The Neutron Lifetime

F. E. Wietfeldt
Tulane University
Neutron Decay

$\Delta m c^2 = 1.29 \text{ MeV}$
Neutron Decay

$$\Delta mc^2 = 1.29 \text{ MeV}$$

**effective 4-fermion interaction**
(Fermi, 1934)

$$\mathcal{M} = [G_V \bar{p} \gamma_\mu n - G_A \bar{p} \gamma_5 \gamma_\mu n][\bar{e} \gamma_\mu (1 + \gamma_5) \nu]$$

- vector
- axial vector

A. Neutron decay and the weak coupling constants

II. THEORETICAL ASPECTS OF THE NEUTRON

The electron and antineutrino are needed because the weak interaction conserves both charge and lepton number. The pseudoscalar interaction is important in other systems (the pseudoscalar interaction is important in other systems) forms under spatial rotations and reflections. The Hamiltonian. Experiments and theory later showed that the Hamiltonian for beta decay was first written by Fermi (1934), in analogy to the quantum electrodynamic theory, as a 4-fermion vector interaction involving the neutron, proton, electron, and antineutrino. The term provides the maximal parity violation of the weak interaction.

**LIFETIME**

While both Snell et al. and Robson convincingly demonstrated evidence for the daughter system. This is why, for example, contrast of both cases and...
Neutron Decay

\[ \mathcal{M} = [G_V \bar{p} \gamma_\mu n - G_A \bar{p} \gamma_5 \gamma_\mu n][\bar{e} \gamma_\mu (1 + \gamma_5)\nu] \]

representing the effective 4-fermion interaction (Fermi, 1934)

related reactions:

- \( n + e^+ \leftrightarrow p + \bar{\nu} \) (Big Bang nucleosynthesis)
- \( p + e^- \leftrightarrow n + \nu \) (Big Bang nucleosynthesis)
- \( p + p \rightarrow ^2H + e^+ + \nu \) (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)

\[ \Delta m c^2 = 1.29 \text{ MeV} \]
Neutron Decay Parameters

Phenomenological ($J = 1/2 \rightarrow J = 1/2$) beta decay formula [Jackson, Treiman, Wyld, 1957]:

$$dW \propto \frac{1}{\tau} F(E_e) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + b \frac{m_e}{E_e} + A \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B \frac{\vec{\sigma}_n \cdot \vec{p}_v}{E_v} + D \frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_v)}{E_e E_v} \right]$$

For allowed beta decay, neglecting recoil order terms, the standard electroweak model (Weinberg, Glashow, Salam, et al.) predicts:

$$a = \frac{1 - \lambda^2}{1 + 3\lambda^2}, \quad b = 0, \quad A = -2 \frac{\lambda^2 + \text{Re}(\lambda)}{1 + 3\lambda^2}, \quad B = 2 \frac{\lambda^2 - \text{Re}(\lambda)}{1 + 3\lambda^2}$$

$$D = 2 \frac{\text{Im}(\lambda)}{1 + 3\lambda^2} \approx 0, \quad \tau \propto \frac{1}{G_V^2 + 3G_A^2}$$

$$\lambda \equiv \frac{G_A}{G_V}$$
1) Find $G_A$, $G_V$
1) Find $G_A$, $G_V$

2) Test SM

Mostovoy Parameters, model-independent consistency test of SM:

Predicted | Actual
---|---
$F_1 = 1 + A - B - a = 0$ | $F_1 = 0.0025 \pm 0.0064$
$F_2 = aB - A - A^2 = 0$ | $F_2 = 0.0034 \pm 0.0050$

Precise comparisons of $a$, $b$, $A$, $B$, $D$ are sensitive to:

- scalar and tensor weak currents
- right handed weak currents
- new CP violation
- CVC violation and second-class currents (Gardner and Zhang, 2000)
- SUSY (Profumo, Ramsey-Musolf, and Tulin, 2007)
3) Big Bang nucleosynthesis

