s flux

e-p coincidence
\[ \tau_n = 1108 \pm 216 \text{ s} \]
A major step forward
Christensenen et al. in 1972

e-spectrometer; \( \tau_n = 918 \pm 14 \) s
Proton counting experiments at KI in Moscow

1972 Christensen result: $\tau_n = 918 \ (14) \ s$

1978 KI result: $\tau_n = 877 \ (11) \ s$

In 1980 Byrne et al. found $\tau_n = 937 \ (18) \ s$ [withdrawn in the meantime]. They concluded in a Letter to Nature 310, 212 (1984) “... a third direct measurement has given the value $\tau_n = 877 \pm 11 \ s$, which is totally at variance with all other evidence. We suggest here that .... exclude values of $\tau_n$ outside the range $911 \pm 10 \ s$ ...
Neutron Decay

\[ n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV} \]
Importance of Neutron Decay Parameters

- $\tau_n$: Big Bang Nucleosynthesis - determines primordial helium abundance
- $g_\nu$: determines $V_{ud}$, test of CKM unitarity
- $g_a$: axial vector coupling in weak decays
- D: search for new CP violation
- $a, A, B$: precise comparison is sensitive to non-SM physics:
  - right handed currents
  - scalar and tensor forces
  - CVC violation
  - second class currents

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

\[ \frac{\hbar}{\tau_n} \propto (g_V^2 + 3g_A^2) F(E) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \vec{\sigma} \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right] \]

\[ \tau_n \propto \frac{1}{g_V^2 + 3g_A^2} \approx 886 \text{ s} \]

\[ \lambda = \frac{g_A}{g_V} \]

\[ a = \frac{1 - \lambda^2}{1 + 3\lambda^2} \approx -0.102 \]

\[ A = -2 \frac{\lambda^2 + \text{Re}(\lambda)}{1 + 3\lambda^2} \approx -0.110 \]

\[ B = 2 \frac{\lambda^2 - \text{Re}(\lambda)}{1 + 3\lambda^2} \approx 0.983 \]

\[ D = 2 \frac{\text{Im}(\lambda)}{1 + 3\lambda^2} \approx 0 \]

neutron lifetime

electron-neutrino asymmetry

spin-electron asymmetry

spin-neutrino asymmetry

spin-electron-neutrino triple correlation
Big Bang Nucleosynthesis

- Proton
- Neutron

Matter
Antimatter
Annihilation
1 µs

Nucleon
Freeze Out
1 s

Light Element
Formation
10 min
Light Element Abundances

PDG BBN Review (2007)
Light Element Abundances

CKM Unitarity

- $|V_{us}|$ and $|V_{ub}|$ obtained from high-energy experiments
- $|V_{ud}|$ obtained from:
  1. $0^+ \rightarrow 0^+$ nuclear beta decay
  2. neutron beta decay
  3. pion beta decay

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]
\[ 0^+ \rightarrow 0^+ \text{ Nuclear Beta Decay} \]

- Corrected $ft$ ($F_t$) values should be constant
- \[ |V_{ud}|^2 \propto \frac{1}{\langle F_t \rangle} \]
- \[ |V_{ud}|^2 = 0.9490 \pm 0.0005 \]
$|V_{ud}| \propto g_v$

$\tau_n \propto \frac{1}{(g_v^2 + 3g_A^2)}$

$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$

$\lambda = \frac{g_A}{g_v}$
CKM Unitarity

Beta Asymmetry (PDG)

Neutron Lifetime (PDG)

PDG 2005
CKM Unitarity

- Beta Asymmetry (PDG)
- Neutron Lifetime (PDG)
CKM Unitarity

Beta Asymmetry (PDG)

Perkeo II

CKM Unitarity (Vus)

Neutron Lifetime (PDG)
**Current Situation**

- **Beta Asymmetry (PDG)**
- **Perkeo II (preliminary)**
- **CKM Unitarity (Vus)**
- **Neutron Lifetime (PDG)**
- **Neutron Lifetime (Serebrov)**
# Energy Scales/Nomenclature

