Neutron Lifetime Measurements

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Workshop on Fundamental Neutron Physics
April 6, 2007
The Neutron

- 1930: Bothe and Becker in Germany bombard beryllium with alpha particles and observe a non-ionizing and penetrating radiation. Assumed to be gamma rays.

- 1932: Irène and Frédéric Joliot-Curie let the radiation hit a block of paraffin and observe that it caused the wax to emit protons. Interpret the protons as ejected by gammas.

- Rutherford and Chadwick do not think that gamma rays are responsible.

- 1932: Neutron discovered in experiment by Chadwick.

Neutron Decay

• 1934: Chadwick and Goldhaber detect the photo-disintegration of the deuteron in the reaction

\[ ^2H + \gamma \rightarrow ^1H + n + Q \]

From the \( Q \)-value, they determine an estimate for the neutron mass, which is greater than the proton mass.

• The implication is that the neutron is energetically allowed to decay:

\[ n \rightarrow p + e^- + \bar{\nu}_e + 783 \text{ keV} \]

• 1948: Snell and Miller at Oak Ridge definitely observe the neutron decay into a proton (and Robson 1950 at Chalk River).
—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{1}{4} \times 1\frac{1}{8}$ inch aperture in the center of the graphite plate, and dynode of a secondary electron multiplier. The dynode is specially enlarged so as to cover in the neutron beam; (2) with and without a thin foil over the multiplier aperture; (3) with and without the accelerating voltage. In a total counting rate of about 300 per min., about 100 are sensitive to operations (1), (2), and (3). In the absence of the accelerating field or with the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample $(4 \times 10^4)$ give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincident ones are presently being sought between the disintegration betas and the collected protons.

Snell and Miller, Phys. Rev. 74, 1217A (1948)
"...half-life in the range 10-30 minutes...consistent with all our observations."
"...half-life...minimum of 9 minutes and a maximum of about 25 minutes."

Fig. 1. Plan view of the apparatus.

Fig. 2. Electron multiplier counting rate as a function of magnetic field for a potential of 15 kv on the high voltage electrode. The solid curve corresponds to the boron shutter "out" and the dotted curve to the boron shutter "in."

Fig. 3. Variation of number of focused protons with the potential on the high voltage electrode.
History of Neutron Lifetime 1950-2005

Physics from Neutron Decay

- Solar physics: $p + p \rightarrow ^2H + e^+ + \nu_e$

- Big Bang Nucleosynthesis and light element abundance.

- Test of CKM unitarity; determination of $V_{ud}$.

- Over-constrained measurements give model-independent SM checks.

- Look for scalar, tensor forces, non-SM physics.

- Measurement of radiative corrections.

- New source of time-reversal ($CP$) violation?
Neutron Decay Parameters

- $(m_n + m_p)c^2 = 1877 \text{ MeV}$; $(m_n - m_p)c^2 = 1293 \text{ keV}$

- Decay products: $n \rightarrow p + e^- + \bar{\nu}_e$; $\tau_n \approx 15 \text{ min.}$
  
  $0 < T_e < 783 \text{ keV}$
  $0 < T_p < 751 \text{ eV}$

- Other decay modes:
  
  $n \rightarrow p + e^- + \bar{\nu}_e + \gamma$ $BR(15\text{ keV}) \approx 3 \times 10^{-3}$
  
  $n \rightarrow H^0 + \bar{\nu}_e$ $BR \approx 4 \times 10^{-6}$

Beta Decay Probability of a Free Neutron

With one possible matrix element (V-A)

$$\mathcal{M} = \frac{G_F}{2\sqrt{2}} V_{ud} \bar{\psi}_p \gamma_\mu (f + g\gamma_5) \psi_n \bar{\psi}_e \gamma^\mu (1 + \gamma_5) \psi_\nu$$

we can calculate the transition probability

$$W = \frac{1}{\tau} = \frac{2\pi}{\hbar} |\langle f | \mathcal{M} | i \rangle|^2 \rho_f$$

Define new coupling constants

$$g_A \equiv G_F V_{ud} g(0) \quad g_V \equiv G_F V_{ud} f(0)$$

and express the lifetime tau as

$$\tau^{-1} \propto f \xi,$$

where $f$ is a kinematic factor and

$$\xi = g_V^2 |\langle 1 \rangle|^2 + g_A^2 |\langle \sigma \rangle|^2$$
Beta Decay Probability of a Free Neutron

