PENeLOPE: testing of a one-of-a-kind neutron storage magnet
(Precision Experiment on the Neutron Lifetime Operating on Proton Extraction)

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Outline

• Motivation to measure neutron lifetime
• Magnet design
• Magnet training
HISTORY OF THE UNIVERSE

Creation of the light elements

Creation of the dark matter

Radiation background is visible

Structure formation

Dark energy accelerated expansion

Big Bang

Inflation

High-energy cosmic rays

LHC protons

RHIC & LHC heavy ions

Accelerators

Possible dark matter relic

Possible dark matter relic

Possible dark matter relic

Possible dark matter relic

Possible dark matter relic

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE
Neutrons and cosmology: nucleosynthesis

\( t < 1 \text{ s}, \ kT > 1.3 \text{ MeV} \) (15 billion °C)*

**thermal equilibrium**

\[ p + e^- \rightleftharpoons n + \nu \]

\[ n + e^+ \rightleftharpoons p + \nu \]

\( t > 100 \text{ s}, \ kT < 0.1 \text{ MeV} \) (1.2 billion °C) 

**nucleosynthesis**

\[
\begin{align*}
  d + p & \rightarrow ^3\text{He} + \gamma \\
  d + d & \rightarrow ^3\text{He} + p \\
  d + d & \rightarrow ^3\text{He} + n \\
  ^3\text{He} + n & \rightarrow ^3\text{H} + p \\
  ^7\text{Li} + p & \rightarrow ^4\text{He} + ^4\text{He} \\
  ^7\text{Be} + n & \rightarrow ^7\text{Li} + p \\
  ^3\text{He} + ^4\text{He} & \rightarrow ^7\text{Be} + \gamma \\
  ^3\text{He} + ^4\text{He} & \rightarrow ^7\text{Be} + \gamma
\end{align*}
\]

\( 1 \text{ s} < t < 100 \text{ s}, \ 0.1 \text{ MeV} < kT < 1.3 \text{ MeV} \)

**neutron decay**

\[ n \rightarrow p + e^- + \nu \]

\[
\frac{n_n}{n_p} = \frac{1}{6} \rightarrow \frac{1}{7}
\]

\( t > 100 \text{ s}, \ kT < 0.1 \text{ MeV} \), bec. of γ/B

**deuterium fusion**

\[ n + p \rightarrow d + \gamma \]

*\( T \) in sun 6000°C at surface to 15 Mio°C in the core
The long story of the neutron lifetime $\tau_n$

Big Bang Nucleosynthesis: parametrization of helium abundance

$$Y_p = 0.228 + 0.023 \log \eta_{10} + 0.012 N_\nu + 0.018(\tau_n - 10.28)$$

- the particle data group (PDG) reviews all major particle properties annually
- PDG "world" averages of the neutron lifetime for the last 50 years
  $\tau_{n0} = 880.4 \pm 1.4 \text{ s}$
  $\tau_{PDG} = 11.6 \pm 1.5 \text{ y}$

$\Rightarrow$ PENeLOPE

(\textit{Precision Experiment on the Neutron Lifetime Operating with Proton Extraction})

- Combination of magnetic storage of ultracold neutrons and in-situ proton detection
Ultra-cold neutrons, why?

UCN are really cold:
\[ E_{\text{kin}} < 300 \text{ neV} \Leftrightarrow T < 3 \text{ mK} \]

They can be manipulated using:

- **Strong interaction**
  (Fermi potential up to 350 neV, total reflection from walls)

- **Gravitation**
  (100 neV \( \Leftrightarrow 1.02 \text{ m} \))

- **Magnetic interaction**
Why are ultra-cold neutrons cool?

UCN are really cold:

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- **Strong interaction**
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- **Gravitation**
  (100 neV \( \equiv \) 1.02 m)

- **Magnetic interaction**
  (force on magnetic moment)

\[ \mu_n = -60.3 \frac{\text{neV}}{T} \]

\[ \vec{F} = \nabla (\mu_n \vec{B}) \]

\[ U = -\mu_n \cdot \vec{B} \approx 240 \text{ neV for } 4 \text{ T} \]
PENeLOPE principle

Goal: $\Delta \tau_n < 0.1 \text{ s}$
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

**protons**
- 0-800 eV initially
- accelerated to 30 keV
- collection efficiency 70%

**electrons**
- 0-760 keV
- follow field lines
- not influenced by "lab" high voltage
- collection efficiency 35%

**neutrons**
- 30-120 neV
- low-field seekers
- chaotic trajectories
The PENeLOPE magnet

- **24 thick, short solenoids** (up to 5 cm thick)
- **alternating** current directions create large **axial** repelling **forces** (up to 1.2 MN)
- **NbTi** wire
  - between 32 and 58 wire layers
  - high current density (315 A/mm$^2$)
  - **maximum field 5.5 T**
  - usable field 1.8 T
  - **very little space** for support structure
  - high inductive voltages (4 kV)
Stress control

Different stresses act on the coil package:

- On **cooldown** stainless steel former shrinks more than coil
- On **energization**, coils want
  - to **expand** radially
  - to **separate axially** due to alternating current directions

⇒ **Winding tension** had to be chosen (165 MPa) so that
  - coil does not detach from former
  - winding layers do not separate
  - former doesn’t buckle

⇒ **support structure** has to be rigid enough to withstand
  > 1 MN axially

![Stress diagrams showing tangential and radial stresses during cooldown and energization.](image-url)
Magnet construction

Winding outer coil at Babcock-Noell, Würzburg

Winding detail

Laser welding outside of coil stack

Laser welding inside of coil stack
Magnet tests
Clamped coil stack
- to facilitate repairs if needed
- nominal current not reached
- quench current dropped after 4 quenches

Single coils
⇒ all reached nominal current

Laser-welded coil stack
⇒ long, but successful training
4 bottom coils (BC), 2 inner coils (IC), 2 outer coils (OC)

- quenches start at 35% of nominal current
- slope very flat
- no particular coil causes the quenches

Any ideas?