- **Era of Nucleosynthesis**: 3 minutes ago, protons, neutrons, electrons, and neutrinos (antimatter rare)
- **Era of Atoms**: 300,000 years ago, plasma of hydrogen and helium nuclei plus electrons
- **Era of Galaxies**: 1 billion years ago, atoms and plasma (stars begin to form)
3) Big Bang nucleosynthesis

nucleon freeze out

Time Since Big Bang

present

1 billion years

300,000 years

3 minutes

0.001 seconds

$10^{-10}$ seconds

$10^{-35}$ seconds

$10^{-43}$ seconds

Era of Nucleosynthesis

Era of Nuclei

Era of Atoms

Era of Galaxies

Major Events Since Big Bang

stars, galaxies and clusters (made of atoms and plasma)

atoms and plasma (stars begin to form)

plasma of hydrogen and helium nuclei plus electrons

protons, neutrons, electrons, neutrinos (antimatter rare)

elementary particles (antimatter common)

elementary particles

elementary particles

Humans observe the cosmos.

First galaxies form.

Atoms form; photons fly free and become background radiation.

Fusion ceases; normal matter is 75% hydrogen.

Matter annihilates antimatter.

Electromagnetic and weak forces become distinct.

Strong force becomes distinct, perhaps causing inflation of universe
n/p \sim e^{\frac{\Delta mc^2}{kT}}
nucleon freeze out

3) Big Bang nucleosynthesis
3) Big Bang nucleosynthesis

\[ \frac{n}{p} \sim \frac{\Delta mc^2}{kT} \]

nucleon freeze out

\[ \tau_n \]
4) \( V_{ud} \):

matrix element:

\[
\mathcal{M} = [G_V \bar{p} \gamma_\mu n - G_A \bar{p} \gamma_5 \gamma_\mu n] [\bar{e} \gamma_\mu (1 + \gamma_5) \nu]
\]
4) $V_{ud}$:

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$$G_V = G_F V_{ud} C_V \quad G_A = G_F V_{ud} C_A$$

$$C_V = 1 \quad \text{(CVC)} \quad C_A = \lambda \quad \text{(affected by npQCD)}$$

$$G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2} \quad \text{(muon lifetime)}$$
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$$\tau_n = \frac{2\pi^3\hbar^7}{(G_V^2 + 3G_A^2)m_e^5 c^4 f_R} = \frac{4908.7(1.9) s}{|V_{ud}|^2(1 + 3\lambda^2)}$$

(Marciano and Sirlin, 2006)
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(Marciano and Sirlin, 2006)

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

- Wavelength (Å)
- Velocity (m/s)
- Kinetic Energy (eV)

- Fast
- Epithermal
- Thermal
- Cold
- Very Cold
- Ultra Cold
Three Methods

1) Beam method

\[ \Gamma = \frac{-dN}{dt} = \frac{N}{\tau} \]

Neutrons in detection volume: \[ N_{\text{det}} = \rho_n V_{\text{det}} = \phi_v \left( \frac{A_{\text{beam}}}{L_{\text{det}}} \right) \]

Neutron lifetime: \[ \tau = \frac{A_{\text{beam}} L_{\text{det}}}{\Gamma \phi_v \left( \frac{1}{V_{\text{det}}} \right)} \]

