The Neutron Lifetime, the Big Bang and the Spallation Neutron Source

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University of Tennessee / Oak Ridge National Laboratory
- Neutron Decay and Big Bang Nucleosynthesis
- Measuring the Neutron Lifetime
- The Spallation Neutron Source (SNS)
The neutron Lifetime and the Standard Model
n → p^+ + e^- + \bar{\nu}_e

Neutron decay is best viewed as an interaction:

In the standard quark model this simple picture is complicated by the fact that it is the quarks within the nucleon which interact:

This is the point of departure for the construction of a theory of beta decay.
We construct a Weak Hamiltonian that couples a down quark to an up quark, and an electron to an electron neutrino:

\[ < \nu_e | H_{weak} | e^- > < d | H_{weak} | u > \]
We construct a Weak Hamiltonian that couples a down quark to an up quark, and an electron to an electron neutrino:

\[ < \nu_e \mid H_{\text{weak}} \mid e^- > < d \mid H_{\text{weak}} \mid u > \]

Question: How do we accommodate V-A (parity violation)
Including V-A ("Parity Violation")

A “Handed” Interaction Requires:

A VECTOR  \hspace{1cm} \text{the “Push”}
and
An Axial Vector  \hspace{1cm} \text{the “Twist”}
Including V-A ("Parity Violation")

A “Handed” Interaction Requires:

A VECTOR the “Push”
and
An Axial Vector the “Twist”

The relative sign of the vector and axial-vector determines the “handedness"
V-A in the “Ideal “Quark-Lepton Interaction

\[ H_{\text{weak}} = G_{\text{weak}} \left\langle \nu_e \left| \gamma_\mu - \gamma_\mu \gamma_5 \right| e^- \right\rangle \left\langle d \left| \gamma_\mu - \gamma_\mu \gamma_5 \right| u \right\rangle \]

“V-A”

Vector “minus” Axial Vector Means a “Left-Handed” Interaction

“vector” operator \(\downarrow\) “axial-vector” operator
Neutron Decay is a Bit More Complicated

The strongly interacting quarks within the neutron modify the relative size of the vector and axial vector couplings.

But since the strong interaction conserves parity, this does not change the relative phase (handedness),

It only changes the “pitch” of the “screw”

\[ H_{\text{weak}} = G_{\text{weak}} \langle \nu_e \mid \gamma_\mu - \gamma_\mu \gamma_5 \mid e^- \rangle \langle d \mid (g_V \gamma_\mu - g_A \gamma_\mu \gamma_5) \mid u \rangle \]

If Neutron Decay is Purely Left-Handed, only two parameters completely describe it.
Theory Summary

- Our interest in fundamental symmetry violation led us to examine neutron beta decay as a “model” system.

- If the Standard Model for the Electro-Weak Interaction is correct, only two parameters, $g_A$ and $g_V$, are required. ($g_A/g_V$ can be thought of as the “pitch” of the screw)

- The experimental challenge is to determine whether or not all the phenomenology in neutron beta decay can consistently be explained by two just parameters.

- If two parameters are not enough, something is wrong. This be an indication of something new...perhaps an indication of incomplete symmetry breaking!
Phenomenology of Neutron Beta Decay

Momentum Must Be Conserved!
Phenomenology of Neutron Beta Decay

Momentum Must Be Conserved!

V-A says that neutrinos are purely "Left-Handed" with
\[ \vec{\sigma} \cdot \vec{p} = -1 \]

Conservation of linear and angular momentum implies that there are strong correlations between the initial neutron spin and decay particle momenta.
Correlations in Neutron Decay

Parity violation implies a rich phenomenology in neutron decay. V-A implies that all experimental quantities can be related to the axial and vector coupling constants $g_A$ and $g_V$. 

$$dW \propto \frac{1}{\tau_n} F(E_e) \left[ 1 - a \frac{p_e \cdot p_v}{E_e \cdot E_v} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot p_e}{E_e} + B \frac{\sigma_n \cdot p_v}{E_v} \right]$$

$$\tau_n \propto \frac{1}{(g_A^2 + 3g_V^2)}$$

$$a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$b = 0$$

$$A = -2 \frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$B = 2 \frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 - \left(\frac{g_A}{g_V}\right)^2}$$

