Fundamental Physics with HeII UCN Sources: The Neutron Lifetime and Electric Dipole Moment

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Significance

- Neutron Lifetime:
  - Big Bang Nuclosynthesis
  - Unitarity Tests

- Neutron Electric Dipole Moment
  - Tests of the Standard Model
  - Supersymmetry
  - Big Bang Baryogenesis
  - QCD $\theta$ parameter
What Do the Experiments Have in Common?

- Use superthemaal UCN production in HeII
- Signal detection using charged particle scintillations in HeII
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)
\~ Population of 12 K phonons
\~ $e^{-\frac{12}{K_b T_{bath}}}$
INCIDENT NEUTRON SPECTRUM

W. 0K

Penetrate Walls

E* / A

3 shown interaction

E > Evw

\frac{1}{2} 2 - e^{-E* / A}

\text{Limit from Liouville's theorem applied to neutrinos alone.}

\text{Suw} \rightarrow \text{Pe}
Intercalated Graphite

1st STAGE

2nd STAGE

- CARBON HEXAGON LAYER
- = LAYER OF INTERCALATE (ALKALI METAL ATOM)

\( K/C \times 10^{-2} \)

\( T_G - T_C \) (in K)
NIST 8.9 Å Monochromator

Φ = 5 x 10^6 n cm^{-2} s^{-1}
85 % reflectivity
Monochromator Spectrum

Counts [arb. units]

λ [nm]

Transmission
Reflection

1.4 1.2 1.0 0.8 0.6 0.4 0.2 0

30 x 10^3
20
10
0
Wavelength Filtering

Counts [arb. units]
Wavelength [nm]

- Unfiltered
- ZYH graphite
- Bi filter

ZYH graphite

Bi

diameter: 4”
thickness: 2.5”
**Detection**

- Recoiling charged particle creates an ionization track in the helium.

- Helium ions form excited $\text{He}_2^*$ molecules (ns time scale) in both singlet and triplet states.

- $\text{He}_2^*$ singlet molecules decay, producing a large prompt ($<20 \text{ ns}$) emission of extreme ultraviolet (EUV) light.

- EUV light (80 nm) converted to blue using the organic fluor (d)TPB (tetraphenyl butadiene).
Light Collection

- TPB evaporated onto Gore-tex (lifetime)
- dTPB doped into dPS and coated onto acrylic (EDM)
- Clear $\text{B}_2\text{O}_3$ beam stop
- PMTs at room temperature
- 12 p.e. signal for 360 keV beta
  > 90 % efficiency (measured in lifetime experiment)
Determination of the Neutron Lifetime Using Magnetically Trapped UCN
Produce UCN using the "superthermal" technique
Confine low field seekers within a magnetic bottle
Detect each neutron as it decays using scintillation techniques
Magnet Form
Racetrack Coil
Copper-Nickel Tube
Graphite
Neutron Shielding
TPB-coated GoreTex
Solenoids
Acrylic Lightguide
Beamstop
Trapping Region
Experimental Method

**Experimental Method**

**Raw Data**

- **“trapping”**
- **“non-trapping”**

Count Rate [s⁻¹] vs. Time [s]
Systematic Effects

- Absorption by $^3$He- Isotopically pure ($10^{-15}$) $^4$He
- Marginal Trapping - field ramping
- Majorana (Spin-Flip) Transitions- no zero-field regions
- Thermal (phonon) Upscattering - $T < 250$ mK
- Backgrounds - time dependent and time independent
Trapping/Lifetime Data

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

\[ A = (1.92 \pm 0.03) \text{s}^{-1} \]
\[ \tau = (677 +13/-12) \text{s} \]

\[ A = (1.10 \pm 0.06) \text{s}^{-1} \]
\[ \tau = (844 +53/-47) \text{s} \]

\( \checkmark \) No trapped neutrons
Future Plans

- KEK high-current quadrupole
- Another run @ NIST
- Move experiment to the NCSU UCN source or the Spallation Neutron Source
KEK High-Current Q-pole

- Maximum field is 4.9 T at 4.2K
  (70 T/m gradient)
- 30 % increase at 1.8 K
- $\varnothing = 14 \text{ cm, } l = 1.14 \text{ m}$
- Have on loan from KEK
Turning the Q-pole into a Trap

- Conservative approach:
  - design 30% under load line
  - axial depth 10% higher than radial depth

Yields trap with:
- $B = 3.1 \, \text{T}$
- $\phi = 12 \, \text{cm}$, $l = 42 \, \text{cm}$
### Upgrade Estimates

\[ \varepsilon_\tau = \frac{d_T}{\tau} \approx \frac{dS}{S} = \frac{\sqrt{(dT)^2 + (dB)^2}}{S} \approx \sqrt{\frac{2b}{n}} \quad (b > n) \]

