Precision measurements of neutron beta decay I
– Neutron lifetime –

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Content

• Neutron sources
  ➢ Reactors, spallation sources
  ➢ Neutron energies, cold and ultracold, neutron transport

• Towards neutron decay

• Measuring the neutron lifetime (partial and total width)
  ➢ Beam experiments
  ➢ Storage experiments

• Status and the neutron lifetime puzzle
  ➢ Interpretations and their exclusion

• Outlook

Disclaimer: I never measured the neutron lifetime myself. At least not directly.
Neutron sources for slow-neutron particle physics

Research reactors

- Fission of $^{235}$U, chain reaction
- Neutron yield: $2-3 / fission$ (-1 for chain reaction)
- Neutron energy: Up to $\sim 10$ MeV
- Heat: $\sim 180$ MeV/n
- Operation: Typically continuous, High time-averaged flux

Spallation neutron sources

- Spallation of heavy nuclei by GeV protons
- Neutron yield: $30-40 / proton$
- Neutron energy: Up to proton energy
- Heat: $\sim 30$ MeV/n
- Operation: Typically pulsed, High peak flux

Neutron facilities

Accelerator-driven neutron sources??

- CANS (Compact Advanced Neutron Source)
- HiCANS (High-Current Accelerator-driven Neutron Source)
Several proposals as national sources for neutron scattering, interest for statistics-limited neutron decay to be seen
Neutrons – from fast to cold to experiment

From fast to cold by moderation

Fast n: \( > 1 \text{MeV} \)
Intermediate: \( 1 \text{ MeV} \ldots 1 \text{eV} \)
Slow: \( < 1 \text{eV} \)
\( > 1000 \text{ K} \) epithermal: \( 1 \text{ eV} \ldots 100 \text{ meV} \)
\( 300 \text{ K} \) thermal: \( 100 \text{ meV} \ldots 12 \text{ meV} \)
\( 30 \text{ K} \) cold: \( 12 \text{ meV} \ldots 120 \text{ µeV} \)
\( < 1 \text{ K} \) very cold: \( 120 \text{ µeV} \ldots 300 \text{ neV} \)
\( < 3 \text{ mK} \) ultra cold: \(< 300\text{neV} \)

From production to experiment

- Mirrors & SuperMirrors \((m=2, 3...)\):
  \[ \theta_{c,Ni} = 1.73 \frac{\text{mrad}}{\text{Å}} \lambda, \theta_{c,SM} = m \theta_{c,Ni} \]
- Neutron guides:
  - Go away from source
    - Gain space
  - Reduce background (distance, curvature)
  - Define neutron phase space
- Typical dimensions:
  - \( 6\times10 \text{ cm}^2, 80 \text{ m} \)

Neutron beams are large, divergent, inhomogeneous
Neutrons – from cold to ultra-cold

Phase space selection or transformation
- Does not increase phase space density
- PF2@ILL:
  - 4 UCN ports
  - Stored UCN density 30/cm³
  - $3 \cdot 10^4$ UCN/cm³ s

Superthermal UCN sources
- Problems with moderators:
  - $T_{UCN} \ll T_{moderator}$
  - Moderation inefficient for slow neutrons: see optical potential instead of individual nuclei
- Solution: “Converter” where
  - UCN can only scatter to narrow energy band with $E^* \gg kT_{converter}$ and $E^* \gg E_{UCN}$
  - Only neutrons with $E^*$ can scatter to $E_{UCN}$
  - Neutron absorption is very small
  - Upscattering of UCN suppressed by Boltzmann factor $\exp(-E^*/kT_{converter}) \ll 1$
- Sources:
  - Superfluid $^4$He sources:
    - ILL, RCNP, TRIUMF, WWR-M
  - Solid $D_2$ sources:
    - LANL, PSI, Mainz, Pulstar, FRM-II

[Steyerl, Nucl. Instr. Meth. 125 (1975) 461]
n’s interactions – What is special about UCN?