Neutron beta decay measurements give:

$$\left(\frac{g_A^2 + 3g_V^2}{g_A^2} \right) \left/ g_V \right.$$
The FREE neutron is unstable against beta-decay

\[ \tau_n \approx 890 \text{ s} \]
Some Theoretical Implications the Neutron Lifetime

Cosmology:

The neutron lifetime sets the time scale over which nucleosynthesis occurs during the Big-Bang. The comparison of the neutron lifetime, the cosmological He/H (or D/H) ratio, and the number of neutrino species provides a prediction for the Universal Baryon Density. This is a critical component of the “Dark Matter Problem.”

Particle Physics:

A comparison between the neutron lifetime and neutron decay correlations provides an important test of the standard model, and provides a insight into the origin of parity violation.

Astrophysics:

The reaction which provides the dominant source of energy in the Sun (pp fusion) is governed by the same matrix element as neutron decay. The neutron lifetime is a key parameter of the solar models which are involved in the “Solar Neutrino Problem”
**Important Processes with the same Feynman Diagram as Neutron Decay**

![Feynman Diagram]

- **Primordial element formation**
  \[ n + e^+ \leftrightarrow p + \nu_e \]
  \[ p + e^- \leftrightarrow n + \nu_e \]
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]

- **Solar cycle**
  \[ p + p \rightarrow ^2H + e^+ + \nu_e \]
  \[ p + p + e^- \rightarrow ^2H + \nu_e \] etc.

- **Neutron star formation**
  \[ p + e^- \rightarrow n + \nu_e \]

- **Pion decay**
  \[ \pi^- \rightarrow \pi^0 + e^- + \bar{\nu}_e \]

- **Neutrino detectors**
  \[ \nu'_e + p \rightarrow e^+ + n \]

- **Neutrino forward scattering**
  \[ \nu_e + n \rightarrow e^- + p \] etc.

After D. Dubbers
Review of Big-Bang Nucleosynthesis
## The Time Scale for the Big Bang (1)

<table>
<thead>
<tr>
<th>Time Since Big Bang</th>
<th>T (K)</th>
<th>ρ (g/cm³)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10⁻⁴³s</td>
<td></td>
<td></td>
<td>Quantum era Universe consists of “soup” of leptons &amp; quarks</td>
</tr>
<tr>
<td>~10⁻⁴³s</td>
<td>10³²K</td>
<td></td>
<td>Grand Unification Era Gravity separates from other Grand Unified Forces</td>
</tr>
<tr>
<td>~10⁻³⁵s</td>
<td>10²⁷K</td>
<td></td>
<td>End of Grand Unification Strong Force breaks symmetry w/ ElectroWeak Force.</td>
</tr>
<tr>
<td>~10⁻³⁵s - 10⁻³³s</td>
<td></td>
<td></td>
<td>Inflationary epoch Universe inflates by a factor of 10³⁰ or more (“observable Universe” expands from size of an atomic nucleus to size of a pea).</td>
</tr>
</tbody>
</table>

**ρ**: Mass density
### The Time Scale for the Big Bang (2)

<table>
<thead>
<tr>
<th>Time Since Big Bang</th>
<th>$T$ (K)</th>
<th>$\rho$ (g/cm$^{-3}$)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 10^{-12}$s</td>
<td>$10^{15}$K</td>
<td></td>
<td>Particle Era Electromagnetic force and Weak Force break symmetry.</td>
</tr>
<tr>
<td>$\sim 10^{-6}$s</td>
<td>$10^{13}$K</td>
<td></td>
<td>Quark $\rightarrow$ Hadron transition. Protons and neutrons (plus antiprotons and antinucleons) are formed from quarks - at this time the “matter” particles have an excess of $\sim$one in a billion over “antimatter” particles.</td>
</tr>
<tr>
<td>0.01s</td>
<td>$10^{11}$K</td>
<td>$4 \times 10^{9}$</td>
<td>The Universe is expanding rapidly, scale is doubling every 0.02s. As Universe expands it cools, $T \sim 1/R$. Although the temperature is too low for Protons and neutrons to be created from the thermal energy of the early universe reactions such as: $\nu_e + n \rightarrow p^+ + e^-$ And vice-versa, maintain an equal number of proton/neutron balance shifts in favor of less massive protons.</td>
</tr>
<tr>
<td>1 s</td>
<td>$10^{10}$K</td>
<td>$4 \times 10^{5}$</td>
<td>Weakly interacting neutrinos “decouple” from the rest of the Universe</td>
</tr>
</tbody>
</table>
### The Time Scale for the Big Bang (3)

