Neutron Lifetime – the bottle method

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This talk:

**T violation**

Electric dipole moment: $d < 0.29 \times 10^{-25}$ e·cm, CL = 90%

Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm$^2$, (S = 1.3)

Magnetic radius $\sqrt{\langle r_M^2 \rangle} = 0.862^{+0.009}_{-0.008}$ fm

Electric polarizability $\alpha = (11.6 \pm 1.5) \times 10^{-4}$ fm$^3$

Magnetic polarizability $\beta = (3.7 \pm 2.0) \times 10^{-4}$ fm$^3$

Charge $q = (-0.2 \pm 0.8) \times 10^{-21}$ e

Mean $n\bar{n}$-oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free $n$)

Mean $n\bar{n}$-oscillation time $> 1.3 \times 10^8$ s, CL = 90% [f] (bound $n$)

Mean $nn'$-oscillation time $> 414$ s, CL = 90% [g]

**B violation**

Mean life $\tau = 880.0 \pm 0.9$ s (S = 1.4)

$c\tau = 2.6381 \times 10^8$ km

Magnetic moment $\mu = -1.9130427 \pm 0.0000005 \mu_N$

Low Energy QCD

**PDG 2013**

\[ I(J^P) = \frac{1}{2}(\frac{1}{2}^+) \]

Mass $m = 1.0086649160 \pm 0.000000004$ u

Mass $m = 939.565379 \pm 0.000021$ MeV [a]

$(m_n - m_{\bar{n}}) / m_n = (9 \pm 6) \times 10^{-5}$

$m_n - m_p = 1.2933322 \pm 0.0000004$ MeV

$= 0.00138844919(45)$ u

Mean life $\tau = 880.0 \pm 0.9$ s (S = 1.4)

$c\tau = 2.6381 \times 10^8$ km

Magnetic moment $\mu = -1.9130427 \pm 0.0000005 \mu_N$
If the electrons were to feel the strong force, there would be no chemistry or crystallography or biology -- only nuclear physics.

S. Weinberg

\[ n \rightarrow p^+ + e^- + \overline{\nu}_e + 782 \text{ keV} \]
Heracles & the Hydra

Beyond the Standard Model (BSM) theories

Experimentalist
Outline

• Why?
  – Neutron beta-decay theory
  – Impacts to cosmology

• How?
  – Beam method
  – Bottle method (material, magnetic)

  Houston, we got a problem! The two methods don’t agree.

• What’s the solution?
  – Current experiments (with the bottle technique)
Neutron Lifetime Measurement

PDG average

Experiments
Measurements of Free Neutron Lifetime

Precision improves over time, but accuracy?

PDG 2004-2010: $885.7 \pm 0.8$ s
PDG 2011: $881.0 \pm 1.5$ s
PDG 2013: $880.0 \pm 0.9$ s
PDG 2014: $880.3 \pm 1.1$ s

Reanalysis of bottle experiments by Serebrov, et al. (878.5 ± 0.7 ± 0.3) seconds
Two Different Techniques, Two Lifetimes?

\[ \tau_n(\text{beam}) = 887.3 \pm 2.8 \text{ s} \]

\[ \Delta \tau_n = 7.7 \pm 2.9 \text{ s} \]

NIST beam lifetime (2005)

Updated NIST beam lifetime

887.7 ± 1.2 ± 1.9 s (2013)

\[ \tau_n(\text{bottle}) = 879.6 \pm 0.6 \text{ s} \]
Two Complementary Techniques

Cold Neutron Beam

- Alpha, triton detector
- Precision aperture
- $^6\text{Li}$ deposit
- Mirror (+800 V)
- Trap electrodes
- Door open (ground)
- Proton detector
- Neutron beam

Ultracold Neutron (UCN) Bottle

- Fill
- Store
- Count

Number Observed vs. Time
Neutron beta-decay

Parity violation:
V-A weak interaction

\[ H_{\beta} = H_{V,A} \]
\[ = \bar{e} \gamma_\lambda (1 - \gamma^5) \nu_e \bar{p} (g_V + g_A \gamma^5) \gamma^\lambda n \]

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

Vector (Fermi, \( \Delta J=0 \))