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy</th>
<th>Wavelength</th>
<th>Temperature</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>&gt; 500 keV</td>
<td></td>
<td></td>
<td>&gt; 1 x 10^7 m/s</td>
</tr>
<tr>
<td>Epihermal</td>
<td>500 keV - 25 meV</td>
<td></td>
<td>1 x 10^7 m/s - 2200 m/s</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>25 meV</td>
<td>0.18 nm</td>
<td>300 K</td>
<td>2200 m/s</td>
</tr>
<tr>
<td>Cold</td>
<td>25 meV - 0.05 meV</td>
<td>0.18 nm - 4 nm</td>
<td>300 K - 0.6 K</td>
<td>2200 m/s - 100 m/s</td>
</tr>
<tr>
<td>Very Cold</td>
<td>50 ueV - 0.2 ueV</td>
<td>4 nm - 64 nm</td>
<td>0.6 K - 0.002 K</td>
<td>100 m/s - 6 m/s</td>
</tr>
<tr>
<td>Ultracold</td>
<td>&lt; 0.2 ueV</td>
<td>&gt; 64 nm</td>
<td>&lt; 2 mK</td>
<td>&lt; 6 m/s</td>
</tr>
</tbody>
</table>
Ultracold Neutrons

- **Strong Interaction**

\[
\sin \theta \leq \sin \theta_c = \left( \frac{V}{E} \right)^{1/2}
\]

\[
V = \frac{2 \pi \hbar^2}{m} \text{ Na}
\]

\[V \sim 10^{-7} \text{eV}\]

- **Gravitational Interaction**

\[V_g = mgh\]

\[10^{-7} \text{eV/m}\]
Ultracold Neutrons

- Magnetic Interaction

\[ V_m = - \mu \cdot B \]
\[ 10^{-7} \text{eV/T} \]
Types of Measurements

• Cold Beam
• Material Bottle
• Magnetic Storage
Cold Beam Technique

neutron decay rate $\Gamma = \frac{N}{\tau}$

so $\tau = \frac{\phi V_{\text{det}}}{v \Gamma}$

Need to measure:
1. decay rate $\Gamma$
2. effective decay volume $V_{\text{det}}$
   - use linear extrapolation vs. trap length
3. neutron flux weighted by inverse velocity
   - use $1/v$ neutron flux monitor
UCN Bottle Technique

\[ \frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_{\text{wall}}} + \ldots \]

\[ \tau = \frac{T}{\log \left(\frac{N_0}{N}\right)} \]
Magnetic Storage

- Originally proposed in 1961 by Vladimirskii
- First realized in 1983 by Abov et al. using a combination both magnetic and gravitational interactions.

\[
dN(t)/dt = -(N_0/\tau) e^{-t/\tau}
\]
# Lifetime Measurements

<table>
<thead>
<tr>
<th>Technique</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>① Neutron Beam</strong>&lt;br&gt;Detect decay products from a beam with a well defined neutron fluence rate</td>
<td>Absolute neutron flux ($10^{-3}$)</td>
</tr>
<tr>
<td><strong>② Material Bottle</strong>&lt;br&gt;Measure change in number of confined neutrons as a function of time</td>
<td>Understanding neutron energy spectrum&lt;br&gt;Loss mechanisms (walls)</td>
</tr>
<tr>
<td><strong>③ Magnetic Bottle</strong>&lt;br&gt;Measure change in number of confined neutrons as a function of time</td>
<td>Complicated Orbits&lt;br&gt;Spin Flips</td>
</tr>
<tr>
<td><strong>④ Magnetic Trap</strong>&lt;br&gt;Count decay products of magnetically trapped neutrons as a function of time and measure the slope.</td>
<td>Complicated Orbits&lt;br&gt;To date: poor signal to noise</td>
</tr>
</tbody>
</table>

\[
\frac{dN}{dt} = N \lambda
\]

\[
\frac{N_1}{N_2} = e^{-\lambda(t_1-t_2)}
\]

\[
\ln\left(\frac{N}{N_0}\right) = -\lambda t
\]
Existing Measurements
Beam Lifetime

- alpha, triton detector
- precision aperture
- $^6$Li deposit
- mirror (+800 V)
- trap electrodes
- door closed (+800 V)
- neutron beam
- proton detector
- B = 4.6 T

Beam Lifetime
Beam Lifetime

alpha, triton detector

precision aperture

$^6$Li deposit

mirror (+800 V)

trap electrodes

door open (ground)

B = 4.6 T

proton detector

neutron beam
Measurement of the Neutron Lifetime by Counting Trapped Protons

J. Byrne, P. G. Dawber, J. A. Spain, and A. P. Williams
University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. D. Scott
Scottish Universities Research and Reactor Center, East Kilbride, Glasgow G75 0QU, United Kingdom

J. Pauwels, R. Eykens, and A. Lamberty
Commission of the European Communities, Joint Research Center, Central Bureau for Nuclear Measurements, B-2440 Geel, Belgium
(Received 21 March 1990)

The neutron lifetime $\tau_n$ has been measured by counting decay protons stored in a Penning trap whose magnetic axis coincided with a neutron-beam axis. The result of the measurement is $\tau_n = 893.6 \pm 5.3$ s which agrees well with the value predicted by precise measurements of the $\beta$-decay asymmetry parameter $A$ and the standard model.