<table>
<thead>
<tr>
<th>Time Since Big Bang</th>
<th>T (K)</th>
<th>ρ (g/cm³)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15s</td>
<td>3 x 10⁹K</td>
<td>4 x 10⁴</td>
<td>Temperature is below threshold for creation of electron/positron pairs $e^+/e^-$ annihilate: $e^+ + e^- → γ + γ$ The Universe is “reheated” about 35% by annihilation.</td>
</tr>
<tr>
<td>3 min</td>
<td>10⁹K</td>
<td>400</td>
<td>Era of Nucleosynthesis Nuclei can begin to hold together, e.g. $p + n → d + γ$ At this time the baryons are divided into about 87% protons 13% neutrons.</td>
</tr>
<tr>
<td>3 1/2 min</td>
<td>10⁸K</td>
<td></td>
<td>End of Nuclear Reactions Neutrons have been “used-up” forming $^4$He Universe is now 80% H nuclei ($p^+$) &amp; 20% He nuclei</td>
</tr>
<tr>
<td>5 x 10⁵ yr</td>
<td>4000K</td>
<td></td>
<td>Era of Recombination nuclei &amp; electrons “recombine to form atoms Universe becomes transparent</td>
</tr>
<tr>
<td>10⁹ yr</td>
<td></td>
<td></td>
<td>Era of Galaxy Formation</td>
</tr>
</tbody>
</table>
Some of the reactions in Big Bang Nucleosynthesis

\[
\begin{align*}
    n & \rightarrow p + e + \bar{\nu} \\
    p + n & \rightarrow d + \gamma \\
    p + D & \rightarrow ^3\text{He} + \gamma \\
    D + D & \rightarrow ^3\text{He} + n \\
    D + D & \rightarrow T + p \\
    D + T & \rightarrow ^4\text{He} + n \\
    D + ^3\text{He} & \rightarrow \text{He} + p \\
    ^3\text{He} + ^3\text{He} & \rightarrow ^4\text{He} + 2\ p \\
    \ldots & \\
    \ldots & 
\end{align*}
\]
v’s decouple here
The Cosmic He/H Ratio Depends upon three quantities:

1) The Cooling rate of the Universe
   Given by the heat capacity of the Universe
   Determined mainly by the number of “light particles” \((m \leq 1 \text{ MeV})\)
   Includes photons, electrons (positrons), neutrinos \((x3)\)

2) The Rate at which Neutrons are decaying
   The neutron lifetime

3) The rate at which nuclear interactions occur
   Determined by the the logarithm of the density of nucleons \((\text{baryons})\)
The Parameters of Big Bang Nucleosynthesis

\[ Y_p = 0.228 + 0.023 \log \eta_{10} + 0.012 N_v + 0.018 (\tau_n - 10.28) \]
We can “invert” this line of reasoning. If we measure the Helium Abundance, the Neutron Lifetime, and if we know the Number of “light” Neutrinos is 3, We can determine the density of “ordinary” matter in the universe.

\[
\log \eta_{10} = \left[ 0.264 - Y_P + 0.018(\tau_n - 10.28) \right] / 0.023
\]
The Cosmic Helium Abundance “$Y_p$” vs the Baryon Density

Density of “Normal Matter” (protons & neutrons)
A Brief Digression on the Mass of the Universe

From Big Bang Nucleosynthesis, we conclude that, averaged over the entire universe, there are a few protons per cubic meter.

Is this a lot, or this it a little?

