UCNTau: Study of Lifetime Measurement in a Magneto-Gravitational Trap

A. Saunders

The goal: to provide an experimental testbed to study the systematics involved in reaching a 0.1 s measurement of the neutron lifetime, and use it to make a 1 s measurement as part of the process.

UCNτ Collaboration:


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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.
Systematic Effects to be Studied with Prototype

• Phase space
  – Quasi-bound orbits
  – Phase space independent detection
• UCN spectral effects
  – Monitor accuracy
  – Cleaning efficiency per height
• Unexpected UCN losses
  – Spin flips: field zeroes, non-adiabicity
  – Residual gas
  – Vibrations
  – Weak spots in Halbach array
• Detector effects
  – Efficiency
  – Position dependence
  – Gain effects, thresholds
  – Backgrounds: natural, proton-generated, UCN-generated
Asymmetric Trap → Mixing Phase Space

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

- Leads to **quick cleaning (~ seconds)** of the quasi-bound UCN with large tangential velocities.
R&D: Monte-Carlo Simulations on Neutron Tracking

Questions:
- Phase Space evolution.
- Detection efficiency as a function of time.
- Chaotic trajectory or not?

Tools under development:
- Import and/or recreate geometry in GEANT4 without overlap, gaps, or other errors.
- Input finite-element-analysis results for realistic magnetic field.
- Collect trajectories for marginal trapping and phase space analysis.
- Track spin.
- Investigate different cleaning techniques.
- Perform emptying and filling experiment.
- Perform β detection experiment.
Transport Simulation

GEANT4 in feed guides
Home brew in trap

Does not yet track UCN spin

Tracks equations of motion modeled magnetic field
Example: rapid mixing of phase space

- 0 s
• 1s
• $2s$
• 3 s
In-Trap Simulation

Center of Mass Along Symmetry Axis

-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0

center of mass (cm)

0 100 200 300 400 500

time (s)
Horizontal cleaner eliminates marginal UCNs (in simulation!)
Cleaning Time

Cleaning and Storing of UCN

number of UCN killed in 0.5 s window

time [s]

Remove cleaner here
A variety of measurement schemes to detect neutron $\beta$-decay

1. **Detect decayed $\beta$s** in real time.
   - Decay betas are guided along the guiding fields into beta detectors mounted at the two ends.
   - Require at least 0.1 T of holding fields.

2. **Measure survival UCN** by draining the UCN into a UCN detector mounted on the bottom of the trap.
   - The UCN draining efficiency depends on the storage time and the UCN spectrum evolution.
   - Susceptible to phase space evolution during long (~200 s) draining time.

3. **Pump & Dump**
   - Convert the lifetime trap into an ionization chamber detector on demand.
   - Avoids the time-dependent detection efficiency.
   - Use BF$_3$/Ar gas mixture.

4. **Proton collection and amplification**

5. **Vanadium dagger**
R&D: Vanadium solid state detector

<table>
<thead>
<tr>
<th>Neutron scattering lengths and cross sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>V</td>
</tr>
<tr>
<td>50V</td>
</tr>
<tr>
<td>51V</td>
</tr>
</tbody>
</table>

**Negative UCN potential**  
**Good UCN absorber**

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

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

1. Insert vanadium foil to absorb neutrons
2. Extract foil into shielded counter
3. Perform $\beta$-$\gamma$ coincidence measurement.

$\beta$ : 1.073 MeV, $\gamma$ : 1.4 MeV

$T^{1/2} = 3.743$ m

Use several detectors to get position information on UCN distribution inside the trap.
V Measurement sequence
Demonstration of Vanadium activation and Counting of UCN

Vanadium Counting Setup

Expose for ~10 minutes
Hand carry to counter
Installed between S1 and S2

UCN

Stainless Steel guide

250 mm Al window

S1 S2

CsI

2 m

51V

51V + n → 52V (T1/2 = 3.74 m)

52V → 52Cr+ β- + γ (1.434 100%)

2 m

HpGe

Measured γ-spectrum from UCN-activated V foil

Counts (arb)

Energy (MeV)

raw
background
signal
• Betas provide a clean signal with low background
• The background in the CsI detector is considerably higher
• Detecting the \( \gamma \) and \( \beta \) in coincidence provides excellent background rejection
Relative UCN flux monitoring: preliminary measurements
• LANL source (available now, with best performance ever).
  – 80 UCN cm\(^{-3}\) at the gate valve.
  – Beam sharing with UCNA,B experiment.
  – 200 s fill, followed by a 1 hour measurement (6% duty).
  – Can run simultaneously with UCNA by filling while UCNA measures background.