PACS numbers: 14.20.Dh, 13.30.Ce

Self-consistency among experimental values for the neutron lifetime $\tau_n$, the various angular and polarization correlation coefficients in free-neutron $\beta$ decay, and $f$ values of pure Fermi $0^+ \rightarrow 0^+$ superallowed $\beta$ transitions provides one of the best tests of the standard $V-A$ theory of semileptonic weak processes. For neutron decay. In an earlier version of this technique the magnetic field was oriented normal to the neutron beam.

In the parallel configuration any dependence on the spatial distribution and velocity distribution of the neutrons within the neutron beam is eliminated and $\tau_n$ is given by
ILL Beam Lifetime

\[ \tau_n = 893.6 \pm 5.3 \text{ s} \]

NIST Beam Lifetime

NIST Beam Lifetime

Proton Pulse Height Spectrum
(32.5 keV; 20 µg/cm² Au)

Proton Arrival Time Spectrum
(32.5 keV; 20 µg/cm² Au)

Beam Lifetime

alpha, triton detector
precision aperture

$^6\text{Li}$ deposit

B = 4.6 T

mirror (+800 V) trap electrodes door open (ground)

proton detector neutron beam

NIST Beam Lifetime

Proton Pulse Height Spectrum
(32.5 kV; 20 µg/cm² Au)

Proton Arrival Time Spectrum
(32.5 kV; 20 µg/cm² Au)

Normalized Proton Counts vs. Trap Length
(32.5 kV; 20 µg/cm² Au)

NIST Beam Lifetime

\[ \tau_n = 885.5 \pm 3.4 \text{ s} \]

Bottle Experiments

• MamBo I - material bottle
• MamBo II - material bottle
• Bottle w/Upscatter - material bottle
• ILL Bottle - material bottle
• Gravitrap - material bottle
• NESTOR - magnetic storage ring
• ILL permanent magnet
MamBo I

- Fill with UCN
- Vary surface area to volume ratio
  \[ \frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_{\text{wall}}} + \ldots \]
- Extrapolate to infinite volume

W. Mampe et al., PRL, 63 (1989) 593
MamBo I

\[ \tau_n = 887.6 \pm 3 \text{ s} \]

W. Mampe et al., PRL, 63 (1989) 593
\[ \tau_n = 881 \pm 3 \text{ s} \]
(unpublished)

Pichlmaier, PhD thesis, TU Munich
Rotating Gravitational Bottle

V. Nesvizhevsky et al., JETP 75(3) (1992) 405
Rotating Gravitational Bottle

\[ \tau_{st}^{-1} \times 10^4 (s^{-1}) \quad \tau_{st}(s) \]

\[ \tau_n = 888.4 \pm 3.3 \text{ s} \]

V. Nesvizhevsky et al., JETP 75(3) (1992) 405
Bottle w/Upscattering

W. Mampe et al., JETP Lett, 57 (1993) 82
Bottle w/Upscattering

\[ \tau_n = 882.6 \pm 2.7 \text{ s} \]

W. Mampe et al., JETP Lett, 57 (1993) 82
ILL Bottle Lifetime

ILL Bottle Lifetime

ILL Bottle Lifetime

Scheme of the experiment

First experiment when UCN are stored inside the inner vessel with small loose at wall reflections

Second experiment when UCN are stored inside the outer vessel with large loose at wall reflections

\[ V = 65 \text{ l} \quad T = 300 \text{ K} \quad T = -9 ^\circ \text{C} \]

\[ V = 20 \text{ l} \quad T = -26 ^\circ \text{C} \]

ILL Bottle Lifetime

circles - inner chamber
triangles - outer chamber
\[ \tau_n = 885.4 \pm 0.9 \pm 0.4 \text{ s} \]

Measurement Summary
ILL Gravitrap

ILL Gravitrap

ILL Gravitrap

ILL Gravitrap

Storage time, s

\[ \tau_{\text{st}} = 872.2 \pm 0.3 \text{ s} \]

\[ \tau_{\text{st}} = 865.6 \pm 0.6 \text{ s} \]

Gravitrap

\[ \tau_n = 878.5 \pm 0.7 \pm 0.3 \text{ s} \]

Measurement Summary
We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. For the average, we only use measurements with an error less than 10 s.

The most recent result, that of SEREBROV 05 (for a more detailed account, see SEREBROV 08A), is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of 885.7 ± 0.8 s must be suspect.

For recent reviews of neutron physics, see NICO 05A and SEVERIJNS 06.