• **Strong**
  - Nuclear force, binding in nuclei
  - Neutron detection: $^3\text{He}(n,p)t$, Gd$(n,\gamma)$
  - Neutron optical potential $V = \frac{2\pi\hbar}{m_n} bN$
    
    $$V = \mathcal{O}(100)\text{ neV}$$

• **Weak**
  - Decay $n \to p + e + \bar{\nu}_e$
  - Spin rotation in non-magnetic materials
  - Parity violation in hadronic interactions:
    
    $$p(n_{\text{pol}},\gamma)d$$

• **Electromagnetic**
  - Magnetic moment $\mu_n = -60\text{ neV/T}$
  - Magnetic scattering
  - Magnetic potential $V = -\mu_n B$
    
    $$V = 60\frac{\text{neV}}{T} B$$

• **Gravitational**
  - Free fall
  - Gravitational potential $V = mg\ell$
    
    $$V = 102\frac{\text{neV}}{m} h$$

• **Kinetic energy**
  - $\lambda \nu = 3956 \frac{\text{Å}}{\text{s}}, \quad E = 5.22 \frac{\text{neV}}{(\text{m/s})^2} \nu^2$
  - Cold: $\nu \sim 1\text{ km/s}, \quad E(1\text{ km/s}) = 5\text{ meV}$
  - UCN: $\nu \sim 5 \frac{\text{m}}{\text{s}}, \quad E = 130\text{ neV} \left(\frac{\nu}{5\text{ m/s}}\right)^2$  → Confinable by 3 interactions
Neutron facilities

... with slow neutrons beams for particle physics:

- **Europe**
  - Reactors: ILL (cold, UCN), FRM II (cold, UCN), Mainz (UCN)
  - **Spallation:** PSI (*continuous*, UCN), ESS (??)

- **America**
  - Reactors: NIST (cold), PULSTAR (UCN)
  - **Spallation:** LANL (UCN), SNS (cold, UCN-EDM), TRIUMF (UCN)

- **Japan**
  - **Spallation:** RCNP (UCN), JPARC (cold, UCN)

European facilities

**ILL – High flux reactor (Grenoble, F)**
- 58 MW\textsubscript{th}, 2 cold sources, 1 hot source
- 40 Instruments, 800 exps/a, 1400 visitors/a
  - **PF1B**: most intense cold neutron beam for particle physics, highest neutron polarization
  - **PF2**: most intense UCN beams
  - **SuperSUN**: highest UCN density

**ESS – Long-pulse spallation source (Lund, S)**
- 2-5 MW, 14 Hz, 3 ms, 1 cold source, POT 2025
- 15 instruments in construction
  - Proposal **ANNI**: most intense pulsed cold neutron beam facility (see lecture II)
  - Studies for **UCN/VCN** sources ongoing
  - No such instrument before 2030ies 😞

For particle physics opportunities at the ESS, including neutrinos, see: *Physics Reports 1023 (2023) 1–84.*
### Facilities for particle physics with neutrons

#### Cold

<table>
<thead>
<tr>
<th>Facility</th>
<th>Pulsed</th>
<th>Capture flux density ([10^9 \text{ n/cm}^2/\text{s}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF1B (ILL)</td>
<td>No</td>
<td>20</td>
</tr>
<tr>
<td>MEPHISTO (FRM II)</td>
<td>No</td>
<td>18\textsuperscript{(sim)}</td>
</tr>
<tr>
<td>NG-C (NIST)</td>
<td>No</td>
<td>8.3</td>
</tr>
<tr>
<td>FnPB (SNS)</td>
<td>Yes</td>
<td>3.8/(1.4 MW)</td>
</tr>
<tr>
<td>FP12 (LANSCE)</td>
<td>Yes</td>
<td>0.1</td>
</tr>
<tr>
<td>NOP (J-PARC)</td>
<td>Yes</td>
<td>1.2/MW\textsuperscript{(sim)}</td>
</tr>
<tr>
<td>ANNI (ESS)</td>
<td>Yes</td>
<td>50\textsuperscript{(sim)}</td>
</tr>
</tbody>
</table>

**Note:** Facilities for particle physics with neutrons include facilities ranging from PF1B (ILL) to ANNI (ESS). Each facility is characterized by whether it is pulsed (Yes/No) and the capture flux density in \([10^9 \text{ n/cm}^2/\text{s}]\). Facilities such as MEPHISTO (FRM II) show a simulated flux density of 18 n/cm\(^2\)/s.