Here

\( \langle 1 \rangle \) - Fermi matrix element; vector

\( \langle \sigma \rangle \) - Gamov-Teller matrix element; axial

Evaluate the matrix elements for the case of neutron decay gives

\[ |\langle 1 \rangle|^2 = 1 \quad |\langle \sigma \rangle|^2 = 3 \]

Substitution yields

\[ f \tau = \frac{K/\ln 2}{(g^2_V + 3g^2_A)} \]

Neutron Decay w/ Radiative Corrections

\[ \tau = \frac{1}{f(1 + \delta_R)} \frac{K/ln 2}{G_F^2 V_{ud}^2 (1 + \Delta V^R)(1 + 3\lambda^2)} \]

where \( f(1 + \delta_R) = \text{statistical rate fct + rad. corrections} \)

\( (1 + \Delta V^R) = \text{radiative corrections (nucleus independent)} \)

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

Lifetime and Correlation Coefficients

\[ dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + \frac{a}{E_e} \frac{p_e \cdot p_{\nu}}{E_e E_{\nu}} + \sigma_n \cdot \left( \frac{A}{E_e} \frac{p_e}{E_{e}} + \frac{B}{E_{\nu}} \frac{p_{\nu}}{E_{\nu}} + \frac{D}{E_e E_{\nu}} \frac{p_e \times p_{\nu}}{E_{e} E_{\nu}} \right) \]

**Lifetime**

\[ \tau = \frac{1}{f(1 + \delta_R)} \frac{K/ln2}{(1 + \Delta^V_R)(g_V^2 + 3g_A^2)} = (885.7 \pm 0.8) \text{ s} \]

**Electron-antineutrino asymmetry**

\[ a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} = (-0.103 \pm 0.004) \]

**Spin-electron asymmetry**

\[ A = -2 \frac{|\lambda|^2 - |\lambda|\cos\phi}{1 + 3|\lambda|^2} = (-0.1173 \pm 0.0013) \]

**Spin-antineutrino asymmetry**

\[ B = 2 \frac{|\lambda|^2 - |\lambda|\cos\phi}{1 + 3|\lambda|^2} = (0.981 \pm 0.004) \]

**Triple correlation**

\[ D = 2 \frac{|\lambda|\sin\phi}{1 + 3|\lambda|^2} = (-4 \pm 6) \times 10^{-4} \]

**Coupling ratio**

\[ \lambda = \frac{|g_A|}{|g_V|} e^{i\phi} = (-1.2695 \pm 0.0029) \]

**PDG, 2006 update**

Standard Model Test

\[ g_A (\text{GeV}^{-2}) \]

\[ g_V (\text{GeV}^{-2}) \]

Electron Asymmetry

Neutron Lifetime

Nuclear Lifetimes
CKM matrix represents a rotation of the quark mass eigenstates to the weak eigenstates.

\[
\begin{pmatrix}
  d_w \\
  s_w \\
  b_w
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- Unitarity requires \( |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \) (unless...)

- \( |V_{us}| \) obtained from kaon decay experiments; theoretical question on calculation of form factor \( f_+(0) \).

- \( |V_{ud}| \) obtained from
  1. nuclear lifetimes,
  2. pion beta decay, and
  3. neutron beta decay.
$\left| V_{udl} \right|_{0^+} = 0.97377 \pm 0.00027$

Pion decay: $\left| V_{udl} \right|_{\pi^+} = 0.9728 \pm 0.0030$

Neutron decay: $\left| V_{udl} \right|_{n} = 0.9745 \pm 0.0016$

Contributions in neutron system (PDG 2006):

$\frac{\sigma}{\tau} = 0.09\%$, $\frac{\sigma}{\lambda} = 0.23\%$, and $\frac{\sigma}{th.} = 0.04\%$

**Significant improvements are feasible.**
Status of the Neutron Lifetime

PDG $\tau = (885.7 \pm 0.8) \text{s}$
Status of the Neutron Lifetime

PDG $\tau = (885.7 \pm 0.8) \text{ s}$
New result from Serebrov et al.
The Exponential Decay Law: \( N = N_0 e^{-\lambda t} \)

1. “In beam” method:

\[ -\frac{dN}{dt} = N \lambda \]

Register the decay products from a well-defined volume traversed by a neutron beam of well-determined fluence rate.