2) UCN bottle method

3) Magnetic storage

\[ N(t) = N_0 e^{-t/\tau} \]
The beam neutron lifetime method

neutron decay rate: \[ \Gamma = -\frac{dN}{dt} = \frac{N}{\tau} \]
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neutron lifetime: \[ \tau = \frac{A_{\text{beam}} L_{\text{det}}}{\Gamma} \left( \frac{\phi}{v} \right) \]
for a “white” neutron beam:

$$\tau = \frac{A_{\text{beam}} L_{\text{det}}}{\Gamma} \int \frac{\phi(v)}{v} dv$$
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neutron absorption cross section in thin “1/v” counter:

$$\sigma_{\text{abs}} = \sigma_{th} \frac{v_{th}}{v}$$

$$v_{th} = 2200 \text{ m/s} \quad \text{reference thermal neutron velocity}$$
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neutron count rate: \[ R_n = \varepsilon_{\text{th}} A_{\text{beam}} v_{th} \int \frac{\phi(v)}{v} dv \]

charged particle count rate: \[ R_p = \varepsilon_p \Gamma \]
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\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} v_{th}} \]
for a “white” neutron beam:

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\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{\text{th}} v_{\text{th}}} \]

most challenging
Measurement of the Neutron Lifetime

Using a Proton Trap

J.S. Nico, M.S. Dewey, and D.M. Gilliam
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

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

alpha, triton detector

precision aperture

$^6$Li deposit

B = 4.6 T

mirror (+800 V)

trap electrodes

door closed (+800 V)

proton detector

neutron beam

Li deposit (+800 V)

trap electrodes

door closed (+800 V)

neutron beam
\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{\text{th}} v_{\text{th}}} \]
\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} \nu_{th}} \]

\[ L_{\text{det}} = nl + L_{\text{end}} \]
\[ \tau = \frac{R_n \varphi_p L_{\text{det}}}{R_p \varphi_{th} v_{th}} \]

\[ L_{\text{det}} = nl + L_{\text{end}} \]

# trap electrodes
\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} v_{th}} \]

\[ L_{\text{det}} = nl + L_{\text{end}} \]

- \( \tau \) = precision aperture
- \( R_n \) = neutron beam
- \( \varepsilon_p \) = proton detector
- \( L_{\text{det}} \) = neutron beam
- \( nl \) = mirror trap electrodes
- \( L_{\text{end}} \) = door closed
- \( +800 \) V = trap electrodes
- \( +800 \) V = mirror electrodes
- \( B = 4.6 \) T = door closed
- \( ^6\text{Li} \) deposit
- \( +800 \) V = closed door
- \( 6 \) = trap electrodes
- \( n \) = length of electrode + spacer
- \( \varepsilon_{th} \) = length of electrode + spacer
- \( v_{th} \) = length of electrode + spacer
- \( \# \text{ trap electrodes} \) = length of electrode + spacer
\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} v_{th}} \]

\[ L_{\text{det}} = nl + L_{\text{end}} \]

- \( \varepsilon \) = precision aperture
-ân, triton detector
-6Li deposit
-mirror (+800 V)
-trap electrodes
-door closed (+800 V)
-neutron beam
-proton detector
-B = 4.6 T

Total effective end region length = length of electrode + spacer

\# trap electrodes

\( L_{\text{det}} \) = total effective end region length
\[ \tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{\text{th}} v_{\text{th}}} \]

\[ L_{\text{det}} = nl + L_{\text{end}} \]

\[ \frac{R_p}{R_n} = \tau^{-1} \left( \frac{\varepsilon_p}{\varepsilon_{\text{th}} v_{\text{th}}} \right) (nl + L_{\text{end}}) \]
Proton Trap
Proton Pulse Height Spectrum
(32.5 kV; 20 \( \mu \text{g/cm}^2 \) Au)

Counts

ADC Channel (7.47 ch. = 1 keV)
Proton Arrival Time Spectrum
(32.5 kV; 20 µg/cm² Au)

Counts

Proton Pulse Height Spectrum
(32.5 kV; 20 µg/cm² Au)
Fit of $\frac{R_p}{R_n}$ vs. number trap electrodes
Lifetime vs. Backscatter

extrapolated result
886.8 ± 1.2 s
(stat. error only)

measured lifetime (s)

backscatter fraction

27.5 kV
30 kV
32.5 kV
1/v neutron counter

- Silicon surface-barrier detector
- Precision aperture to define detector solid angle
- Neutron beam
- Neutron target (silicon wafer with $^6\text{LiF}$ deposit)
$1/v$ neutron counter