The only sensible way to answer this question is to respond:

Compared to What?
A Scale for the Density of the Universe

- From red-shift observations we know that the Universe is in a state of (nearly) uniform expansion.
- If the density of the Universe is sufficiently high, this expansion will come to a stop and a universal collapse will ensue.
- If the density of the Universe is sufficiently low, it will expand forever.
- The critical density of the universe is given by the Hubble constant $H$, and the Gravitational constant $G$

$$\rho_{critical} = \frac{3}{8\pi} \frac{H^2}{G}$$

- We define:

$$\Omega = \rho / \rho_{critical}$$
An Upper Limit for $\Omega$

- If $\Omega$ were sufficiently large, the universe could NOT have attained its apparent age $(1/H)$ without collapsing.

- Very simple arguments based on the fact that the universe is here and still expanding today indicate that:

$$\Omega_{\text{total}} < 2.5$$
A Lower Limit for $\Omega$

By simply counting the number of stars and galaxies we can get

$0.005 \leq \Omega_{\text{total}}$
Ω is NOT necessarily constant over time

If Ω > 1 at any time, Then Ω will continue to grow larger with time
If Ω < 1 at any time, Then Ω will tend toward zero with time

Only if Ω = 1 EXACTLY, will it stay constant for all time

We observe that Ω is NOW not too far from 1 (0.01 < Ω < 2.5). Thus:

Ω was EXTREMELY close to 1 early in the big bang (|Ω-1| ≤ 10^{-16})

This raises the “Fine Tuning” question:

If Ω was so very nearly equal to 1, Isn’t it reasonable that it equals 1?

For many compelling reasons (fine tuning, inflation, CMB, …),

We strongly believe that Ω = 1 EXACTLY
The "Preposterous" Universe

~3% "Ordinary" Matter

~30% "Dark" Matter

~67% "Dark Energy"
Neutron lifetime provides a measurement of the Cosmic Baryon Density:

\[ \Omega_B \equiv \frac{\rho_{\text{Baryon}}}{\rho_{\text{critical}}} \]

\[ \Omega_B = (3.3 \pm 0.7)\% \] \hspace{1cm} \text{BBN}

This can be compared with the determination from the Cosmic Microwave Background:

\[ \Omega_B = (2.3 \pm 0.1)\% \] \hspace{1cm} \text{CMB}

The largest uncertainty to the nuclear theory of BBN is the experimental value of the neutron lifetime.
Determination of the Neutron Lifetime
Measurement of the Neutron Lifetime

“Bottle” Method

An ensemble of “ultracold” neutrons is confined in a material or magnetic bottle. The population in the bottle decreases as:

\[ N = N_0 e^{-t/\tau_n} \]

“Beam Method”

A detector counts neutron decay products from a well defined volume traversed by a neutron beam with known neutron density. The decay rate in the volume will be:

\[ - \frac{dN}{dt} = \frac{N}{\tau_n} \]
Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

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National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

F. E. Wietfeldt
Tulane University, New Orleans, Louisiana 70118, USA

X. Fei and W. M. Snow
Indiana University and Indiana University Cyclotron Facility, Bloomington, Indiana 47408, USA

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University of Tennessee/Oak Ridge National Laboratory, Knoxville, Tennessee 37996, USA

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium

R. D. Scott
Scottish Universities Research and Reactor Centre, East Kilbride G75 0QU, United Kingdom
(Received 16 November 2004; published 25 May 2005)

A measurement of the neutron lifetime $\tau_n$ performed by the absolute counting of in-beam neutrons and their decay protons has been completed. Protons confined in a quasi-Penning trap were accelerated onto a silicon detector held at a high potential and counted with nearly unit efficiency. The neutrons were counted by a device with an efficiency inversely proportional to neutron velocity, which cancels the dwell time of the neutron beam in the trap. The result is $\tau_n = (886.3 \pm 1.2{\text{stat}} \pm 3.2{\text{sys}})$ s, which is the most precise measurement of the lifetime using an in-beam method. The systematic uncertainty is dominated by neutron counting, in particular, the mass of the deposit and the $^6\text{Li}(n,t)$ cross section. The measurement technique and apparatus, data analysis, and investigation of systematic uncertainties are discussed in detail.