2. Neutron “bottles”:

\[ \frac{N_1}{N_2} = e^{-\lambda(t_1 - t_2)} \]

An ensemble of ultracold neutrons in confined gravitationally or materially. Measure the change in neutron population.

3. Measure the slope of exponential decay:

\[ \ln\left(\frac{N}{N_0}\right) = -\lambda t \]

Watch the decay product of an ensemble of neutrons as a function of time and measure the slope.
<table>
<thead>
<tr>
<th>Technique</th>
<th>Detection</th>
<th>Issues</th>
<th>Approach</th>
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<tbody>
<tr>
<td>(1) cold in-beam</td>
<td>proton trap and neutron counter</td>
<td>$10^{-3}$ absolute efficiencies</td>
<td>fastidiousness</td>
</tr>
<tr>
<td>(2) UCN material confinement</td>
<td>neutron monitor</td>
<td>UCN energy distribution; wall effects</td>
<td>“cleaning”; spectrum measurement</td>
</tr>
<tr>
<td>(2’) UCN magnetic confinement</td>
<td>neutron and/or proton monitor</td>
<td>UCN energy distribution; orbits (spin flip)</td>
<td>“cleaning”; spectrum measurement</td>
</tr>
<tr>
<td>(3) UCN in He-4 (or vacuum)</td>
<td>monitor decay electrons</td>
<td>signal and background</td>
<td>more signal, less background</td>
</tr>
</tbody>
</table>
MamBo I at ILL


\[ \lambda_{st} = \lambda_n + \lambda_{loss} + \ldots \]

Vary \( A \) and \( V \) of confinement and extrapolate to infinite \( V \).
Additional corrections for gravity, filling and counting time, ...

$$\lambda_n = (887.6 \pm 3) \, s$$
UCN Gravitational Trap Experiment

A. Serebrov¹,³, V. Varlamov¹, A. Kharitinov¹, A. Fomin¹, Yu. Pokotilovski², P. Geltenbort⁴, J. Butterworth⁴, I. Krasnoschekova¹, M. Lasakov¹, K. Schechenbach⁵, R. Taldaev¹, A. Vassiljev¹, and O. Zherebtov¹

¹ - Petersburg Nuclear Physics Institute
² - Joint Institute for Nuclear Research, Dubna
³ - Paul Scherrer Institut
⁴ - Institute Laue-Langevin
⁵ - Technische Universität München
Method of “Gravitrap” Experiment

- Confine UCNs gravitationally in material “bottle” (low temperature fomblin oil)

- Storage lifetime as a function of UCN energy and temperature

- For an ideal wall (step function potential):

\[ \lambda_{st} = \lambda_n + \eta \gamma \]

where

\[ \eta = -\frac{Im(V_F)}{Re(V_F)} \] = wall loss coefficient

\[ \gamma = \text{loss-weighted collision frequency} \]

- Use two traps to reduce systematics: measure \( \lambda_{st}^1, \lambda_{st}^2 \)
  calculate \( \gamma^1, \gamma^2 \)

- Extrapolate neutron lifetime as function of gamma
1 – neutron guide from UCN Turbine;
2 – UCN inlet valve;
3 – beam distribution flap valve;
4 – aluminium foil (now removed);
5 – “dirty” vacuum volume;
6 – “clean” (UHV) vacuum volume;
7 – cooling coils;
8 – UCN storage trap;
9 – cryostat;
10 – mechanics for trap rotation;
11 – stepping motor;
12 – UCN detector;
13 – detector shielding;
14 – evaporator
Low temperature fomblin oil

- Why fomblin?
  - Contains only C, O, and F (no H)
  - Small neutron capture X-section
  - At low temp, inelastic scattering is small
  - Liquid fills in gaps
  - Uniform films by vapor deposition

- Calculation by Pokotilovski of

\[ \eta = 2 \times 10^{-6} \]

See INT talk next week.
Temperature dependence

(a) UCN storage lifetime measured during warming and cooling of LTF covered wide Be-Cu trap