Neutron target (silicon wafer with $^6\text{LiF}$ deposit)

Silicon surface-barrier detector

Precision aperture to define detector solid angle

Neutron beam

neutron detection efficiency: $\varepsilon_{th} = \frac{\sigma_{th}}{4\pi} \int \int \Omega(x, y) \rho(x, y) \theta(x, y) dx dy$
1/v neutron counter

neutron detection efficiency: $\varepsilon_{th} = \frac{\sigma_{th}}{4\pi} \int \int \Omega(x,y) \rho(x,y) \theta(x,y) dx dy$

Si detector solid angle
1/v neutron counter

Silicon surface-barrier detector

Precision aperture to define detector solid angle

Neutron beam

Neutron target (silicon wafer with $^6$LiF deposit)

neutron detection efficiency: $\varepsilon_{th} = \frac{\sigma_{th}}{4\pi} \int \int \Omega(x,y)\rho(x,y)\theta(x,y)\,dx\,dy$

Si detector solid angle

areal density of Li foil
1/v neutron counter

Silicon surface-barrier detector

Precision aperture to define detector solid angle

Neutron target (silicon waver with $^6$LiF deposit)

Neutron beam

neutron detection efficiency: $\varepsilon_{th} = \frac{\sigma_{th}}{4\pi} \int \int \Omega(x,y)\rho(x,y)\theta(x,y)\,dx\,dy$

Si detector solid angle

areal density of Li foil

neutron beam density
Error Budget

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<th>Uncertainty (s)</th>
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<tr>
<td>(^6\text{LiF}) deposit areal density</td>
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<tr>
<td>(^6\text{Li}) cross section</td>
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2005: \(\tau_n = 886.3 \pm 3.4\) s
## Error Budget

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2005: $\tau_n = 886.3 \pm 3.4$ s
Absolute neutron flux measurement to $< 0.1\%$ precision

- $^{10}$B alpha-gamma device now working at NIST
  0.06\% precision recently achieved! (Andrew Yue, NIST)

- $^3$He gas scintillation chamber (Tulane, NIST) - in construction/testing

- neutron radiometer (Indiana, Michigan) - under development
Absolute neutron flux measurement to < 0.1% precision

- $^{10}$B alpha-gamma device now working at NIST
  0.06% precision recently achieved!
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  2013 improved result:
  $$\tau_n = 887.7 \pm 2.3 \text{ s}$$

- $^3$He gas scintillation chamber (Tulane, NIST) - in construction/testing

- neutron radiometer (Indiana, Michigan) - under development
1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.
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2. Store UCN for a variable storage time interval $\Delta t$. 

Ultracold neutron bottle method
1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.

2. Store UCN for a variable storage time interval $\Delta t$.

3. Empty the bottle and count the remaining UCN in a detector.
Ultracold neutron bottle method

1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.

2. Store UCN for a variable storage time interval $\Delta t$.

3. Empty the bottle and count the remaining UCN in a detector.

4. Repeat steps 1-3 using different wall collision rates to account for wall losses (upscattering, absorption).
UCN storage time

radioactive decay law:

\[ N(\Delta t) = N_0 e^{-\Delta t / \tau_{\text{stor}}} \]

\[ \tau_{\text{stor}} = \frac{\Delta t}{\ln \left( \frac{N_0}{N(\Delta t)} \right)} \]

\[ \frac{1}{\tau_{\text{stor}}} = \frac{1}{\tau_n} + \frac{1}{\tau_{\text{wall}}} \]
UCN storage time

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\[ \frac{1}{\tau_{stor}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}} \]

neutron loss rate due to upscattering and absorption from wall collisions
UCN bottle neutron lifetime

![Graph showing the relationship between inverse storage time and wall loss rate.