#### UCN

<table>
<thead>
<tr>
<th>Source</th>
<th>Converter</th>
<th>Density in storage vol UCN cm(^{-3})</th>
<th>Useful current (10^4) UCN s(^{-1})</th>
<th>Source storage time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANL area B [78]</td>
<td>SD(_2)</td>
<td>52</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>ILL turbine [75]</td>
<td>liq. D(_2)</td>
<td>&gt;40</td>
<td>100</td>
<td>&lt;1 sec</td>
</tr>
<tr>
<td>ILL LHe [79]</td>
<td>LHe</td>
<td>&gt;55</td>
<td>0.14</td>
<td>67</td>
</tr>
<tr>
<td>RCNP [81]</td>
<td>LHe</td>
<td>26</td>
<td>1</td>
<td>81</td>
</tr>
<tr>
<td>PSI [82]</td>
<td>SD(_2)</td>
<td>23</td>
<td>4.2</td>
<td>90</td>
</tr>
<tr>
<td>Mainz [83]</td>
<td>SD(_2)</td>
<td>18</td>
<td>0.12</td>
<td>Few sec</td>
</tr>
<tr>
<td>ILL SuperSUN Phase 1</td>
<td>LHe</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


**Target parameters:**
- SD\(_2\): >30, >10, Few sec
- LHe: 5000, 3000, N/A
- 1500\(^*\), 100\(^*\), 150
- 12000, 7000, 10

\(^*\) polarized UCN

**Updated from:** Young et al, J. Phys. G. Nucl. Part. Phys. 41 (2014) 114007

**Warning:** What counts is what arrives in the experiment. This depends on many more factors (spectrum, divergence, area or volume, transport, design of experiment, ...)

**Taken from:** Theroine et al, ESS Instrument Construction Proposal ANNI, (2015)
Towards neutron decay

- **Rutherford 1920:**
  - Atomic nuclei composed of H nuclei and electrons. An electron can be bound very closely to a H nucleus (much more tightly than in an H atom), forming a neutral doublet.
  - These “atoms” [today: neutron] would be difficult to detect, may be impossible to contain in a vessel, can readily enter atoms and unite with nuclei, or be disintegrated by its intense field

- **These free “atoms” could not decay spontaneously because of binding energy:**
  - $m_{\text{atom}} < m_p + m_e$

- **Chadwick 1932, 1933:**
  - Discovery of the neutron
  - Neutron mass smaller than that of hydrogen atom – consistent with Rutherford model
  - Good reasons to consider neutron as elementary particle: binding energy [at the time] larger than mass of electron, spin considerations, hydrogen atom should transform into neutron

- **Curie & Joliot 1934**
  - Neutron mass estimate heavier than H atom, energy release $n \rightarrow p + e$ from mass $2.1 \cdot 10^6$eV

- **Chadwick & Goldhaber 1934**
  - First precision measurement of $m_n$ from $D + \gamma \rightarrow p + n$ and measurement of proton energy
  - Neutron “definitively” heavier than H atom $\Rightarrow$ free neutrons decay $n \rightarrow p + e + \nu$ unless $m_\nu \sim m_e$
Discovery of neutron decay

• Snell & Miller, 1948


- Experimental factors:
  - Proton collection and counting efficiency (10%)
  - Number of neutrons in the sample \(4 \cdot 10^4\)

- Results:
  - Estimate \(\tau_{1/2} = 30\) min
  - “...much safer however to say that neutron half-life must exceed 15 minutes”

- Next step: Search coincidences

Shows common challenges of beam lifetime measurements:
  - Accurate knowledge of number of neutrons
  - Accurate knowledge of detection efficiency of decay products
  - Backgrounds
Measurement of the neutron lifetime

**Beam method**

- Measure specific activity of neutron beam: “Counting the dead”
  $$\dot{N} = \frac{n_{e,p}}{\epsilon_{e,p}}$$
  $$\tau = -\frac{N}{\dot{N}}$$
- Two absolute measurements:
  - Total number of neutrons
  - Total rate of decay products (protons or electrons – corrected for all losses)
- $\tau_{\text{Beam}} = \text{specifically decay branch into electrons or protons}$ → Partial decay width

**UCN Storage method**

- Measure number of stored neutrons in function of time: “Counting the survivors”
  $$N(t) = N_0 \exp \left( -\frac{t}{\tau} \right)$$
- Relative measurement but:
  - Quantify or exclude all other loss channels
- $\tau_{\text{Bottle}} = \text{all decay branches (and other types of neutron disappearance)}$ → Total decay width

$$\tau = -\frac{N}{\dot{N}}$$
Counting the dead: \( n \rightarrow pev, \quad m_n - m_p - m_e = 782 \text{ keV} \)

\[ E_e: 0 \ldots 782 \text{ keV} \]

- Directly detectable
- Threshold effects
- Detector non-linearity, real spectrum (Fierz term?)