(b) UCN counted during final 1000 s of storage

Trap Temperature, °C

Average counts/cycle

\[ \tau_{\text{st}} \text{ s} \]
Extrapolation (E)

\[ \tau_n = 875.55 \pm 1.6 \text{ s} \]

world average \( \tau_n = 885.7(7) \text{ s} \)

\[ \tau_n = 878.07 \pm 0.73 \text{ s} \]

\[ \chi^2 = 1.2 \]
Extrapolation (size)

\[ \tau_n = 878.07 \pm 0.73 \text{ s} \]

\[ \chi^2 = 1.2 \]
Extrapolation ($E + \text{size}$)

\[ \eta = (2.23 \pm 0.19) \times 10^{-6} \]

\[ \chi^2 = 0.95 \]

\[ \tau_n = 878.07 \pm 0.73 \text{ s} \]

\[ \chi^2 = 1.2 \]
\[ \tau_n [s] = 878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}} \]

<table>
<thead>
<tr>
<th>Size extrapolation</th>
<th>Value, s</th>
<th>Uncertainty, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-lifetime</td>
<td>878.07</td>
<td>0.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Value, s</th>
<th>Uncertainty, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of ( \gamma ) values calculation</td>
<td>0</td>
<td>0.236</td>
</tr>
<tr>
<td>Influence of mu-function shape</td>
<td>0</td>
<td>0.144</td>
</tr>
<tr>
<td>Spectrum uncertainties</td>
<td>0</td>
<td>0.104</td>
</tr>
<tr>
<td>Uncertainties of traps sizes(1mm)</td>
<td>0</td>
<td>0.058</td>
</tr>
<tr>
<td>Influence of the residual gas</td>
<td>0.40</td>
<td>0.024</td>
</tr>
<tr>
<td>Uncertainty of LTF critical energy (20 neV)</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>Total systematic effect</td>
<td>0.40</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Proton Trap Experiment

M. S. Dewey, D.M. Gilliam, and J.S. Nico
National Institute of Standards and Technology

F.E. Wietfeldt
Tulane University

X. Fei and W.M. Snow
Indiana University

G.L. Greene
University of Tennessee/ORNL

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
Institute for Reference Materials and Measurements, Belgium

R.D. Scott
Scottish Universities Research and Reactor Centre, U.K.
The “in-beam” Method

Neutron rate is proportional to the alpha rate:

\[
\dot{N}_n = k \dot{N}_\alpha = \epsilon \Omega \int \int \left( \frac{\rho t N_A}{M} \right) \sigma_0 v_0 \frac{I(v)}{v} dAdv = \epsilon \Omega \left( \frac{\rho t N_A}{M} \right) \sigma_0 v_0 \int \int \frac{I(v)}{v} dAdv
\]

Mean number of neutrons passing a fiducial volume:

\[
N = \int_0^L dz \int \int \frac{I(v)}{v} dAdv = L \int \int \frac{I(v)}{v} dAdv \quad \Rightarrow \quad \dot{N}_\alpha = k \frac{N}{L}
\]

\[
\tau = \frac{N}{\dot{N}_p} = \frac{\dot{N}_\alpha L}{k \dot{N}_p} \quad \text{where} \quad k = \epsilon \Omega \frac{\rho t N_A}{M} \sigma_0 v_0
\]
The "in-beam" Method

\[ \tau = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p} \left( \frac{\varepsilon_p}{\varepsilon_o v_o} \right) (nl + L_{\text{end}}) \]

Requires absolute knowledge of neutron and proton counting.
Fit for lifetime and end effects....

Neutron Physics Program:
• 25 postdocs
• 19 Ph.D. theses
• 27 graduate students
• 30 undergraduate students
• 20 collaborating institutions
Physics Program:
- UCN $n$ lifetime
- Absolute neutron fluence ($\tau_n$)
- Neutron charge radius
- Neutron spin rotation
- $n$-$^3$He scattering length
- Magnetic dipole moment
- Precision radiative decay
- aCORN
- emiT III
- Proton asymmetry
- Improved proton trap lifetime
- $n$-$^3$He scattering length
- Magnetic dipole moment
- Precision radiative decay
- aCORN
- emiT III
- Proton asymmetry
- Improved proton trap lifetime
- Nab ....?
Trapping Cycle - 10 ms