Axial Vector (Gamow-Teller, \( \Delta J=1 \))

<table>
<thead>
<tr>
<th>n DECAY MODES</th>
<th>Fraction ((\Gamma_i/\Gamma))</th>
<th>Confidence level</th>
<th>( p ) (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p e^- \bar{\nu}_e )</td>
<td>100%</td>
<td>([k]) ((3.09 \pm 0.32) \times 10^{-3})</td>
<td>1</td>
</tr>
<tr>
<td>( p e^- \bar{\nu}_e \gamma )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neutron beta-decay

Parity violation:
V-A weak interaction

\[ H_\beta = H_{V,A} \]

\[ = \overline{e} \gamma_\lambda (1 - \gamma^5) \nu_e \bar{p} (g_V + g_A \gamma^5) \gamma^\lambda n \]

**Vector (Fermi, \(\Delta J=0\))**

**Axial Vector (Gamow-Teller, \(\Delta J=1\))**


**Polarized neutron**
The Weak-Interaction Dance Party

This Saturday!
Wine and beer
Dress casual
Please observe the “Wienberg-Glashaw-Salem” rules → Left-Handed Particles Only

Left-Handed (admitted)

Right-Handed (Not allowed)
Mirror Symmetry is Broken!

THE MIRROR DID NOT SEEM TO BE OPERATING PROPERLY.

Gamow-Teller transition

\[ n \rightarrow p \]

RH antiparticle

\[ e^- \rightarrow \bar{v} \]

LH particle

\[ n \rightarrow p \]

LH antiparticle

\[ e^- \rightarrow \bar{v} \]
Girl before a mirror, Picasso
1932
Cabbibo-Kobayashi-Maskawa (CKM) Matrix

\[
\begin{pmatrix}
  d_w \\
  S_w \\
  b_w
\end{pmatrix} =
\begin{pmatrix}
  0.97419(22) & 0.2257(10) & 0.003959(16) \\
  0.9750(8) & 0.223(4) & 0.0035(25) \\
  0.2256(10) & 0.97334(23) & 0.0415(11) \\
  0.222(3) & 0.9742(8) & 0.040(3) \\
  0.00874(37) & 0.0407(10) & 0.999133(43) \\
  0.009(5) & 0.039(4) & 0.9992(2)
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014 < 1
\]

\[
= 1.0000 \pm 0.0004
\]

Good agreement with unitarity!
V_{ud} for CKM Unitarity Test

f: Phase space factor = 1.6886
(Fermi function, nuclear mass, size, recoil)

\[ 1/\tau_n = fG_F^2|V_{ud}|^2m_e^5(1+3g_A^2)(1+RC)/2\pi^3 \]

RC = \[ \frac{\alpha}{4\pi} \int_0^\infty dQ \frac{m_w^2}{Q^2 + m_w^2} F(Q^2) \]

From \( \mu \)-decay: 0.6 ppm (MuLan 2011)

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

• 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 \( \Delta \tau/\tau = 4 \times 10^{-4} \).
• Significance in Astrophysics (more coming).
Cosmology: Primordial Nucleosynthesis

\[ \Delta E = 1.293 \text{ MeV} \]

\[ n/p = \exp(-\Delta E/k_B T) \]

\[ n/p = \frac{1}{6} \]

\[ n/p = \frac{1}{7} \]

\[ k_B T \approx 0.1 \text{ MeV} \quad k_B T \approx 1 \text{ MeV} \]

\[ n + e^+ \leftrightarrow p + \bar{\nu}_e, \]

\[ n + \nu_e \leftrightarrow p + e^- \]