Limits on lifetimes for bound neutrons are given in the section “p PARTIAL MEAN LIVES.”

<table>
<thead>
<tr>
<th>VALUE (s)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>885.7 ± 0.8 OUR AVERAGE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>886.3 ± 1.2 ± 3.2</td>
<td>NICO 05</td>
<td>CNTR</td>
<td>In-beam n, trapped p</td>
</tr>
<tr>
<td>885.4 ± 0.9 ± 0.4</td>
<td>ARZUMANOV 00</td>
<td>CNTR</td>
<td>UCN double bottle</td>
</tr>
<tr>
<td>889.2 ± 3.0 ± 3.8</td>
<td>BYRNE 96</td>
<td>CNTR</td>
<td>Penning trap</td>
</tr>
<tr>
<td>882.6 ± 2.7</td>
<td>MAMPE 93</td>
<td>CNTR</td>
<td>Gravitational trap</td>
</tr>
<tr>
<td>888.4 ± 3.1 ± 1.1</td>
<td>NESVIZHEV... 92</td>
<td>CNTR</td>
<td>Gravitational trap</td>
</tr>
<tr>
<td>887.6 ± 3.0</td>
<td>MAMPE 89</td>
<td>CNTR</td>
<td>Gravitational trap</td>
</tr>
<tr>
<td>891 ± 9</td>
<td>SPIVAK 88</td>
<td>CNTR</td>
<td>Beam</td>
</tr>
</tbody>
</table>

We do not use the following data for averages, fits, limits, etc.: 785.5 ± 0.7 ± 0.3, 886.8 ± 1.2 ± 3.2, 888.4 ± 2.9, 893.6 ± 3.8 ± 3.7, 878 ± 27 ± 14, 877 ± 10, 876 ± 10 ± 19, 903 ± 13 ± 13, 937 ± 18 ± 18, 875 ± 95, 881 ± 8, 918 ± 14.

10 IGNAZOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.
11 This SEREBROV 05 result is 6.5 standard deviations from our average of previous results and 5.6 standard deviations from the previous most precise result (that of ARZUMANOV 00).
12 This measurement has been withdrawn (J. Byrne, private communication, 1990).

In 1980 Byrne et al. found $\tau_n = 937 (18)$ s [withdrawn in the meantime]. They concluded in a Letter to Nature 310, 212 (1984) “… a new direct measurement of $\tau_n$ is 10 s and 20% below the average value $\tau_n = 885.7$ s with the average at variance with all other evidence. We suggest here that …. exclude values of $\tau_n$ outside the range 911 ± 10 s …
Reanalyses

• Recent reanalysis by Fomin and Serebrov
• Incorporated quasi-elastic scattering from the walls
• Shifted the MamBo value down by $7.3 \pm 1.6$ s
• Also reanalyzed Mampe ’93 result, which also shifts lifetime to a lower value.

\[ \tau_n = 880.3 \pm 3 \text{ s} \]
\[ \tau_n = 881.5 \pm 2.4 \text{ s} \]
Gravitational-Magnetic Trap
Permanent Magnet Trap

- Permanent magnets (1 T at surface)
- Filled from either below or on top
- Depolarization characterized by coating inner walls with Fomblin to retain spin-flipped neutrons
- Estimate 0.5 s in 50 days at ILL

V.F. Ezhov, 7th UCN Workshop (2009)
Permanent Magnet Trap

\[ \tau_n = 878.2 \pm 1.9 \text{ s} \]

V.F. Ezhov, 7th UCN Workshop (2009)
Magnetic Storage Ring

\[ \tau_n = 877 \pm 10 \text{ s} \]

W. Paul et al., Z Physics C, 45 (1989) 25
Measurement Summary
Planned Experiments

• Beam
  – Improved flux measurement for NIST expt. (Nico et al.)
  – J-Parc ion chamber (Otono et al.)

• Material Bottle
  – Accordion Bottle (Steryl et al.)
  – Updated gravitational trap (Serebrov et al.)

• Magnetic Trapping (Magneto-Gravitational)
  – PENeLOPE (Picker et al.)
  – LANL permanent magnet (Bowman et al.)

