Ultracold Neutrons at LANSCE

Leah Broussard

Los Alamos National Laboratory

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The Standard Model (and Beyond)

Some Curiosities

- Lots of “Why?’s”
  - Why 3 generations?
  - Why so many parameters?
  - Why these masses?
  - Why left-handed weak interaction?
- What is Dark Matter?
- Why so much matter?
- Where is gravity?
- And more…

Finding the missing pieces

- High Energy frontier (LHC) vs. Precision frontier (beta decay)
- Complementary approaches
  - High energy: Direct search for heavy particles
  - Precision: Measure deviations from SM expectation
Neutron Beta Decay

- Semileptonic charged weak interaction
- Standard Model: V - A (left-handed)
- Lifetime \( \sim 15 \) minutes

What we can measure:

- Total decay rate (lifetime):
  \[
  \frac{1}{\tau_n} = \mathcal{W} = K (G_F V_{ud})^2 \left( 1 + 3 \left( \frac{G_A}{G_V} \right)^2 \right) \left( 1 + \Delta_R \right) f_n p_e E_e (E_0 - E_e)^2 \left[ 1 + m_e b \frac{f_b}{f_n} \right]
  \]

- Angular correlations:
  \[
  \frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[ 1 + a \frac{p_e \cdot p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \langle \sigma^* \rangle \cdot \left( A \frac{p_e}{E_e} + B \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right) \right]
  \]

Testing the Standard Model

- A, a + \( \tau \) → V, A interactions (\( V_{ud} \), RL symmetry, . . .)
- B, b → S, T interactions (BSM interactions, MSSM, . . .)
# Ultracold Neutrons

<table>
<thead>
<tr>
<th>Class</th>
<th>Energy</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>&gt; 1 MeV</td>
<td>Fission reactions / Spallation</td>
</tr>
<tr>
<td>Slow</td>
<td>eV – keV</td>
<td>Moderation</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.025 ev</td>
<td>Thermal equilibrium</td>
</tr>
<tr>
<td>Cold</td>
<td>μeV – meV</td>
<td>Cold moderation</td>
</tr>
<tr>
<td>Ultracold</td>
<td>≤ 300 neV</td>
<td>Downscattering</td>
</tr>
</tbody>
</table>

## How cold is Ultracold?
- Temperature < 4 mK
- Velocity < 8 m/s
- Usain Bolt ∼ 12 m/s

## UCN can be bottled
- Gravitational \( V = mgh \): 100 neV / meter
- Magnetic \( V = -\vec{\mu} \cdot \vec{B} \): 60 neV / Tesla

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

- \( ^{58}\text{Ni} \): 335 neV
- DLC: 250 neV
- BeO: 250 neV
- Cu: 170 neV
Manipulating UCN

Material bottles: UCN guides

- Features of good UCN guides:
  - Low “loss per bounce” ($< 10^{-5}$)
  - High Material Potential ($> 200$ neV)
  - Low depolarization ($\sim 10^{-6}$)

Magnetic selection: UCN polarizers

- Neutron magnetic moment $\mu$ due to spin
- 100% polarization possible

(note: neutron magnetic moment is negative)
Ultracold Neutron Facility at LANSCE

- 800 MeV proton beam + tungsten target → spallation neutrons
- Single scatter in solid deuterium: CN → UCN + phonon
- Remove phonons: SD$_2$ cooled to 4K
- “Flapper” shields UCN from SD$_2$
- 50 UCN/cc at shield wall
- Pulsed beam: Low background
Experimental Programs at the UCN Facility: UCNA
Experimental Programs at the UCN Facility: UCNA

<table>
<thead>
<tr>
<th>Corr. +/- Uncertainty (%)</th>
<th>Mendenhall (2013)</th>
<th>In analysis (TBS 8/14)</th>
<th>Next Step</th>
<th>Source of improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>+/- 0.46</td>
<td>+/- 0.40</td>
<td>+/- 0.28</td>
<td>Decay rate!</td>
</tr>
<tr>
<td>Depolarization</td>
<td>+0.67 +/- 0.56</td>
<td>+0.67 +/- 0.1</td>
<td>+0.6 +/- 0.1</td>
<td>Shutter+ ex situ</td>
</tr>
<tr>
<td>Backscatter</td>
<td>+1.36 +/- 0.34</td>
<td>+0.5 +/- 0.15</td>
<td>+0.5 +/- 0.15</td>
<td>Thin windows</td>
</tr>
<tr>
<td>Angle effect</td>
<td>-1.21 +/- 0.30</td>
<td>-0.8 +/- 0.2</td>
<td>-0.8 +/- 0.1</td>
<td>Windows+APD</td>
</tr>
<tr>
<td>Energy Reconstruction</td>
<td>+/- 0.31</td>
<td>+/- 0.08</td>
<td>+/- 0.08</td>
<td>Xenon + LED</td>
</tr>
<tr>
<td>Total Sys.</td>
<td>+/- 0.82</td>
<td>+/- 0.28</td>
<td>+/- 0.22</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+/- 0.94</td>
<td>+/- 0.5</td>
<td>+/- 0.35</td>
<td></td>
</tr>
<tr>
<td>Dominated by systematics</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Dominated by statistics</td>
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<td></td>
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<tr>
<td>Intended to be balanced</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Experimental Programs at the UCN Facility: UCN_B

- 3-body decay: $\nu$-asymmetry from proton/electron directions
- $B$ is sensitive to $b$, $b_\nu \rightarrow$ non-Standard Model Scalar and Tensor interactions
Experimental Programs at the UCN Facility: UCNB
Experimental Programs at the UCN Facility: UCNB

Novel thick, large area, highly segmented silicon detectors

Biased to -30 kV to accelerate protons

Custom preamplifiers: 24 ch instrumented
Experimental Programs at the UCN Facility: UCN\(\tau\)

Neutron lifetime

- Precise tests of Standard Model
- Big bang nucleosynthesis
- Reactor and solar neutrino flux predictions

Beam vs. Bottle

- Beam experiments: neutron flux?
- UCN bottle experiments: loss in the walls?
Experimental Programs at the UCN Facility: UCNτ

Magneto-gravitational Trap

- World’s largest permanent magnet array
- Neutrons bounded by magnetic field on bottom, gravity on top
- No wall losses!
Experimental Programs at the UCN Facility: UCN$\tau$

First storage time measurement (Feb 2013)

![Fill-and-dump Storage Measurement](image)

- $\tau = 860 \pm 19$
- $\chi^2/DOF = 0.89$

Current status

- Precision studies of systematics
- In-situ UCN counting
- Quasibound UCN cleaning?
- Monte Carlo UCN simulations
- Goal for prototype: 1 s precision measurement
- Ultimate experimental goal: 0.1 s precision