DOI: 10.1103/PhysRevC.71.055502 PACS number(s): 21.10.Tg, 13.30.Ce, 23.40.-s, 26.35.+c
The Neutron Lifetime: In-Beam Method

\[ \text{neutron decay rate } \Gamma = \frac{N}{\tau} \]

so \[ \tau = \frac{\phi \, V_{\text{det}}}{v \, \Gamma} \]

Need to measure:

1. decay rate \( \Gamma \)
2. effective decay volume \( V_{\text{det}} \)
   - use linear extrapolation vs. trap length
3. neutron flux weighted by inverse velocity
   - use 1/v neutron flux monitor
The NIST Penning Trap Lifetime Experiment
The NIST Penning Trap Lifetime Experiment

"Opening the Trap"

- alpha, triton detector
- precision aperture
- $^6\text{Li}$ deposit
- mirror (+800 V)
- trap electrodes
- door open (ground)
- $B = 4.6 \text{ T}$
- proton detector
- neutron beam
Neutron Lifetime Data Fit

Normalized Proton Counts vs. Trap Length
(32.5 kV; 20 μg/cm² Au)

Proton-Bkgd/Alpha vs. Electrode Number

Residuals vs. Electrode Number
## Error Budget (all entries in seconds)

<table>
<thead>
<tr>
<th>Source of Correction</th>
<th>Correction</th>
<th>$\sigma_{\text{current}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{LiF}$ deposit areal density</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>$^6\text{Li}$ cross section</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Neutron detector calibration</td>
<td></td>
<td></td>
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<tr>
<td>Absorption of neutrons by $^6\text{Li}$</td>
<td>+5.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Scattering of neutrons by Si substrate</td>
<td>-0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Neutron beam profile and detector solid angle</td>
<td>+1.3</td>
<td>0.1</td>
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<td>Neutron beam profile and $^6\text{Li}$ deposit shape</td>
<td>-1.7</td>
<td>0.1</td>
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<tr>
<td>Absorption of neutrons by Si substrate</td>
<td>+1.2</td>
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<tr>
<td>Neutron counting statistics</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Neutron counting dead time</td>
<td>+0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Proton counting statistics</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron beam halo</td>
<td>-1.0</td>
<td>1.0</td>
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<tr>
<td>Trap nonlinearity</td>
<td>-5.3</td>
<td>0.8</td>
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<tr>
<td>Proton backscatter calculation</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>-0.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Ultracold Neutrons and Neutron Bottles
Coherent ("Optical") Interaction Between Neutrons and Matter

\[ E_{\text{kinene}} \leq \frac{1}{40} \text{ eV} \]

\[ \sim 50 \text{ MeV} \]

\[ \sim 10^{12} \text{ cm} \] (nucleus)

E-M wave interacting with matter

Phase Shift \( \Rightarrow \) Index of Refraction
At low energies $S$-wave scattering dominates, phase shift is given by

$$\cot(\delta) = \frac{-1}{kb_{coh}}$$

For "random" well depths and "random" well size, it is unlikely to obtain a positive coherent scattering length:

$$b_{coh} \text{ critical range for } b_{coh} < 0$$

Index of refraction is therefore $<1$ for most nuclei *

*In the vicinity of $A \approx 50$ ($V, Ti, Mn$) nuclear sizes are such that $b_{coh} < 1$ and thus $n > 1$
**Neutron Index of Refraction**

\[ n^2 = 1 - \frac{\lambda^2 N_{b_{coh}}}{2\pi} \quad \rightarrow \quad \cos \varphi_{\text{crit}} = n \]

For sufficiently large neutron wavelength, \( \lambda \), \( n=0 \) and \( \cos \varphi_{\text{crit}} = 90^\circ \)

This implies that neutrons will be reflected at ALL ANGLES!
Cold Neutrons

Characterized by a thermal velocity comparable to $T \approx 20K$

$v \approx 500 \text{ m/s}$

$E_k \approx 5 \text{ meV}$

$\lambda \approx 5 \text{ Å}$

Cold Neutrons

Characterized by a thermal velocity comparable to $T \approx 20K$

$v \approx 5 \text{ m/s}$

$E_k \approx 100 \text{ neV}$

$\lambda \approx 500 \text{ Å}$

Material Bottle

$V_{eff} \approx 200 \text{ neV}$ for Ni, Be, Cu, ...