neutron decay

\[ n \rightarrow p + e^- + \bar{\nu}_e. \]
Big-Bang Nucleosynthesis

$n + \nu_e \leftrightarrow p + e^-$

$n + e^+ \leftrightarrow p + \bar{\nu}$

0.1 MeV (entropy-delayed nucleosynthesis)

1 MeV

Neutrinos decouple from thermal bath

Fig. 7.3. Composition of matter in the early universe.
Big-Bang Nucleosynthesis

1. $n \rightarrow ^1H + e^- + \bar{\nu}$
2. $^1H + n \rightarrow ^2H + \gamma$
3. $^2H + ^1H \rightarrow ^3He + \gamma$
4. $^2H + ^2H \rightarrow ^3He + n$
5. $^2H + ^2H \rightarrow ^3H + ^1H$
6. $^2H + ^3H \rightarrow ^4He + n$
7. $^3H + ^4He \rightarrow ^7Li + \gamma$
8. $^3He + n \rightarrow ^3H + ^1H$
9. $^3He + ^2H \rightarrow ^4He + ^1H$
10. $^3He + ^4He \rightarrow ^7Be + \gamma$
11. $^7Li + ^1H \rightarrow ^4He + ^4He$
12. $^7Be + n \rightarrow ^7Li + ^1H$
\[ Y_p = 0.228 + 0.023 \log \eta_{10} + 0.012 N_\nu + 0.018 (\tau_n - 10.28) \]

\[ Y_p = 0.2471 \pm 0.0002 \text{ (theory) } \]
\[ \pm 0.0002 (\tau_n, 2014 PDG value) \]
\[ \pm 0.0001 (CMB) \]
Cosmic Microwave Background

$\Delta T = 0.1 \text{ mK}$
$Y_p$ & Non-Standard Model Cosmology

- Sensitive to the number of relativistic particle (neutrino) species.

$$\tau = 885.7(8)s \Rightarrow 878.5(8)s$$

$$\Rightarrow \Delta Y_p / Y_p = -0.0015$$

$$\Rightarrow \Delta N_\nu = +0.12$$

where $N_\nu$ is the # of light neutrino species ($N_\nu = 3$ in Standard Model)

present value of $N_\nu = 3.68 \pm 0.4/-0.3$ (Izotov/Thuan 2010)

$\Delta N_\nu$ improves to $\pm 0.2$ from Planck data (2013)

Will we get $N_\nu = 4$ at 5$\sigma$?
What kind of universe we would have today,

– if the neutron is lighter than the proton?
– if the $G_F$ is stronger by an order of magnitude?
– if the neutron does not decay?

Other Relevant Processes

\[ n + e^+ \leftrightarrow p + \bar{\nu} \] (big-bang nucleosynthesis)
\[ p + e^- \leftrightarrow n + \nu \] (big-bang nucleosynthesis, neutron star formation)
\[ p + p \rightarrow ^2H + e^+ + \nu \] (solar fusion)
\[ p + p + e^- \rightarrow ^2H + \nu \] (solar fusion)
\[ \nu + n \rightarrow e^- + p \] (neutrino detection)
\[ \bar{\nu} + p \rightarrow e^+ + n \] (antineutrino detection).
Measure the Muon Lifetime

IU P451 Modern Physics Laboratory:
Cosmic Ray

MuLAN experiment, PSI

\[ \tau_\mu = 2.1969811(22) \times 10^{-6} \text{ s} \]
“Why is it so hard to measure the neutron lifetime”? Give me three reasons:
"Why is it so hard to measure the neutron lifetime"? Give me three reasons:

• Neutron is charge-neutral
  – Hard to guide and focus.
  – Hard to detect. Low energy neutrons are non-ionizing.

• Low S/N: Low density of free neutrons & large BG
  – Cold neutron beam: $10^{10}/\text{cm}^2\text{-s}$ (cold neutrons) $\rightarrow 10^5 /\text{c.c.}$
  – UCN: 40 /c.c.

• Long lifetime, susceptible to other loss mechanisms (capture, upscattering, etc..)
Ultra-Cold Neutrons (UCN)

- What are UCN?
  - Very slow neutrons
    \[(v < 8 \text{ m/s} \rightarrow \lambda > 500 \text{ Å})\]
    that cannot penetrate into certain material.