- (Back)scattering by detector and materials

\( E_p: 0 \ldots 751 \text{ eV} \)

- Acceleration required
- Threshold effects suppressed:
  \[ E_{\text{det}} = E_p + V \]
- Extraction & focusing by electrostatic field
- Sensitivity to stray fields, charges

- Scattering by rest gas, losses in dead layers

\( \bullet \) Lowly ionizing \( \rightarrow \) Background from gammas and electrons

\( \bullet \) Highly ionizing \( \rightarrow \) Background from ions
Accurate detector collimation

Neutron beams are large, divergent, inhomogeneous

→ Convolution of neutron density distribution with detector solid angle needed

• Proton detection by thin-window proportional counter.
• Beam profile was measured in 900 squares of 3×3 mm².
• Adding of barrier voltage to stop decay protons for background measurement.

4π detection

• Magnetic field
  • Transversal homogeneous field of 0.7 T.
  • Electron detection in plastic scintillators.
  • Backscattered electrons detected in opposite scintillator (collection of full energy).

Sosnovsky et al, Nucl. Phys. 10 (1959) 395
Bondarenko et al, JETP Lett. 28 (1978) 303
Christensen et al, Phys. Rev. D 5 (1972) 1628
Source volume & Det solid angle

4π detection

- Magnetic field, pulsed beam
  - Longitudinal field of 1.7 T upwards bent at both ends.
  - Electron and backscatter detection by plastic scintillators.
  - Pulsed beam for full containment.

4π detection

- Drift chamber for electrons, pulsed beam
  - Electron threshold of a few eV.
  - Pulsed beam for full containment.
  - Simultaneous measurement of neutron density by $^3\text{He}(n,p)t$ with same geometry and dead time.


Same concept: Hirota et al, Prog. Theor. Exp. Phys. 2020, 123C02
Neutron counting

Continuous beams $\tau = -\dot{N}/N$

Observe neutrons traversing active volume

- Number of neutrons in volume: $N = \varrho_n V$
- Neutron with velocity $v$ stays for time $\frac{L}{v}$

$$\varrho_n = \int \frac{1}{v} \frac{d\Phi}{dv} dv$$ particle flux $\Phi = \int \frac{d\Phi}{dv} dv$

- Neutron capture cross section:
  $$\sigma(v) = \frac{\sigma_{th} v_{th}}{v}$$ capture flux $\Phi_c = \int \frac{v_{th} d\Phi}{dv} dv$

$(v_{th} = 2200 \text{ m/s})$ density & $\Phi_c$: $\varrho_n = \Phi_c / v_{th}$

$1/v$ law: valid with relative error $< 10^{-4}$ except for strong absorbers or absorbers with low-lying capture resonances

- Capture rate in thin foil (areal atom density $\varrho_{foil}$)

$$R = a \varrho_{foil} \int \sigma(v) \frac{d\Phi(v)}{dv} dv$$

$$R = a \varrho_{foil} \sigma_{th} v_{th} \varrho_n = a \varrho_{foil} \sigma_{th} \Phi_c$$

Examples

- Activation (Na, Mg, Au), separate readout
- Low-efficiency proportional counters
- $^6$LiF deposit

Example importance of thin:
Deposit with 0.4% absorption for $v_{th}$ resulted in correction of $+5.2(8)$ s to $\tau$ because of deviation from $1/v$ for deposit of this thickness.

Remark pulsed beams

Observe neutrons in a pulse for a given time, independent on their respective velocity.

- Need number of neutrons in pulse, not capture flux.
- Longitudinal magnetic field 4.6 T $\rightarrow$ Proton cyclotron radius < 1 mm
- Penning trap for protons of variable length $\rightarrow$ Get rid of end effects
- Cycles of accumulation (100 ms) and counting (76 $\mu$s)
  - improved S/BG
  - BG measurement after emptying the trap

\[ N_{p} = \frac{1}{\tau} \frac{\epsilon_{p}}{\epsilon_{0} v_{th}} (n l + L_{end}) \]

$L_{end}$ depends on trap length (magnetic field, beam divergence). Correction by MC simulation for each trap length. Correspond to $-5.3(8)$ s correction on $\tau$. 