<table>
<thead>
<tr>
<th>Setup</th>
<th># trapped</th>
<th>Thresh.</th>
<th>Signal ampl. (s^{-1})</th>
<th>Constant (s^{-1})</th>
<th>Time-dep ampl. (s^{-1})</th>
<th>( \sigma_\tau (s) ) in 40 days</th>
<th>( \varepsilon_\tau = 0.5% ) (# of days)</th>
<th>( \varepsilon_\tau = 0.1% ) (# of days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>500</td>
<td>1.5-1.5</td>
<td>0.175</td>
<td>2.0</td>
<td>4</td>
<td>110</td>
<td>&lt;1000</td>
<td>&lt;1000</td>
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<td>2001</td>
<td>1200</td>
<td>2-2</td>
<td>0.76</td>
<td>12.5</td>
<td>2.1</td>
<td>55</td>
<td>&lt;18</td>
<td>441</td>
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<tr>
<td>2003</td>
<td>3000</td>
<td>3-3</td>
<td>2.0</td>
<td>13.6</td>
<td>2.9</td>
<td>22</td>
<td>&lt;0.1</td>
<td>&lt;1.2</td>
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<tr>
<td>NIST</td>
<td>1650</td>
<td>3-3</td>
<td>1.1</td>
<td>11</td>
<td>2.9</td>
<td>36</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>NIST/KEK</td>
<td>3\times10^4</td>
<td>3-3</td>
<td>20</td>
<td>22</td>
<td>5.5</td>
<td>2.9</td>
<td>18</td>
<td>441</td>
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<tr>
<td>SNS/KEK</td>
<td>8.5\times10^5</td>
<td>3-3</td>
<td>550</td>
<td>4</td>
<td>150</td>
<td>0.15</td>
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<td>&lt;0.1</td>
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<tr>
<td>NCSU/KEK</td>
<td>1\times10^7</td>
<td>3-3</td>
<td>6500</td>
<td>11</td>
<td>&lt;0.1</td>
<td>0.036</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

- Blue: no magnet ramp
- Yellow: magnet ramp
Summary

- We can perform a competitive lifetime measurement at NIST with the KEK magnet in the next 3 years.

- Upon a successful outcome, we will move either to the planned NCSU PULSTAR UCN source or to the SNS 0.89 nm beamline to make a significantly improved measurement.
Search for the Electric Dipole Moment of the Neutron
We are developing a new experimental technique to search for the neutron electric dipole moment (EDM) that offers a factor of at least 50 increase in sensitivity over existing experiments when operated at LANSCE and a 500 fold increase at when operated at the SNS.
Neutron EDM

- A permanent EDM $\vec{d}$: separation of the charged constituents of the neutron

$$\vec{d} \cdot \vec{E}$$

- The current experimental technique (ILL) will likely yield $d < 5 \times 10^{-26} \text{e}\cdot\text{cm}$

- We hope to obtain roughly $d < 10^{-28} \text{e}\cdot\text{cm}$ with UCN stored in superfluid $^4\text{He}$
Look for a difference in precession frequency $(f = gB \pm 2dE)$ for $E$ parallel and anti-parallel to $B$.

For $d = 10^{-25}$ $e \cdot cm$ in a 10 kV/cm electric field, we expect a shift in frequency of $\approx 0.5$ $\mu$Hz.
Figure of Merit

\[ E \cdot \sqrt{N \tau} \]

\[ \rightarrow x 180 \text{ when operated at LANSCE} \]

\[ E \rightarrow 5 \ E \]
\[ \tau \rightarrow 5 \ \tau \]
\[ N \rightarrow 200-2000 \ N \]

By performing the experiment directly in superfluid helium-4 (dielectric properties + superthermal production) that is doped with polarized helium-3 which serves as a magnetometer and spin precession analyzer
Proposed Experiment

- Dilution Refrigerator (1 of 2)
- Helium Purifier
- 3He Atomic Beam Polarizer
- Measurement Cell
- Beam Entrance
- 4-layer Magnetic Shield
Look for a difference in precession frequency

\[ f_n - f_3 = (\gamma_n - \gamma_3)B \pm 2dE \]
\( ^3\text{He} \) Magnetometry

\[ ^3\text{He} + n \rightarrow t + p \]

\[ \sigma(\text{parallel}) < 10^2 \text{ b} \quad \sigma(\text{anti-parallel}) \approx 10^4 \text{ b} \]

UCN loss rate:

\[ 1 - p_3 \cdot p_n = 1 - p_3p_n\cos[(\gamma_n-\gamma_3)B_0 + 2dE]t \]

\[ |\gamma_n-\gamma_3| = |\gamma_n|/10 \quad - \text{Sensitivity to static magnetic fields is reduced by an order of magnitude!} \]

The fractional concentration of \( ^3\text{He} \) must be adjusted to maximize the lifetime \( \tau \)

\[ x = \text{Atoms} - ^3\text{He} / \text{Atoms} - ^4\text{He} \approx 10^{-10} \]
Operation of the Experiment

- Fill cell with superfluid helium, doped with polarized $^3\text{He}$
- Accumulate UCN for about 1000 s while ramping up HV (superthermal production)
- Flip spins 90° with respect to $B_0$ by RF pulses
- Observe scintillation signal and SQUID signal as a function of time for 1000 s
- Ramp HV to zero, drain cell of spent $^3\text{He}$
$^3$He Atomic Beam Polarizer

- Final testing is in progress
- Expected flux detected
- Average velocity $< 100$ m/s
- Polarization measurements are consistent with the 100% expectation
- Differential pump stages will be added soon, final tests will be completed
High Voltage System

Uses a capacitive amplification technique
full scale test apparatus
High Voltage System

- Normal State LHe holds 570 kV at 7.3 cm (≈ 40% higher than “expected”)
- Design field (50 kV/cm) at 7.3 cm holds for > 11 hr
- Max leakage current: 20 pA (3% of tolerable limit)
- Short-duration breakdown not affected by neutron radiation \((10^6 s^{-1}, \text{MeV})\)

Exceeds specifications
Progress in Other Areas

The diffusion of helium-3 in superfluid helium-4 has been measured and characterized; this is an important parameter for controlling the geometric phase systematic.

Ultracold Neutrons were produced at LANSCE by scattering cold neutrons in superfluid helium; 180 second cell lifetime was due to the superfluid fill hole. Production rate extrapolated to improved moderator, higher target current, better guides is 0.5/cc/sec, implying 250/cc UCN density at FP12 of LANSCE.

A helium isotopic purification apparatus has been operated.

A baseline model along with realistic technical scheme for operating the experiment has been developed.

We have acquired and operated a dilution refrigerator.
EDM Experiment at the SNS