- Long storage time
- Low radiation background
- 100% polarization

→ Precision measurements
### Material Potential

\[ V_F = \frac{2\pi\hbar^2 N b_C}{m_n} \]

**Fermi potential**

<table>
<thead>
<tr>
<th>Material</th>
<th>(V_F) (neV)</th>
<th>(v_c) (m/s)</th>
<th>(\eta) ((\times10^{-4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(_2)O</td>
<td>170</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Be (BeO)</td>
<td>250</td>
<td>6.9</td>
<td>2.0-8.5</td>
</tr>
<tr>
<td>C</td>
<td>180</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>60</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>50</td>
<td>3.2</td>
<td>2.9-10</td>
</tr>
<tr>
<td>SiO(_2) (quartz)</td>
<td>110</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>170</td>
<td>5.6</td>
<td>2.1-16</td>
</tr>
<tr>
<td>Fe</td>
<td>220</td>
<td>6.5</td>
<td>1.7-28</td>
</tr>
<tr>
<td>Co</td>
<td>70</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>230</td>
<td>6.8</td>
<td>5.1</td>
</tr>
</tbody>
</table>

### Critical velocity

\[ v_c = \sqrt{\frac{2V_F}{m_n}} \]
Neutron Trap Experiments

Mambo (Mampe’s bottle)
- Fomblin Oil
- Vary V/A ratio
- Mambo II: pre-spectrum

Measures the Storage Time

\[
\frac{1}{\tau_{\text{mea}}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{\text{heat}}} + \frac{1}{\tau_{qb}} + \ldots
\]
Material Bottle

A. Serebrov (2008)

Dubbers & Schmidt (2011)
The size of correction:

\[ \tau_\beta - \tau_{mea} = \Delta \tau = 1 \, s \]

\[ \tau_{ab} = \frac{\tau_{mea} \tau_\beta}{\tau_\beta - \tau_{mea}} = \frac{\tau_{mea}}{\Delta \tau} \tau_\beta \approx 10^6 \, s = 12 \, \text{days} \]

Q: How well do we have to measure each (non-beta-decay) loss time?

A. the same precision as the lifetime.
B. 10 times more precise than the lifetime.
C. 10 time less precise than the lifetime.
D. 100 times less precise than the lifetime.
How well to measure each non-beta-decay loss?

\[
F = \frac{1}{\tau_{\text{mea}}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{ab}}} + \frac{1}{\tau_{\text{up}}} + \frac{1}{\tau_{\text{sf}}} + \frac{1}{\tau_{\text{heat}}} + \frac{1}{\tau_{\text{qb}}} + \ldots
\]

\[
dF = -\left(\frac{d\tau_{\text{mea}}}{\tau_{\text{mea}}}\right)\frac{1}{\tau_{\text{mea}}} = -\left(\frac{d\tau_\beta}{\tau_\beta}\right)\frac{1}{\tau_\beta} - \left(\frac{d\tau_{\text{ab}}}{\tau_{\text{ab}}}\right)\frac{1}{\tau_{\text{ab}}} + \ldots
\]

\[
\frac{d\tau_\beta}{\tau_\beta} = \frac{d\tau_{\text{mea}}}{\tau_{\text{mea}}} \cdot \frac{\tau_\beta}{\tau_{\text{mea}}} - \frac{d\tau_{\text{ab}}}{\tau_{\text{ab}}} \cdot \frac{\tau_\beta}{\tau_{\text{ab}}} + \ldots
\]

Each loss is a new degree of freedom, so this is a vector sum.

\[
\frac{d\tau_\beta}{\tau_\beta} = \sqrt{\left[\left(\frac{d\tau_{\text{mea}}}{\tau_{\text{mea}}} \cdot \frac{\tau_\beta}{\tau_{\text{mea}}}\right)^2 + \left(\frac{d\tau_{\text{ab}}}{\tau_{\text{ab}}} \cdot \frac{\tau_\beta}{\tau_{\text{ab}}}\right)^2\right]} + \ldots
\]

If the trap storage time is long, so that the correction to the beta-decay lifetime is short:

\[
\tau_{\text{ab}} = \frac{\tau_{\text{mea}}\tau_\beta}{\tau_\beta - \tau_{\text{mea}}} = \frac{\tau_{\text{mea}}}{\Delta\tau} \tau_\beta \approx 10^6 \text{ s}
\]

\[
\frac{d\tau_{\text{ab}}}{\tau_{\text{ab}}} \cdot \frac{\tau_\beta}{\tau_{\text{ab}}} = \frac{d\tau_{\text{ab}}}{\tau_{\text{mea}}} \cdot \frac{\Delta\tau}{\tau_{\text{mea}}} = p \times \frac{1}{10}
\]

\[
\frac{d\tau_\beta}{\tau_\beta} = p
\]

\[
\frac{d\tau_{\text{ab}}}{\tau_{\text{ab}}} = p \times \frac{1}{10} \times \frac{\tau_{\text{mea}}}{\Delta\tau} = 100 \ p
\]