Byrne et al, Phys. Rev. Lett. 65 (1990) 289
Byrne et al, EPL 33 (1996) 187
• Proton acceleration to 25-35 kV

• Detection with Si surface barrier detectors and passive ion-implanted planar detectors

• Measurements with different detectors (dead layers) and acceleration potentials to correct for losses:
  ➢ **Monte Carlo simulation** of fraction of lost $f_{\text{Lost},i}$ and of backscattered $f_{\text{Bsc},i}$ protons for each configuration $i$
  ➢ Correction of measured life times $\tau_{\text{measured},i}$ for $f_{\text{Lost},i}$
  ➢ **Extrapolation** to 0 backscattering fraction $f_{\text{Bsc},i}$

\[
\frac{\tau_{\text{measured},i}}{1 + f_{\text{Lost},i}} = \tau + X f_{\text{Bsc},i}
\]
Extensive calibration of neutron monitor

- Comparison with Alpha-Gamma device $\rightarrow$ no need to know $^6$Li(n,t)$^4$He cross section which had relevant uncertainty

$$R_{\alpha,t} = \epsilon_{th} \frac{\lambda_{mo}}{\lambda_{th}} R_n, \quad \lambda_{th} = 1.798 \text{ Å}, \quad \lambda_{mo} = 4.9605(12) \text{ Å}$$

- Uncertainty of neutron efficiency, dominating error budget of [Nico05], reduced by factor 5

$$\tau = 887.7(1.2^{\text{stat}})(1.9^{\text{sys}}) \text{s}$$

No change to the corrections in [Nico05]. Largest: -5.3 s trap nonlinearity, +5.2 s non 1/v of deposit
Summary of important concepts

The long way to precision...

• Use of thin neutron detectors with $\sigma \propto 1/\nu$ compensating for variations in neutron flight time $T \propto 1/\nu$ through the decay volume

• Magnetic guidance of the decay products to the detectors for effective $4\pi$ detection of the charged decay products

• Use of neutron guides to measure far away from the neutron source in a low-background environment

• In-beam trapping of decay protons and their sudden release onto a detector to considerable reduce background

• Use of a proton trap of variable length eliminating edge effects

D. Dubbers and M. G. Schmidt, Rev. Mod. Phys. 83 (2011) 1111
Counting the survivors

Material bottles: Determine losses

- **Capture**
  \[ \psi \propto \exp \left( i \frac{p \cdot x}{\hbar} \right) \]

- **Upscattering:** **Bottles are hot**
  \[ \psi \propto \exp \left( -\frac{\sqrt{2m(V - E_\perp)}}{\hbar} x \right) \]
  \[ \propto \exp \left( -x/x_0 \sqrt{V - E_\perp} \right) \]

  \[ x_0 \sim 20 \text{ nm} \]
  \[ P_{\text{cap}} \approx N_A \sigma_{\text{cap}} x_0 \approx 10^{-5} \]

Magnetic bottles: No losses!?  

- **No contact with matter**
  \[ V = -\mu B, \quad F = \pm \mu V |B| \]

  - Need field gradient

- **Can only store one spin direction**
- **Loss by depolarization / spin flip**

\[ N(t) = N_0 \exp \left( -\frac{t}{\tau} \right) \]
Material bottles – Extrapolations

Ideal

• Typical loss per bounce: $\eta \approx \mathcal{O}(10^{-5})$
• Storage times of several 100 s possible
• Minimize losses: Careful selection and preparation of material surfaces
• Determine losses: Vary collision rate
  $$\gamma = \left(\frac{v}{\Lambda}\right), \quad \Lambda = \frac{4V}{S} \text{ mean free path}$$
in controlled way and extrapolate to 0:
  $$\frac{1}{\tau_{\text{Stor}}} = \frac{1}{\tau} + \eta(v) \gamma \left(v, \frac{V}{S}\right)$$

Reality

• Losses energy-dependent $\rightarrow$ Extrapolation only accurate for monoenergetic neutrons
• Initial spectrum not monoenergetic
• Energy for wall interaction height-dependent
• Spectrum of stored neutrons changes with time: faster neutrons $\rightarrow$ higher losses (via $\gamma$ and $\eta$)
  $\rightarrow$ More than one time constant $\tau_{\text{Stor}}$
  $$N(t) = N_0 \sum_i a_i \exp \left(-\frac{t}{\tau_{\text{Stor},i}}\right)$$
• Change of neutron energy by upscattering
  $\rightarrow$ Calculation of wall loss rate as function of varied feature requires models & assumptions