• Magnetic Trapping (4π magnetic confinement)
  – Halback octupole magnet (Zimmer et al.)
  – NIST Ioffe trap (Mumm et al.)
NIST Neutron Fluence

estimated accuracy of $\tau_n$ will be $\pm \sim 2.2$ s

$\pm 1.5$ s with increased running
Beam Ion-Chamber

\[ \tau_n = 878 \pm 31 \text{ s} \]

Ion-Chamber

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

goal: 0.1% measurement

H. Shimizu, 7th UCN Workshop (2009)
Accordion Bottle

estimated accuracy of $\tau_n$ will be $\pm 1\,\text{s}$

Albert Steryl, private communication (2008)
Gravitrap II

Will run at PF2
estimated accuracy of $\tau_n$ will be $\pm 0.2 \text{ s}$

Serebrov, 7th UCN Workshop (2009)
Magnetic Trapping
PENeLOPE

- Superconducting analog to permanent magnet trap (2 T at wall)
- Rings alternate in current sense
- Decay protons guided to scintillator
- Marginally trapped neutrons and Majorana spin-flips are a problem

S. Materne, 7th UCN Workshop (2009)
PENeLOPE

- proton detector
- neutron absorber to remove marginally trapped neutrons
- 42 superconducting storage coils
  max. storage field: ~ 1.8 T
- cryostat, radiation shield and vacuum tank
- racetrack coils for zero-field suppression:
  min. storage field: > 2.8 mT
  adiabatic condition

UCN buffer volume
UCN filling slit

S. Materne, 7th UCN Workshop (2009)
PENeLOPE

- focussing coils
- detector area reduced by 20%
- storage coils
- field lines

- anticipated statistical precision: ~ 0.1 s

S. Materne, 7th UCN Workshop (2009)
Halback Gravitational

- Shallow Halbach array + gravity for trap, trap door loading
- Guide field for decay betas
- Marginally trapped neutrons experience chaotic orbits and are ejected rapidly
- Goal precision ± 0.1 s
- Presently under construction

P.L. Walstron et al., NIMA, 599 (2009) 82
4\pi \text{ Magnetic Confinement}

- Halbach Octupole PErmanent (H.O.PE.) magnetic trap
- 1.3 T at surface, 8 l volume

9 cm internal bore

K. Leung, 7th UCN Workshop (2009)
H.O.P.E.

UCN beam stop
End solenoid
Bias field solenoid
End solenoid
UCN valve
Focusing magnet
UCN transparent window
Superfluid $^4$He vessel
Drift electrodes
Permanent octupole magnet
Proton extraction electrodes
Proton detector

Radial/Transverse
Axial/Longitudinal

Field Strength (T)

radial distance (cm)

Axial position (cm)

K. Leung, 7th UCN Workshop (2009)
H.O.P.E.

- Initial testing to begin soon, aim to begin measurement in 2010
- Anticipated statistical precision: < 0.5 s

K. Leung, 7th UCN Workshop (2009)
NIST UCN Lifetime

- Produce UCN using the "superthermal" technique
- Confine low field seekers within a magnetic bottle
- Detect each neutron as it decays using scintillation techniques
Ioffe-Type Magnetic Trap
Energy Dissipation: Superthermal Process

- 0.89 nm (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering (by absorption of a 12 K phonon)
  - $\sim$ Population of 12 K phonons
  - $\sim e^{-12 \text{ K/Tbath}}$
Detection of Decay Events

- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He$_2^*$ molecules (ns time scale) in both singlet and triplet states.
- He$_2^*$ singlet molecules decay, producing a large prompt emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the organic fluor (d)TPB (tetraphenyl butadiene).

\[
n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}
\]
Experimental Method

Neutrons remain in trap until they decay.

Detect pulse of light from each decay event.

Turn off neutron beam.

Accumulate neutrons in trap until they decay.

Detect pulse of light from each decay event.
Proof-of-principle Data

\[ W = -(A/\tau) \, e^{-t/\tau} \]

- \( A = (1.92 \pm 0.03) \, s^{-1} \)
- \( \tau = (677 \, +13/-12) \, s \)
- \( A = (1.10 \pm 0.06) \, s^{-1} \)
- \( \tau = (844 \, +53/-47) \, s \)

△ No trapped neutrons
New High-Current Trap

- Quadrupole on loan from the KEK institute, solenoids wound in-house
- Conservative approach:
  - design 30% under load line
- Tested to yield a trap depth and size of:
  - $B \geq 3.0$ T, design 3.1 T
  - $\varnothing \geq 11$ cm, $l \geq 42$ cm
- $\times 20$ more trapped neutrons
NIST UCN Summary

- Apparatus presently ready to take data
- Expect a ± 2 s measurement in ~2yr periods
- < ± 0.5 s measurement possible at upgraded NIST cold source or at the SNS

New Dewar on Beamline at NIST
Summary

• Neutron lifetime is still an important parameter for understanding both the weak interaction and the light element production in BBN

• Experiments are very difficult

• Significant discrepancies in current measurements

• Many experiments are current either in progress or in the planning stages