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Ways to manipulate UCN:

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

R ~ 0.5 m, Bmax = 3.5 T, current density: 250 A/mm

W. Paul et al (1970)

1989: $\tau_n = (877.0 \pm 10) \text{ s}$

Problem: betatron motions mix with the cyclotron motion
UCN Lifetime Experiment at Institut Laue-Langevin

2004

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

increase storage volume from 3.6 l to 15 l

V. Ezhov et al., J. Res. NIST 110 (2005) 345
**UCNτ: Magneto-Gravitational Trap**

- **Avoid material loss (magnetic trap):** Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **Minimize UCN spin-depolarization loss:** EM Coils arranged on the toroidal axis generates holding $\mathbf{B}$ field throughout the trap (perpendicular to the Halbach array field).
Halbach magnetic array

Fields on the top are enhanced.
Fields on the bottom are cancelled.
Asymmetric Trap induces "Phase Space Mixing"

Low symmetry, together with field ripples, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

→ quick cleaning (~ 10s of seconds) of the ‘quasi-bound’ UCN with large tangential velocities.

Adjacent Magnetization \[ \frac{\pi}{2} \] out of phase

PMs in a given row share same alignment

Two torus patches of different curvatures join along middle row
Quasi-bound Neutrons

If the QB neutrons are not sufficiently cleaned, they will leak out of the trap with its own characteristic time constant $\tau_{qb}$. The resulting correction time is:

$$\Delta \tau = \frac{\tau_{\beta}^2}{(t_2 - t_1)} \epsilon \left[ \exp(-t_1/\tau_{qb}) - \exp(-t_2/\tau_{qb}) \right]$$

$t_2 = 2000 \text{ s} \quad t_1 = 200 \text{ s} \quad \epsilon = 0.01$

To limit $\Delta t < 0.1 \text{ s}$ for all $\tau_{qb}$, need $\epsilon < 3e^{-4}$

$\Delta t = 0.1 \text{ s}$
Poincare’s Section of Surface

Two degrees of freedom
UCN Cleaning

\[ E_{\text{max}} = E_0 + 6 \text{ neV} \]

\[ E_0 = 50 \text{ neV}: \text{trap threshold} \]
Incident Angle

Different azimuthal angels $\phi$

$v=2.5 \text{ m/s}, \phi_0 = 0 \text{ deg}$

Increasing $\theta$

$v=2.5 \text{ m/s}, \phi_0 = 20 \text{ deg}$

$v=2.5 \text{ m/s}, \phi_0 = 70 \text{ deg}, N=2000$

$v=2.5 \text{ m/s}, \phi_0 = 90 \text{ deg}$

Increasing stochasticity with $\phi$
Height vs. Transverse Velocity

UCN motion becomes chaotic when the height reaches R/2.
Make the bowl asymmetric \((R_1 \neq R_2)\)

\(v=2.0\text{m/s}, \phi_0=90\text{deg} \) (symmetric)

Thin stochastic regions bounded by KAM curves.

\(v=2.0\text{ m/s}, \phi_0=90\text{ deg} \) (asymmetric)

Strong perturbation, KAM curves are destroyed.
Assembly of the Halbach Array @ IU CEEM (July-Dec. 2012)
Field Ripples on the Halbach Array
Array Insertion at LANL (Jan. 2013)
Halbach Array Trap + $\varepsilon$ (copper tape)
A critical component: The trap door

Gap size ~ 0.003 in. Don’t expect UCN to leak around the trap door.
Holding Field Coils
After one month, ...
The UCN$\tau$ Experiment at LANSCE

UCN$\tau$ Magneto-Gravitational Trap

UCNA Spectrometer (1 UCN/c.c.)