$\tau_{\text{Stor}} = \frac{\Delta t_2 - \Delta t_1}{\ln(N_1/N_1)}$

$N(t) = N_0 \exp \left(-\frac{t}{\tau_{\text{Stor}}}\right)$
General considerations

• Extrapolation methods require isotropic and homogeneous neutron population → corrugated surfaces to obtain chaotic trajectories and avoid quasi-stable ones

• UCN above wall potentials may be stored for some time on quasi-stable trajectories → avoid quasi-stable trajectories → period of spectrum cleaning

• Took over after advent of strong UCN sources available from 1986

General procedure

1. Bottle filling
2. Spectrum cleaning
3. Storing for holding time $\Delta t_i$
4. Counting the survivors
Repeat...
MAMBO @ PF2/ILL

First precision storage experiment (PF2)

• **Variable volume** up to 120 l
• “Fomblin” oil (hydrogen-free fluorated polymer, 106 neV, $\eta=(2-3)\cdot10^{-5}$/bounce) as wall coating
• Temporal spectrum change compensated by choice of storage intervals:
  \[
  \frac{t^a_1}{t^b_1} = \frac{t^a_2}{t^b_2} = \frac{\Lambda^a}{\Lambda^b} \rightarrow \text{number of wall collisions in } t_i \\
  \text{independent on trap-size for each velocity bin} \\
  \rightarrow \text{spectral evolution during storage volume independent}
  \]
• Largest measured $\tau_{\text{Stor}}=730$ s \\
  extrapolated by 150 s to $\tau=887.6(3.0)$ s

Experiment at lowest temperature

- Confinement by walls and gravity
- Two ways to vary wall collision rate:
  - **Variable spectrum**: Gravitational selection of neutron spectrum
  - **Two volumes**: 60 l and 240 l
- Bottle at 15 K, surfaces Be or coated with solid oxygen
- Successive counting of different UCN energy ranges
- Largest measured $\tau_{\text{Stor}} = 876$ s extrapolated by 12 s to $\tau = 888.4(3.3)$ s

Detection of escaping neutrons

- **Two volumes**

- **Detection of upscattered UCN**
  (thermal neutron detectors around storage volume)

- Measurement of initial $N_i$ and final $N_f$ number of UCN and of upscattered UCN $J$. All efficiencies cancel in calculation of $\tau$.

- Fomblin coating, measurements at $+20$, $-9$ and $-26^\circ$C.

- Largest $\tau_{\text{Stor}}=780$ s extrapolated by $100$ s to $\tau=885.4(1.0)$ s

Results so far:

- MAMBO: $\tau_{\text{Stor}}=730$ s   $\tau=887.6(3.0)$ s
- PNPI trap: $\tau_{\text{Stor}}=876$ s   $\tau=888.4(3.3)$ s
- UpsDet trap: $\tau_{\text{Stor}}=780$ s   $\tau=885.4(1.0)$ s

Perfectly consistent: $\langle \tau \rangle=885.8(0.9)$ s

Large extrapolations seem to work, consistent results... but...
Similar to gravitational trap at PNPI

- Confinement by walls and gravity
- Two ways to vary wall collision rate:
  - **Variable spectrum**: Gravitational selection of neutron spectrum
  - **Two volumes**: 60 l and 240 l
- Coating by low-temperature Fomblin:
  - Full **suppression of quasielastic scattering** below -120°C
  - Low remaining losses: $\eta = 2 \cdot 10^{-6}$
  - Coating tested with Ti compared to Be bottle, more efficient than sO$_2$
- Largest measured $\tau_{\text{Stor}} = 872.2$ s
  extrapolated by 6 s to $\tau = 878.5(0.8)$ s


5.6 $\sigma$ deviation from 2005 world average!
Explanations and consequences

- 2.9σ discrepancy to PNPI (1992) result (same group) may be from imperfections of sO$_2$ coating for small volume

- Discrepancy of MAMBO and KI traps (at higher temperatures) probably caused by weak heating of UCN not known at the time, plus heating by shutter movements

- Corrected value for KI trap and result of MAMBO II (2010) consistent with Serebrov 2005

- Serebrov 2005 value was excluded from PDG average until 2010 since too far off, but finally “initiated” shift in bottle value

Lessons

- Agreement with other results does not tell that yours is “right”.