Magnetic Bottle

$mv^2 \approx 2\mu_nB$ for $B \approx 1 \text{ Tesla}$

Gravitational Well

$mv^2 \approx mgh$ for $h \approx 1 \text{ meter}$
$\tau_n = 888.4 \pm 3.1 \text{ s}$

[V. Nesvizhevsky, A. Serebrov et al., JETP 75 (1992) 405]
The Systematic Concern with UCN Bottles

Loss rate in Bottle with material walls:

\[
\frac{1}{\tau_{\text{bottle}}} = \frac{1}{\tau_{\text{decay}}} + \frac{1}{\tau_{\text{absorb}}} + \frac{1}{\tau_{\text{up-scatter}}} + \frac{1}{\tau_{\text{holes}}} 
\]

Neutrons can be lost to absorption on walls, up-scattering on walls, escape through gaps in the wall.

These effects are velocity dependent, not well understood, and depend strongly on trace contamination on walls.
"MAMBO" Ultracold Neutron Bottle

\[ \tau_n = 887.6 \pm 3 \text{ s} \]

[W. Mampe et al., NIM A284 (1989) 111]
Double Bottle with Neutron Loss Monitors

\[
\tau_n = 885.4 \pm 0.9_{\text{stat}} \pm 0.4_{\text{syst}} \text{ s}
\]

[S. Arzumanov, L. Bondarenko et al., NIM A 440 (2000) 511]
### Measurements of the Neutron Lifetime

<table>
<thead>
<tr>
<th>Lifetime $\tau$ [s]</th>
<th>Method</th>
<th>Ref./Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$878.5 \pm 0.8$</td>
<td>Storage of ultra-cold neutrons</td>
<td>A. Serebrov et al. 2005</td>
</tr>
<tr>
<td>$886.8 \pm 3.42$</td>
<td>Neutron beam experiment</td>
<td>M.S. Dewey et al. 2003</td>
</tr>
<tr>
<td>$885.4 \pm 0.95$</td>
<td>Storage of ultra-cold neutrons</td>
<td>S. Arzumanov et al. 2000</td>
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<tr>
<td>$889.2 \pm 4.8$</td>
<td>Neutron beam experiment</td>
<td>J. Byrne et al. 1995</td>
</tr>
<tr>
<td>$882.6 \pm 2.7$</td>
<td>Storage of ultra-cold neutrons</td>
<td>W. Mampe et al. 1993</td>
</tr>
<tr>
<td>$888.4 \pm 3.1 \pm 1.1$</td>
<td>Storage of ultra-cold neutrons</td>
<td>V. Nesvizhevski et al. 1992</td>
</tr>
<tr>
<td>$878 \pm 27 \pm 14$</td>
<td>Neutron beam experiment</td>
<td>R. Kosakowski 1989</td>
</tr>
<tr>
<td>$887.6 \pm 3.0$</td>
<td>Storage of ultra-cold neutrons</td>
<td>W. Mampe et al. 1989</td>
</tr>
<tr>
<td>$877 \pm 10$</td>
<td>Storage of ultra-cold neutrons</td>
<td>W. Paul et al. 1989</td>
</tr>
<tr>
<td>$876 \pm 10 \pm 19$</td>
<td>Neutron beam experiment</td>
<td>J. Last et al. 1988</td>
</tr>
<tr>
<td>$891 \pm 9$</td>
<td>Neutron beam experiment</td>
<td>P. Spivac et al. 1988</td>
</tr>
<tr>
<td>$872 \pm 8$</td>
<td>Storage of ultra-cold neutrons</td>
<td>A. Serebrov et al. 1987</td>
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<tr>
<td>$870 \pm 17$</td>
<td>Neutron beam experiment</td>
<td>M. Arnold et al. 1987</td>
</tr>
<tr>
<td>$903 \pm 13$</td>
<td>Storage of ultra-cold neutrons</td>
<td>Y.Y. Kovsintsev et al. 1986</td>
</tr>
<tr>
<td>$875 \pm 95$</td>
<td>Storage of ultra-cold neutrons</td>
<td>Y.Y. Kovsintsev et al. 1980</td>
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<tr>
<td>$937 \pm 18$</td>
<td>Neutron beam experiment</td>
<td>J. Byrne et al. 1980</td>
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<tr>
<td>$881 \pm 8$</td>
<td>Neutron beam experiment</td>
<td>L. Bondarenko et al. 1978</td>
</tr>
<tr>
<td>$918 \pm 14$</td>
<td>Neutron beam experiment</td>
<td>C.J. Christensen et al. 1972</td>
</tr>
</tbody>
</table>
Measurements of the Neutron Lifetime prior to 2005