UCN$\tau$ 10B UCN Detector

7T Polarizer Field

Zr Vacuum Separation Foil

Gate Valve (80 UCN/c.c.)

6T Pre-Polarizer Magnet (PPM)

UCN$\tau$ Experiment Spallation driven by LANSCE 800 MeV proton accelerator
Operation of the UCNτ Experiment

“Fill & Empty” cycle
1. fill UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Empty UCN

3He Drift Tubes (not pictured)
1. Fill ~200s

To source

To monitor
2. Clean (the E spectrum) ~30s

Low density polyethylene sheet upscatters UCN with enough energy to reach the cleaning height.
3. Store ~50-2000s
4. Dump >200s
Counts in the dump detector

200 s storage run, followed by a 2000 second storage run

\[ \tau_n = \frac{-(t_2 - t_1)}{\log\left(\frac{N_2}{N_1}\right)} \]

Example Fill-and-Empty Run
2013 “Fill and Empty” Measurements

\[ \tau_{\text{trap}} = 860 \pm 19 \, \text{s} \]

\[ \chi^2 / \text{DOF} = 0.89 \]

\( S \)

\( t_{\text{store}} \, [\text{s}] \)
An *in-situ* Vanadium Detector $\rightarrow$ control phase-space evolution

\[ ^{51}V + n \rightarrow ^{52}V \]
\[ ^{52}V \rightarrow ^{52}Cr + \beta^- (0 -- 2.54 \text{ MeV}) + \gamma (1.43 \text{ MeV}) \]

- **Negative Material Potential**
- **Good n Absorber**

**Table: 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>

- **Plastic Scintillator for β’s**
- **Nal for γ’s**

- ① V foil lowered into trap from above (~1s)
- ② Remaining UCN are absorbed (~20s for current small foil)
- ③ V foil raised and activity is measured

\[ T_{1/2} = 3.7 \text{ min.} \]
Cut Criteria:
(1) beta event is not coincident with a beta event in the other detector
(2) beta event pulse-height (460~8000).
(3) beta event is coincident with an NaI event
(4) NaI event a pulse-height (2500~3500)
The Halbach array serves as a very good spin analyzer.
Mod 2 Results (2014-2015 run)

Load 350 s
Clean 400 s
Absorb 30 s
Count 1000s

$\beta_\text{xNaI (photopeak)}$
$\beta_\text{xNaI (>750 keV)}$
$\beta_\text{xNaI (>2000 keV)}$

430 s holding time
2430 s holding time

$\epsilon = 15\%$
$\epsilon = 30\%$
$\epsilon = 60\%$

Fit Background to this region

2014 run data: neutron lifetime measured w/ an in-situ V detector.

Preliminary
$\tau = 8XX \pm 3$ s

- Statistics are sufficient for < 3s.
- Systematics need much more study.
- Trap lifetime appears to be very long.
A new *in-situ* detector: $^{10}\text{B}$ coated ZnS

Thermal evaporation

<table>
<thead>
<tr>
<th>Ion (Label $i$)</th>
<th>Energy ($E^i_0$, MeV)</th>
<th>Probability ($w^i$)</th>
<th>Range ($R^i$, μm)</th>
<th>$R^i/\lambda_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (1)</td>
<td>1.47</td>
<td>94%</td>
<td>3.35</td>
<td>0.17</td>
</tr>
<tr>
<td>$\alpha$ (2)</td>
<td>1.78</td>
<td>6%</td>
<td>4.15</td>
<td>0.21</td>
</tr>
<tr>
<td>$^7\text{Li}$ (3)</td>
<td>0.84</td>
<td>94%</td>
<td>1.78</td>
<td>0.09</td>
</tr>
<tr>
<td>$^7\text{Li}$ (4)</td>
<td>1.02</td>
<td>6%</td>
<td>2.04</td>
<td>0.10</td>
</tr>
</tbody>
</table>

$^{10}\text{B} + n \rightarrow ^7\text{Li} (0.84 \text{ MeV}) + \alpha (1.47 \text{ MeV}) + \gamma (0.48 \text{ MeV}),$