- If your result disagrees, it may still be “right”!

- Small corrections are good – but can still be significantly imprecise.
Magnetic storage

First lifetime measurement with NESTOR

• Guiding and focusing of neutral atoms and neutrons by sextupole field proposed in 1951
  
  Friedburg&Paul, Naturwiss. 38 (1951) 159
  Paul, Int Conf Nucl Phys & Phys Fund Part, Chicago (1951) 172

• Magnetic storage ring for neutrons:
  ➢ Analogy with charged particles. Magnetic moment requires multipoles one order higher
    → Sextupole
  
  ➢ Inner coils replaced by centrifugal force (access, filling from inside)
  
  ➢ Additional coils add higher-order term to harmonic field, to limit oscillation amplitudes

Final result at new, intense UCN source – PF2

• Storage only in radial directions. Trajectories which could mix longitudinal and radial velocities to be removed
  
  ➢ Importance of cleaning →

  ➢ Correction- and model-free lower limit on τ →

  \[ \tau = 877(10) \text{ s} \]

  \[ \tau > 450 \text{s} \]
Magnetic storage

Losses and Counting

- Can only store low field seekers → Losses by depolarization
  - Adiabaticity condition:
    \[ \frac{1}{B} \frac{dB}{dt} \ll \frac{-2\mu_n}{h} B \equiv \omega_L \]
  - Avoid \( B = 0 \), cancellation of fields

- Marginally trapped neutrons
  - Prevent quasi-stable trajectories
  - Clean the UCN spectrum

- Count survivors or decay products – it remains a “bottle” experiment:
  \[ \frac{N_n(t)}{N_n(0)} = \frac{n_{e,p}(t)}{n_{e,p}(0)} = \exp\left(-\frac{t}{\tau_{\text{Stor}}}\right) \]

Experiments

- Magnetic field from coils
  - NESTOR \( \tau = 877(10) \) s
  - NIST-UCN experiment
    - In-situ UCN production and storage in 250 mK \(^4\)He bath
    - Detect decay electron by He scintillation
      \( \tau = 833^{+74}_{-63} \) s
  - PENeLOPE
  - Magnetic field with permanent magnets
    - Magneto-gravitational trap \( \tau = 878.3(1.9) \) s
    - UCN\( \tau \) Next slide
    - Hope \( \tau = 878(39) \) s
    - \( \tau \)SPECT
      - Ezhov et al, JETP Lett. 107 (2018) 671

- https://ultracoldneutrons.uni-mainz.de/tauspect/
Trap

- $M_1$: Monitor detectors to correct for variations in UCN source intensity and UCN energy spectrum (e.g. D$_2$ crystal quality)
- Buffer volume for pre-cleaning and smoothing of fluctuations in UCN production rate (2018)

UCN detector

- $^{10}$B-coated ZnS scintillator
Measuring procedure

1) UCN from source: $E_n \lesssim 180$ neV

2) Polarize (5.5 T solenoid) and spin-flipp to become low-field seeker

3) Fill (from below)

4) Clean: $E_n \gtrsim 38$ neV (50 s), lift cleaners
   - Upscattering by PE sheets
   - Capture in lowered detectors

5) Hold for 20 ... 1550 s
   - Pairs of short and long holding times ($\leq 500$ s)
   - Blinding: Adjust nominal holding times by factor unknown to analysis team

6) Count with detector lowered from top:
   - At height of cleaners (40 s): detect uncleaned or heated UCN
   - Middle (20 s)
   - Bottom (150 s)

Pattie et al, Science 360 (2018) 627
Analysis

- 3 analyses A, B, C (methods, algorithms, choices)
- Long scintillation time constants of ZnS result in rate-dependent effects (dead time, pileup, ...)
- Different strategies in analysis C
  - Paired analysis: Combine each pair of short and long holding time. Weighted average
    ➢ Less sensitivity to long-term drifts
  - Global analysis: Maximize likelihood of observing data for global $\tau$ and nuisance parameters
    ➢ Higher statistical sensitivity
- Depolarization from varying holding field, fit
  \[ \lambda_{DP} = 0.0^{+1.0}_{-0.0} \cdot 10^{-7} \text{ s}^{-1} \]
- Gas up-scattering calculated run by run from pressure and periodic rest gas analysis data
  \[ \tau = 877.75 \pm 0.28_{\text{stat}} + 0.22/-0.16_{\text{sys}} \text{ s} \]
Status of the neutron lifetime

PDG 2023
WEIGHTED AVERAGE
878.4±0.5 (Error scaled by 1.8)

Beam lifetime not included
Little influence: 878.6±0.6 s (esf 2.2)

<\tau_{Beam}> = 888.0±2.0 s

Explanation for 4.6\sigma difference?