• PSI source (commissioning).
• Pulstar source (commission this year?).
• TRIUMF source (funding secured this year, construction?)
UCN Source in Area B at LANSCE
Timeline

• Complete Halbach array and holding coils (2012)
• Offline monitoring tests (Q3/Q4 2012)
• Install low-field spin-flipper (2012)
• Comprehensive simulation (2012-)
• Preliminary storage measurement, systematics studies
  – cleaning/marginal trapping
  – demonstrate vanadium technique
  – source fluctuations/monitoring
• Use measurements to understand/control systematics, push towards next gen. experiment
Construction Progress
Summary

• UCN in a Magneto-gravitational Trap
  – No material interactions
  – Only conservative fields are present. Monte-Carlo simulations are reliable.
• Will initially use operating UCN$_{D_2}$ spallation source at LANSCE
  – Compatible beam-sharing with UCNA, B experiments
• PPM and spin flipper can select spin state
• Large trap volume, > 1 UCN cm$^{-3}$ in the experiment (> 10 UCN cm$^{-3}$ in the source), sufficient statistics for 1 s measurement; 0.1 s more challenging.
• Room temperature experiment, study of versatile detecting schemes possible.
• Hopefully trapping neutrons this accelerator cycle! Comparison of systematic effects to Monte Carlo will commence immediately.
Backup slides
Big-Bang Nucleosynthesis

1% change of $\tau_n$
→ 0.75 % change of $^4\text{He}$ abundance (0.61%).
→ 17 % change of $\eta_{10}$ (3.3%)

G. Mathews, T. Kajino, T. Shima, 2004
Probing Physics Beyond the Standard Model Through Neutron $\beta$-Decay

- Neutron beta decay as a probe for physics beyond the standard model
  - Quark mixing in standard model
  - Unitarity sum rule violated?

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$$
The UCN source at LANSCE

Non-specularity = 3%

Loss/bounce = 3.5\times 10^{-4}

\rho = 80 \text{ UCN/cm}^3
Experiment Status

- The major item is the magnet array
  - Support frame is complete
  - About half of magnets are mounted
  - Forming a trap 15 cm deep
  - But magnet company is out of business
  - Rest of material is procured
- Vacuum systems procured
- Vacuum can tested
- UCN detectors ready (tube and box)
- Guides and switches
  - Materials in hand
  - UCNA switch/roundhouse still in design
  - UCN trap door procured
- Cleaner ready for testing
- Support Stand procured
- Still needed items:
  - Beta detectors (?), holding field coils
  - In situ neutron detectors
  - Return yoke (?)
  - Spin flipper
  - Clear space for experiment
### International competition in UCN production

<table>
<thead>
<tr>
<th>Source location</th>
<th>Source type</th>
<th>UCN density [cm⁻³]</th>
<th>comment</th>
<th>when?</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL Grenoble, PF2</td>
<td>LD₂ + turbine</td>
<td>50</td>
<td>still THE source</td>
<td>&gt; 1985</td>
</tr>
<tr>
<td>Los Alamos, 2.4 kW_{av} proton</td>
<td>SD₂</td>
<td>120</td>
<td>in source</td>
<td>now</td>
</tr>
<tr>
<td>Mainz TRIGA upgraded</td>
<td>SD₂</td>
<td>20 \sim 200</td>
<td>in ( V = 10 ) l</td>
<td>now 2009</td>
</tr>
<tr>
<td>ILL Grenoble, H172 upgraded + magnetic trap</td>
<td>He-II (0.5 K)</td>
<td>&gt; 1000 2000 polariised</td>
<td>in ( V = 6.4 ) l up to 40 l</td>
<td>2009 &gt; 2011</td>
</tr>
<tr>
<td>PSI, 12 kW_{av} proton</td>
<td>SD₂</td>
<td>&gt; 1000</td>
<td>in ( V = 2000 ) l</td>
<td>2010</td>
</tr>
<tr>
<td>North Carolina, 1 MW reactor</td>
<td>SD₂</td>
<td>1300</td>
<td>in source</td>
<td>2011</td>
</tr>
<tr>
<td>Munich, 20 MW reactor</td>
<td>SD₂</td>
<td>\sim 10000</td>
<td>in source</td>
<td>2011</td>
</tr>
<tr>
<td>PNPI, 16 MW reactor</td>
<td>He-II (1.2 K)</td>
<td>13000 7700</td>
<td>in 35 l exp. bottle in 350 l exp. bottle</td>
<td>2012</td>
</tr>
<tr>
<td>TRIUMF, 5 kW_{av} proton</td>
<td>He-II (0.8 K)</td>
<td>18000</td>
<td>at exp. port</td>
<td>proposal</td>
</tr>
</tbody>
</table>