$^7\text{Li} (1.02 \text{ MeV}) + \alpha (1.78 \text{ MeV}),$
UCN signal from the ZnS detector (J. Wang, C. Morris)
## Current Systematics Estimates Guiding 2015/2016 Plan

<table>
<thead>
<tr>
<th>Effect</th>
<th>Upper Bound</th>
<th>Direction</th>
<th>Current Eval.</th>
<th>Method of Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>residual gas</td>
<td>&lt; $1 \times 10^{-4}$</td>
<td>+</td>
<td>meas</td>
<td>RGA/cross-section measurements</td>
</tr>
<tr>
<td>depolarization</td>
<td>&lt; $1 \times 10^{-4}$</td>
<td>+</td>
<td>calc</td>
<td>field map, <em>in situ</em> detection</td>
</tr>
<tr>
<td>material loss</td>
<td>&lt; $4 \times 10^{-4}$</td>
<td>+</td>
<td>calc</td>
<td>measure Cu tape loss-per-bounce</td>
</tr>
<tr>
<td>cleaning</td>
<td>&lt; $6 \times 10^{-4}$</td>
<td>+</td>
<td>sim</td>
<td>vary cleaning time/depth, active cleaner</td>
</tr>
<tr>
<td>cleaner reliability</td>
<td>&lt; $5 \times 10^{-4}$</td>
<td>±</td>
<td>sim</td>
<td>verify position reproducibility</td>
</tr>
<tr>
<td>microphonic heating</td>
<td>&lt; $1 \times 10^{-4}$</td>
<td>+</td>
<td>sim</td>
<td>accelerometer measurements</td>
</tr>
<tr>
<td>dead time/pileup</td>
<td>&lt; $1 \times 10^{-4}$</td>
<td>±</td>
<td>calc</td>
<td>pileup ID/artificial dead time</td>
</tr>
<tr>
<td>gain drifts</td>
<td>&lt; $2 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>spectral monitoring/gain monitoring</td>
</tr>
<tr>
<td>time-dep. background</td>
<td>&lt; $5 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>background data analysis</td>
</tr>
<tr>
<td>phase space evolution</td>
<td>&lt; $5 \times 10^{-4}$</td>
<td>±</td>
<td>sim</td>
<td>vanadium time studies, active detector</td>
</tr>
<tr>
<td>UCN monitoring</td>
<td>&lt; $3 \times 10^{-4}$</td>
<td>±</td>
<td>meas</td>
<td>measure monitor response/source stability</td>
</tr>
<tr>
<td>total</td>
<td>&lt; $1.2 \times 10^{-3}$</td>
<td>±</td>
<td></td>
<td>(uncorrelated sum)</td>
</tr>
</tbody>
</table>
Some other efforts
Proposed large volume magnetic storage experiment

PENeLOPE

Magnetic storage of UCN & proton extraction

S. Paul et al.

- proton detectors
- focusing coils
- neutron absorber
- superconducting coils $B \approx 2$ T (at wall)
- volume $\sim 700$ l
- slit for filling

$\rho_{\text{UCN}} = 10^3 - 10^4$ cm$^{-3}$ (PSI /FRM II):

$N_{\text{stored}} = 10^7 - 10^8$

- Statistical accuracy:
  $\delta \tau_n \sim 0.1$ s in 2-4 days

- Systematics:
  - Spin flips negligible (simulation)
  - use different values $B_{\text{max}}$ to check expected $E_{\text{UCN}}$ independence of $\tau$

R. Picker et al., J. Res. NIST 110 (2005) 357

\[
N(t) = N(t_0) \exp \left( -\frac{t}{\tau_n} \right)
\]
ILL Neutron lifetime experiment with magneto-peristaltic UCN extraction from superfluid $^4$He into a magnetic trap

Halbach magnetic octupole (1.3 T) with $V = 5$ liters and $10^6$ neutrons per filling

$\Rightarrow$ statistical accuracy: 0.1 s in 50 days

- Small Volume.
- Source not yet ready.
- Cryogenic experiment adds challenge.
- Symmetric trap.

O. Zimmer, NIM A 554 (2005) 363
K. Leung, O.Z., arXiv:0811.1940
Beam vs Bottle