- **alpha, triton detector**
- **precision aperture**
- **$^6$Li deposit**
- **mirror (+800 V)**
- **central trap electrodes**
- **door closed (+800 V)**
- **proton detector**
- **neutron beam**

$B = 4.6 \, T$
Counting Cycle - 100 µs
Proton Counting

Energy Spectrum

Proton Pulse Height Spectrum
(32.5 kV; 20 µg/cm² Au)

Timing Spectra

Proton Timing Spectrum

- 10 Electrodes
- 7 Electrodes
- 6 Electrodes
- 3 Electrodes

ADC Channel (7.47 ch. = 1 keV)

TDC Channel
**Neutron Counting**

- Si wafer with 6LiF deposit
- Precision aperture
- Silicon detector

- n+^6Li reaction products (alpha + triton) produced isotropically.
- Detect small fraction but with known efficiency

\[ \epsilon = \frac{\sigma_{Li}}{4\pi} \int \int \Omega(x, y) \rho(x, y) \Theta(x, y) dxdy \]

- areal density of deposit
- solid angle
- beam profile

---

![Graph showing neutron counting results with peaks at 2.071 MeV and 2.715 MeV for ^4He and ^3H, respectively, with 239Pu contamination.](image)
Result: Extrapolation in Backscattering

![Graph showing measured neutron lifetime versus backscattering fraction. The graph includes individual data runs and a linear fit.]

- **Measured Neutron Lifetime (s)**
  - Ranges from 875 to 910 s.

- **Backscattering Fraction**
  - Ranges from 0 to 25x10^3.

- **Individual Data Runs**
- **Extrapolated Neutron Lifetime (statistical uncertainty only)**
- **Linear Fit**
TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

<table>
<thead>
<tr>
<th>Source of correction</th>
<th>Correction (s)</th>
<th>Uncertainty (s)</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$LiF deposit areal density</td>
<td>2.2</td>
<td></td>
<td>IV A</td>
</tr>
<tr>
<td>$^6$Li cross section</td>
<td>1.2</td>
<td></td>
<td>IID</td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
<td>IID 1</td>
</tr>
<tr>
<td>Absorption of neutrons by $^6$Li</td>
<td>+5.2</td>
<td>0.8</td>
<td>IV A 2</td>
</tr>
<tr>
<td>Neutron beam profile and detector solid angle</td>
<td>+1.3</td>
<td>0.1</td>
<td>IV A 2</td>
</tr>
<tr>
<td>Neutron beam profile and $^6$Li deposit shape</td>
<td>-1.7</td>
<td>0.1</td>
<td>IV A 2</td>
</tr>
<tr>
<td>Neutron beam halo</td>
<td>-1.0</td>
<td>1.0</td>
<td>IV B</td>
</tr>
<tr>
<td>Absorption of neutrons by Si substrate</td>
<td>+1.2</td>
<td>0.1</td>
<td>IV A 2</td>
</tr>
<tr>
<td>Scattering of neutrons by Si substrate</td>
<td>-0.2</td>
<td>0.5</td>
<td>IV A 3</td>
</tr>
<tr>
<td>Trap nonlinearity</td>
<td>-5.3</td>
<td>0.8</td>
<td>IV C</td>
</tr>
<tr>
<td>Proton backscatter calculation</td>
<td>0.4</td>
<td>0.1</td>
<td>IV D 3</td>
</tr>
<tr>
<td>Neutron counting dead time</td>
<td>+0.1</td>
<td>0.1</td>
<td>IID</td>
</tr>
<tr>
<td>Proton counting statistics</td>
<td>1.2</td>
<td></td>
<td>IV D 2</td>
</tr>
<tr>
<td>Neutron counting statistics</td>
<td>0.1</td>
<td></td>
<td>IID</td>
</tr>
<tr>
<td>Total</td>
<td>-0.4</td>
<td>3.4</td>
<td></td>
</tr>
</tbody>
</table>

$\tau = (886.3 \pm 1.2\,[\text{stat}] \pm 3.2\,[\text{sys}])$ s

Neutron Counting

- Uncertainty dominated by systematics related to neutron counting.