+ insitu He-Î² UCN sources at ILL (Cryo-EDM), NIST (n-lifetime), and SNS (EDM)
UCN Lifetime Experiment at NIST

- Liquid He Source
- Magnetically trapped in liquid Helium.
- Decayed $\beta$s counted.
A superconducting Ioffe trap

UCN production in He-II and in-situ detection (NIST)

P. Huffman et al., Int. workshop Particle Physics with slow Neutrons, May 2008 ILL
UCN Lifetime Experiment at the ILL

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

Unpublished; in development

V. Ezhov *et al.*, J. Res. NIST 110 (2005) 345
Responsibilities

• Construction underway
  – LANL: preliminary concept design, engineer design, vacuum chamber, Halbach PM array
  – IU: Holding field coils (100 gauss air-cooled EM), detector concept design, detailed simulations (GEANT4 neutron tracking, FEA field 3-D map, Garfield gaseous detector)
Halbach array

- Each magnet $90^\circ$ out of phase with its neighbor.
- The array has B field “ripples” of scale $L/4 = 0.5$ in.
- Rotating field is orthogonal to holding field $B_0$. 
Linear Halbach Arrays

- Ideal linear Halbach array - continuous limit

\[ M_x = -B_{\text{rem}} \sin kx \]
\[ B_x = B_{\text{rem}} \left(1 - e^{-kd}\right) e^{-ky} \sin kx \]
\[ M_y = B_{\text{rem}} \cos kx \]
\[ B_y = B_{\text{rem}} \left(1 - e^{-kd}\right) e^{-ky} \cos kx \]

- \(|B|\) approaches maximum of \(B_{\text{rem}}\) when \(d\) is large.
- Zero field on bottom.
Finite Halbach Arrays

• Approximate continuous array with finite-width blocks.
• Magnetization vector $\mathbf{M}$ is constant in magnitude and direction within a block, same magnitude $|\mathbf{M}| = B_{\text{rem}}$ in all blocks.

1st-order array: 0 and 90-deg. blocks

• Low field on bottom, high field on top
Finite Halbach Arrays (cont.)

\[ B_y + iB_x = \sum_{n=1}^{\infty} a_n e^{ik_nx} e^{-k_{ny}} \]

2nd-order array: 0, 45, and 90-deg. blocks

- Finite blocks and slightly non-linear behavior of PM material introduce higher Fourier components.
- Fundamental of 1st-order array is \(0.9003 \times \left(4 / \pi \sqrt{2}\right)\) times the continuous-array field. Next component is the \(n=5\) component.
- Fundamental of 2nd-order array is 0.9745 times the continuous-array field. Next component is the \(n=7\) component.
$V_{ud}$ for unitarity test

Model-independent external radiative correction, $\delta'_R = 1.466 \times 10^{-2}$

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

- $f$: Phase space factor=1.6886 (Fermi function, nuclear mass, size, recoil)
- From \(\mu\)-decay: 8.6 ppm

Model-dependent internal radiative correction, $\Delta R=2.40\times10^{-2}$

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9 s}{\tau_n (1 + 3 \lambda^2)}$$

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 $\Delta \tau/\tau = 10^{-3}$.
Ultracold Neutrons

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

High field seeker

Low field seekers
magnetic quadruple trap
What we have now: 50% trap

- Reduced trap size ~ 82 liters
- But what is the number of UCN trapped?

$v^3dv$ distribution, due to absorption and other losses in a thick $D_2$ source.

Raise the experiment by 1 m

SS guide: 190 neV