- The x-axis represents the wall loss rate (s⁻¹).
- The y-axis represents the inverse storage time (s⁻¹).
- The graph plots several data points, indicating a positive correlation between the inverse storage time and wall loss rate.]

The graph illustrates the relationship between inverse storage time and wall loss rate, where an increase in wall loss rate corresponds to an increase in inverse storage time.
UCN bottle neutron lifetime

inverse storage time (s$^{-1}$)

wall loss rate (s$^{-1}$)

$1 / \tau_n$
Neutron lifetime measurements using gravitationally trapped ultracold neutrons


1Petersburg Nuclear Physics Institute, Russian Academy of Sciences, RU-188300 Gatchina, Leningrad District, Russia
2Joint Institute for Nuclear Research, RU-141980 Dubna, Moscow Region, Russia
3Institut Max von Laue Paul Langevin, Boîte Postal 156, F-38042 Grenoble Cedex 9, France

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Neutron lifetime measurements using gravitationally trapped ultracold neutrons

A. P. Serebrov,1,4 V. E. Varlamov,1 A. G. Kharitonov,1 A. K. Fomin,1 Yu. N. Pokotilovski,2 P. Geltenbort,3 I. A. Krasnoschekova,1 M. S. Lasakov,1 R. R. Taldaev,1 A. V. Vassiliev,1 and O. M. Zherebtsov1

1Petersburg Nuclear Physics Institute, Russian Academy of Sciences, RU-188300 Gatchina, Leningrad District, Russia
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3Institut Max von Laue Paul Langevin, Boîte Postal 156, F-38042 Grenoble Cedex 9, France

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The observed quantities in the Big Bang model are the initial abundance of light elements and the initial abundance of baryons to the number of photons $n_b/n_\gamma$. These quantities depend on the neutron lifetime which can be determined from nuclear and decays.

The observed quantity $n_b/n_\gamma$ is currently estimated to the precision of 3.3% [1]. Similarly, a change in the neutron lifetime by 1% changes the value of the neutron lifetime by $\eta_10^{-3}$. Thus, to verify the nucleosynthesis model in the Big Bang, the relative accuracy of the neutron lifetime measurement must be higher than 10%.

The results presented in this paper have already published in [2].

Our experiment using gravitationally trapped ultracold neutrons (UCN) to measure the neutron lifetime is described in [3].

The cryogenic liquid fluoropolymer oil wall coating to minimize wall losses.
Neutron lifetime measurements using gravitationally trapped ultracold neutrons


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cryogenic liquid fluoropolymer oil wall coating to minimize wall losses

rotate bottle to allow high energy UCN to escape, to vary neutron velocity spectrum

two storage bottles, spherical (large) and cylindrical (small) to vary S/V ratio
The neutron lifetime values for \( \tau \) were 73 s, 93 s, and 83 s, and so forth, since Eq. (17). The effect from uncertainty of the dependence \( \gamma \) on the neutron lifetime is rather weak. Previously it was demonstrated how one can calculate the neutron lifetime for different energy ranges. The average resultant values of the neutron lifetime.

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Magnitude (s)</th>
<th>Uncertainty (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of calculating ( \gamma )</td>
<td>0</td>
<td>0.236</td>
</tr>
<tr>
<td>Influence of shape of function ( \mu(E) )</td>
<td>0</td>
<td>0.144</td>
</tr>
<tr>
<td>UCN spectrum uncertainty</td>
<td>0</td>
<td>0.104</td>
</tr>
<tr>
<td>Uncertainty of trap dimensions (1 mm)</td>
<td>0</td>
<td>0.058</td>
</tr>
<tr>
<td>Residual gas effect</td>
<td>0.4</td>
<td>0.024</td>
</tr>
<tr>
<td>Uncertainty in PFPE critical energy (20 neV)</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>Total systematic correction</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Calculation of Neutron Lifetime Using the Extrapolation Method**

1. By direct measurement of the differential UCN spectrum in the trap: 1. by direct measurement of the differential UCN spectrum and then calculating its differential form. In the second case, the trap walls can be computed according to Eq. (2). The solid, strong, going mainly to systematically low value of neutron lifetime. Extrapolation of spectrum measurement.