PDG 2005: $\tau_n = 887.5 \pm 0.8$
Current Situation

PDG 2005: $\tau_n = 887.5 \pm 0.8$
What Next
# Improving the error on the NIST Beam Experiment

<table>
<thead>
<tr>
<th>Source of Correction</th>
<th>Correction</th>
<th>$\sigma_{\text{current}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{6}\text{LiF}$ deposit areal density</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>$^{6}\text{Li}$ cross section</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Neutron detector calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption of neutrons by $^{6}\text{Li}$</td>
<td>$+5.2$</td>
<td>0.8</td>
</tr>
<tr>
<td>Scattering of neutrons by Si substrate</td>
<td>$-0.2$</td>
<td>0.5</td>
</tr>
<tr>
<td>Neutron beam profile and detector solid angle</td>
<td>$+1.3$</td>
<td>0.1</td>
</tr>
<tr>
<td>Neutron beam profile and $^{6}\text{Li}$ deposit shape</td>
<td>$-1.7$</td>
<td>0.1</td>
</tr>
<tr>
<td>Absorption of neutrons by Si substrate</td>
<td>$+1.2$</td>
<td>0.1</td>
</tr>
<tr>
<td>Neutron counting statistics</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Neutron counting dead time</td>
<td>$+0.1$</td>
<td>0.1</td>
</tr>
<tr>
<td>Proton counting statistics</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron beam halo</td>
<td>$-1.0$</td>
<td>1.0</td>
</tr>
<tr>
<td>Trap nonlinearity</td>
<td>$-5.3$</td>
<td>0.8</td>
</tr>
<tr>
<td>Proton backscatter calculation</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$-0.4$</td>
<td>3.4</td>
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</table>
Neutron Detection Using Absolute Calorimetry
# Improving the error on the NIST Beam Experiment

<table>
<thead>
<tr>
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<th>$\sigma_{\text{projected}}$</th>
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<tr>
<td>$^6$LiF deposit areal density</td>
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<td></td>
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<td></td>
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<td>1.0</td>
<td></td>
<td></td>
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<tr>
<td>Neutron detector calibration</td>
<td></td>
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<tr>
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Current Situation

PDG 2005: $\tau_n = 887.5 \pm 0.8$

Reduce this x2-3
Magnetic Trapping of Ultra Cold Neutrons
Magnetic Trapping of Ultracold Neutrons

[P. Huffman, et. al,  Nature, 403, no.6765, 2000]

Harvard University

P. R. Huffman and A. K. Thompson
NIST, Gaithersburg

R. Golub
HMI, Berlin

S. K. Lamoreaux, G. Greene
Los Alamos National Laboratory

K. J. Coakley
NIST, Boulder
Ioffe-Type Magnetic Trap

figure courtesy J. Doyle
Wonderful Property #2

Production of Ultra Cold Neutrons in Superfluid Helium

- Neutrons of energy $E \approx 0.95$ meV (11 k or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering by absorption of an 11 k phonon is a UCN loss mechanism. But population of 11 K phonons is suppressed by a large Boltzman Factor: $\sim e^{-11/T}$ where $T \sim 200$ mk

Golub and Pendlebury (1977)
Detection of Trapped Neutrons

\[ n \rightarrow p^+ + e^- + \overline{\nu}_e \]

- Recoil electron 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 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) is converted to blue using the organic fluor TPB (tetraphenyl butadiene).
Magnet form
Racetrack coil
Cupronickel tube
Acrylic lightguide
Solenoid
Trapping region
Beam stop
TPB-coated acrylic tube
Neutron shielding
Collimator

*figure courtesy J. Doyle*
Recent Results From
The Harvard/NIST/LANL/HMI Neutron Lifetime Expt.

Figure Courtesy of Paul Huffman