- \tau_{Beam} partial lifetime into proton
- \tau_{Bottle} inclusive lifetime (all branches)

Invisible branches of \mathcal{O}(1%)?

- n\rightarrow H+\bar{\nu} expected is 4\cdot10^{-6}, \Delta\tau gives experimental upper limit
- Dark Decay
  - n \rightarrow \chi \gamma
  - n \rightarrow \chi e^+e^-
  - n \rightarrow \chi \Phi
- Oscillation to mirror neutrons

Fornal & Grinstein, Phys. Rev. Lett. 120 (2018) 191801
Green & Thompson, J. Phys. G 16 (1990) L75
Greene & Geltenbort, Sci.Am. 314 (2016) 36
Searching the invisible branches

\[ n \rightarrow \chi + \gamma \]

monoenergetic \(\gamma\) in range 782…1664 keV

\[ n \rightarrow \chi + e^+ + e^- \]

monoenergetic \(e^+e^-\) pair

→ Search with Compton-suppressed Ge detector at LANL, 1% branch excluded with 97% C.L.

→ Search for peak in beta spectrum in UCNA and PERKEO-II data (see Lecture II)

Constraining all invisible branches/channels

**Conserved Vector Current**
- $F_{t_{0+\rightarrow 0+}}$ must be equal to vector part of neutron $F_t$ value, calculated with $\lambda$

$\rightarrow$ Calculate beta decay lifetime from $F_{t_{0+\rightarrow 0+}}$ and $\lambda$ (from $A$):

$$\tau_\beta = \frac{2}{\ln 2} \frac{\langle F_{t_{0+\rightarrow 0+}} \rangle}{f(1 + \delta_R')(1 + 3\lambda^2)} = \frac{5172.3(1.1)}{1 + 3\lambda^2} \text{ s}$$

Independent on $\Delta R$!

$\rightarrow$ Lifetime puzzle cannot be explained by dark decays

**Lifetime experiments**
- $\tau_{\text{Beam}}$ partial lifetime into proton, should correspond to $\tau_\beta^\lambda$
- $\tau_{\text{Bottle}}$ inclusive lifetime (all branches) does agree with $\tau_\beta^\lambda$

$\tau_{\text{Beam}} = 888.0(2.0)$ s

$\tau_\beta - \tau_{\text{Bottle}}$ gives limit

$BR_{\text{Dark}} < 0.16\%$ (95% C.L.)

(values from 2019)

Czarnecki et al, Phys. Rev. D 100 (2019) 073008
Outlook

Beam lifetime

- NIST experiment: **BL3** (<0.3 s)
  - Larger magnet and trap
  - Improved systematics

- **TPC** experiment at J-PARC
  - Similar to drift chamber experiment

Magnetic storage

- **UCN** (τ < 0.15 s)
  - Further improved results expected
  - **UCN**τ+: fill trap with adiabatic transfer technique to increase statistics

- **PENeLOPE**, **τSPECT**

An ultimate experiment?

- Counting the dead, in absolute terms relative to the stored neutrons, and the survivors

- Just counting the dead in a storage experiment is not equivalent to beam method! :

\[
\frac{N_n(t)}{N_n(0)} = \frac{n_p(t)}{n_p(0)} = \frac{n_e(t)}{n_e(0)} = \exp\left(-\frac{t}{\tau_{\text{Stor}}}\right)
\]

- **UCNproβe** (1.2 s): count number of decay electrons and the number of UCNs in trap to 0.1%

All precision goals from arXiv:2304.03451

\[\tau_{\text{PDG2023}} = 878.4\pm0.5 \text{ s (with scaling factor 1.8)}\]

https://indico.fysik.su.se/event/6570/contributions/9964/attachments/4125/4727/nordita.pdf→


• F. E. Wietfeldt, *Measurements of the Neutron Lifetime*, Atoms 2018, 6, 70.