2. By measuring the integral correction for the UCN decay and losses. In the second case, UCN spectrum and then calculating its differential form. In practice we have dealt with a rather broad spectrum.

For narrow cylindrical and wide quasispherical traps, trap losses are as free parameters. The UCN loss factor and can be used as an estimation of the uncertainty of the dependence \( \gamma \) on the neutron lifetime. Hence the task of calculating the normalized loss rate for a broad UCN spectrum.

The effect from uncertainty of the dependence \( \gamma \) on the neutron lifetime is rather weak. Previously it was demonstrated how one can calculate the neutron lifetime for different energy ranges. The average resultant values of the neutron lifetime.\( \tau = 878.5 \pm 0.8 \) s. But as was previously described and 2. by measuring the integral correction for the UCN decay and losses. In the second case, UCN spectrum and then calculating its differential form. In practice we have dealt with a rather broad spectrum.

The result of the extrapolation to the neutron lifetime is rather weak. Previously it was demonstrated how one can calculate the neutron lifetime for different energy ranges. The average resultant values of the neutron lifetime.

**Simulation of an Experiment by the Monte Carlo Method**

Using the Monte Carlo method. The single adjustable parameter in the Monte Carlo model was extremely difficult to make. The results of measurements for a quasispherical trap, and can be used as an estimation of the uncertainty of the dependence \( \gamma \) on the neutron lifetime. Hence the task of calculating the normalized loss rate for a broad UCN spectrum. But as was previously described and 2. by measuring the integral correction for the UCN decay and losses. In the second case, UCN spectrum and then calculating its differential form. In practice we have dealt with a rather broad spectrum.

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neutron lifetime results

neutron lifetime (s)

year

- beam method
- UCN bottle
- magnetic trap
neutron lifetime results since 1990

\[ \tau_n = 879.6 \pm 0.6 \text{ s} \]

\[ \tau_n = 888.0 \pm 2.1 \text{ s} \]
\[ |V_{ud}|^2 = \frac{4908.7(1.9) \text{s}}{\tau_n(1 + 3\lambda^2)} \]
At the few $10^{-4}$ precision level, $n$ decay will be competitive with $0^+ - 0^+$. 

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

The U.S. program going forward will consist of one neutron beam and one UCN bottle experiment, both designed to scrutinize systematic effects and to reach the 0.1 s level in precision.

**Beam Lifetime 3**
(Tulane, U. Tenn., NIST)

Enlarged version of existing apparatus, trap volume 50x larger, new features to study proton counting systematics

**UCN τ**
(Indiana U., Los Alamos)

Magnetic (Halbach array) wall bottle to eliminate wall losses
Other Current and Planned Efforts
Other Current and Planned Efforts

Magneto-gravitational UCN traps:

1. ILL Permanent magnet bottle (Ezhov, et al.)
2. HOPE: Halbach-octupole magnet
3. PENeLOPE: Superconducting magnet bottle
Other Current and Planned Efforts

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Beam Method:

J-PARC pulsed beam $^3$He TPC
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All with goal of $\sim 0.1 \text{ s n lifetime precision}$
Danke Schön
Extra Slides
Trap nonlinearity effects:

- Inhomogeneity of the axial magnetic field - *important*
- Neutron beam divergence within the trap - *minor*
- Nonuniform electrode and spacer widths - *negligible*
Nonlinearity due to the inhomogeneous magnetic field
Dy foil neutron flux measurements

(a) Upstream end of trap
(b) Downstream end of trap

Graphs showing beam fraction outside a radius vs. radius from beam centroid for effective detector radius and LiF deposit radius.