Towards a 0.1s Measurement of the Neutron Lifetime in a Magneto-Gravitational Trap

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Free Neutron Lifetime

Reanalysis of bottle experiments by Serebrov, et al.

Serebrov et al.,
(878.5 ± 0.7 ± 0.3) seconds

PDG 2010: 885.7 ± 0.8 s
PDG 2011: 881.0 ± 1.5 s
PDG 2012: 880.1 ± 1.1 s

Precision improves over time, but accuracy?
Search for Standard Model Parameters

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

- Kaons + Unitarity [PDG 2010]
- ft(0^+ \to 0^+) [Hardy09]
- ft(0^+ \to 0^+) [Liang09 – DD-ME2]
- ft(0^+ \to 0^+) [Liang09 – PKO1]
- PIBETA [Pocanic04]
$V_{ud}$ for unitarity test

- To approach the theoretical uncertainty of $4 \times 10^{-4}$, it requires experimental precision of $\Delta A/A = 4\Delta \lambda/\lambda < 1 \times 10^{-3}$ and $\Delta \tau/\tau < 0.4 \times 10^{-3}$.

\[ f t (1 + \delta''_R) = \frac{K}{|V_{ud}|^2 G_F^2 (1 + 3 \lambda^2) (1 + \Delta_R)} \]

- model-independent external radiative correction, $\delta'_R = 1.466 \times 10^{-2}$
- model-dependent internal radiative correction, $\Delta R = 2.40 \times 10^{-2}$
- $f$: Phase space factor = $1.6886$ (Fermi function, nuclear mass, size, recoil)
- From $\mu$-decay: 0.8 ppm

\[ |V_{ud}|^2 = \frac{4908.7 \pm 1.9 s}{\tau_n (1 + 3 \lambda^2)} \]
\( \tau_n \) feeds into other fields of physics

- Cosmology: BBN
- Astrophysics: Solar model
- Particle physics: Neutrino production from fission reactors

\[
Y_p = 0.228 + 0.023 \log \eta_{10} + 0.012 N_v + 0.018 (\tau_n - 10.28)
\]
# Comparison of Techniques to Measure $\tau_n$

<table>
<thead>
<tr>
<th>Technique</th>
<th>Lifetime extraction</th>
<th>Challenges</th>
</tr>
</thead>
</table>
| **Neutron Beam**          | Detect decay products (proton) from a beam with a well defined neutron fluence rate. | • Need to know absolute efficiency of the detectors.  
• Absolute neutron flux ($10^{-3}$).                                    |
|                           | $\frac{dN_p}{dt} = \frac{N_n}{\tau}$                                               |                                                                                                |
| **Material Bottle (UCN)** | Measure change in number of confined neutrons as a function of storage time.        | • Loss mechanisms (wall interactions). Need to be controlled to better than 10%.  
• Monte-Carlo unreliable.  
• Spectrum evolution.  
• Large draining time.  
• Complicated orbits                                                     |
|                           | $\ln(N/N_0) = -t/\tau$                                                              |                                                                                                |
| **Magnetic Trap (UCN)**   | Count decay products ($\beta$) of magnetically trapped neutrons in real time.       | • Poor SNR  
• $\beta$-detector is prone to $\gamma$-Compton scattering background.  
• Complicated orbits.                                                 |
|                           | $N_1/N_2 = e^{-\frac{(t_1-t_2)}{\tau}}$                                            |                                                                                                |
Material Bottle

A. Serebrov (2008)

D. Dubbers (2011)
Magneto-Gravitational Trap

- **Halbach array** provides field (along $\eta$) gradient for magnetic levitation.
- **Window-frame electromagnet** provides spin holding field ($\beta$ guiding field) along $\xi$.
- **Gravity** bounds UCN from the top.

\[ |B| = B_{rem}(1 - e^{-kd})e^{-ky} \]

Local Surface Coordinates

PM Array $B$ along $\hat{\eta}$

Guide Coils $B$ along $\hat{\xi}$

B-Field Ripple on Scan Path
UCN detector tubes

Halbach array

Switcher

UCN detector

UCN guide

Trap door

valves

trap door actuator
Strategy towards a 0.1 s Experiment

– Short Term Goal (2012-2013)
  •Prototype experiment at LANL
  •6 hours to get 1 s precision.
  •Measure trap lifetime
  •Detector R&D
  •Study the systematic effects
    – Spectrum dependence
    – Loss mechanism: spin flip, residual gas
    – Fluctuations in UCN flux, UCN spectrum, Spin polarization
    – Detector gain, detector dead-time corrections

  •0.1 s precision
  •1 month of statistics (or 2 weeks with improved UCN source density at LANL 35 ± 6 UCN/cm³ UCN/cm³)

A Neutron Lifetime Workshop will take place November 2012 in Santa Fe to identify the path forwards.
Asymmetric Trap $\rightarrow$ Phase Space Mixing

- Low symmetry (together with field ripples) induces states mixing between circular orbits, through chaotic motion (or not).

- $\rightarrow$ quick cleaning ($\sim$ seconds) of the quasi-bound UCN with large tangential velocities.
UCN Tracking

$E_{\text{trap}} < E < E_{\text{trap}} + 6 \text{ neV}$
Renegade neutrons live longer than 50 s.

$\cos(\theta) = 1$: shooting up

$\cos(\theta) = 0$: skimming along surface
R&D: Vanadium solid-state detector

Segmented detectors to gain information on spatial distribution of UCN inside the trap.

### 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 UCN potential
- Good UCN absorber

\[ ^{50}\text{V} + n \rightarrow ^{51}\text{V} \] (stable)

\[ ^{51}\text{V} + n \rightarrow ^{52}\text{V} \rightarrow ^{52}\text{Cr} + \beta^- + \gamma \] (100%)

\[ \beta : 1.073 \text{ MeV} , \gamma : 1.4 \text{ MeV} \]

\[ T^{1/2} = 3.743 \text{ m} \]

\[ 1.4 \text{ MeV line} \]
Current Status
(Summer 2012)

- LDRD-funded R&D program funded the engineering design and partial construction of the prototype experiment.
- Vacuum chamber completed. Full-scale Halbach array in final stage of assembly.
- Holding field coils are constructed at IU & delivered to LANL.
UCN Source in Area B at LANSCE

Position for the Lifetime Experiment
Summary

• The Lifetime Workshop this fall
  – discuss technical issues, and develop a research strategy
  – a possible proposal

• Unique aspects of UCN\(\tau\) experiment:
  – Avoid material interactions
  – UCN in a Magneto-gravitational Trap
  – Only conservative fields are present. Monte-Carlo simulations are reliable.
  – Room temperature experiment with a large open top \(\rightarrow\) versatile detecting schemes possible.
  – Large trap volume, > 1 UCN cm\(^{-3}\) in the experiment (> 10 UCN cm\(^{-3}\) in the source), large statistics.

• Capitalize on the many years of experience & expertise, built up running the UCN source at LANSCE.
  – Will use operating UCN\(D_2\) spallation source at LANSCE (2012-2013)
  – Compatible beam-sharing with UCNA, B experiments