- Calibrate “1/ν” efficiency neutron monitor via neutron radiometry or alpha-gamma coincidence technique.
Beam Halo Measurement

![Beam Halo Measurement Diagram]

- Vertical Pixels (0.1 mm)
- Horizontal Pixels (0.1 mm)
- Beam Fraction Outside a Radius
  - Radius from Beam Centroid (0.1 mm)
  - Effective Detector Radius
  - Active Si Radius
1. Address reduction of neutron counting systematic.
   - Neutron radiometer LiMg: 0.1% stats; concern with defect formation
   - Neutron radiometer L³He: 2% stats; needs work
   - Absolute fluence with alpha-gamma coincidence technique: online

2. Another round of proton counting??
   - Higher fluence rate (cold source upgrade)
   - Larger area proton detectors
   - Run with multiple neutron counting targets and configurations
     - .............
Magnetically Trapped UCN using Superfluid He-4

F. Dubose, R. Golub, E. Korobkina, C. O’Shaughnessy, G. Palmquist, Pil-Neyo Seo, P.R. Huffman
North Carolina State University

L. Yang and J.M. Doyle
Harvard University

National Institute of Standards and Technology

S.K. Lamoreaux
Yale University
• Confine UCN with a magnetic trap to eliminate wall losses.

• Produce UCN using the superthermal process to increase the UCN density.

• Detect neutron decay from helium scintillation light, giving continuous monitoring of decays.
Superthermal Process


\[ \vec{p}_{\text{ucn}} = \vec{p}_n - \vec{q}_{\text{phonon}} \]

\[ E_{\text{ucn}} = E_n - E_{\text{phonon}} \]
Neutrons with energy ~0.95 meV (0.89 nm or 12 K) can scatter in liquid helium to near rest by the emission of a single photon.

Upscattering suppressed by Boltzmann factor ($e^{-\frac{(12 \text{ K})}{T}}$)
Happy Graduate Students
1) Loading period
   35 minutes

2) Turn off Beam

3) Observation period
   45 minutes
Marginally Trapped Neutrons

- “Positive” trapping runs
- “Negative” background runs

- Ramp magnet to ~30% $B_0$ value to eliminate “marginally” trapped neutrons.

$B_0$ $r_0B_0^{1/3} = \text{const}$ $0.3B_0$
Trapping Data

Fits to $A \exp(-t/\tau)$

- **Ultrapure helium runs**
  \[ A = (1.94 \pm 0.03) \text{ s}^{-1} \]
  \[ \tau = (621 \pm 18/-17) \text{ s} \]

- **Magnet Ramp runs**
  \[ A = (0.95 \pm 0.06) \text{ s}^{-1} \]
  \[ \tau = (831 \pm 58/-51) \text{ s} \]

- **Natural Helium**
  (consistent with zero)
Improving Measurement Precision

- Larger trap: an accelerator-type quadrupole magnet from KEK (B = 3.1 T, D = 12 cm, L = 75 cm)

- Improved signal-to-background
  - include gamma shield in new cryostat design
  - better light collection (small light guide; low temp light detector)

- Develop techniques for measuring $^3$He concentration at $10^{-14}$ level.
Paul, Zimmer,... (TU Munich)
  • Low temperature fomblin bottle

Morozov (Kurchatov Institute, ILL)
  • Low temperature fomblin bottle

Bowman and Penttila (LANL/ORNL)
  • UCN in vacuum quadrupole trap
  • Monitor decay electrons

Yerozolimsky and Steyerl (Harvard and Rhode Island)
  • UCN “accordion-like” trap
  • Coated with low-temperature fomblin oil

Pichlmaier (PSI)
  • Permanent magnet trap
  • Monitor decays

Masuda (KEK)
  • Quadrupole bottle
  • Monitor decays

Precision < 1 s
➢ “The most recent result, that of Serebrov 05, is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of \((885.7 \pm 0.8)\) s must be suspect.”

- PDG 2006 -

➢ New UCN experiments should illuminate the disagreement; results should be imminent (1-2 years). Cold neutron experiment can reduce uncertainty to approximately 1 s and provide distinctly different systematics.

➢ For neutron decay to directly confront theory, both the lifetime and lambda must be improved. UCNA, PERKEO III, and new experiments to measure electron-antineutrino asymmetry (“little a”) should reduce uncertainty in lambda.

➢ Addressing CKM unitarity also needs affirmation of \(|V_{us}|\) in both experiment and theory.