To be continued…
• PENeLOPE, a **one of a kind** superconducting magnet for fundamental physics

• **long development / design stage** necessary

• **tests of** manufactured **coils** are ongoing, but pose quite a few questions

• Experiments planned for 2019
Neutron spin flip suppression

Why central solenoids???

• adiabatic condition for neutron spin transport

\[ \omega_{\text{Larmor}} \gg \frac{\dot{B}}{|B|} \]
Neutron spin flip suppression

- adiabatic condition for neutron spin transport
  \[ \omega_{\text{Larmor}} \gg \frac{\dot{B}}{|B|} \]

- violated in low field regions
  \[ \Rightarrow \] spin flip more likely
  \[ \Rightarrow \] UCN loss from trap
  \[ \Rightarrow \] systematic effect on lifetime measurement

- all storage coil fields are in r-z plane
  - fill low field regions with central current creating azimuthal field

- Central solenoids necessary to prevent neutrons from hitting central current bars
Coil bumpiness...?

Why do thick solenoids have bumps?

- Crossover region
- azimuthal $B_{\phi}$ component

3D laser scan of actual coil

nominal thickness 5.4 cm
Coil bumpiness... consequences

- all bumps above each other
- bumps random

- low field rings of $B_{rz}$
- low field of $B_{\phi}$ due to bumps

$\Rightarrow$ possible global low field region
$\Rightarrow$ control individual coil rotations 😊
$\Rightarrow$ enhanced neutron spin flip!!! 😞
Magnet loadline

![Graph showing magnet loadline](image_url)
Figure 1.2: Simplified schematic of the planned test circuit. The resistors R## next to the inductors (coils) LOC## represent the ohmic resistance developing during a quench.
Electrons and protons

kinetic energy of protons much less than electrons
⇒ electrostatic manipulation possible
⇒ detector on HV
Physics Case 1: Quark mixing

• Cabibbo-Kobayashi-Maskawa Matrix
\[
\begin{pmatrix}
|d'\rangle \\
|s'\rangle \\
|b'\rangle
\end{pmatrix} =
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle
\end{pmatrix}
\]

• Standard Model
\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1
\]

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

• Coupling constants
\[
\lambda = \frac{G_A}{G_V} = -1.2695 \pm 0.0029
\]
\[
A = -2 \frac{|\lambda|^2 + 9 \Re(\lambda)}{1 + 3 |\lambda|^2}
\]
\[
a = \frac{1 - |\lambda|^2}{1 + 3 |\lambda|^2}
\]
PERKEO aSPECT

• Current PDG average
\[
\tau_n = 885.7 \pm 0.8 \text{ s}
\]
<table>
<thead>
<tr>
<th>Source:</th>
<th>10^7 UCN/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy window</td>
<td>70 neV</td>
</tr>
<tr>
<td>Polarized UCN in trap (results full MC including source, guides, slits etc)</td>
<td>10^7 UCN</td>
</tr>
<tr>
<td>Proton collection/detection efficiency</td>
<td>60% / 40%</td>
</tr>
<tr>
<td>Neutron collection/detection efficiency</td>
<td>70% / 90%</td>
</tr>
<tr>
<td>Material storage lifetime</td>
<td>350 s</td>
</tr>
<tr>
<td>Filling / cleaning / ramping / HFS cleaning time</td>
<td>200 s / 200 s / 100 s / 160 s</td>
</tr>
<tr>
<td>Storage times</td>
<td>1000 s / 3000 s / 5000 s / 8000 s</td>
</tr>
<tr>
<td># of cycles necessary to reach 0.1 s in both detection schemes</td>
<td>610</td>
</tr>
<tr>
<td>Time necessary</td>
<td>37 days</td>
</tr>
</tbody>
</table>

\[ N(t) = N_{LFS} \left( (1 - f_M)e^{-\frac{t}{\tau_B}} + f_M \cdot e^{-\frac{t}{\tau_N}} \right) + N_{HFS}e^{-\frac{t}{\tau_{HFS}}} + B \]
Instability of UCN tracks – physics or numerics?

\[ \Delta z = 10^{-17} \text{m}, t = 30 \text{s} \]

\[ \Delta z = 10^{-17} \text{m}, t = 0.7 \text{s} \]
Spin flip suppression

- **spin flip:**
  - systematic studies possible varying the central current
  - around 2-3% of dep. UCN reach UCN detector

**MC simulations:**
- spin-flip loss time $\tau_{SF} > 10^9$ s
- systematic effect: $\Delta \tau_n < 0.01$ s

\[
\frac{dS}{dt} = \omega \times B
\]

*S. Materne, R.P. et al., NIM A 611, (2009).*

**Fig. 2.** Simulation on the storage lifetime of neutrons before spin-flip as a function of the current in the racetrack coils. Every single gray circle represents a single neutron. The mean spin-flip loss lifetime averaged over a current bin is shown as black triangles.

**Fig. 3.** Ratio $R$ of the number of UCN with $\tau_{SF} < 10^9$ s to number of UCN with $\tau_{SF} > 10^8$ s within a racetrack coil current bin versus the current.
Coil revision 2010

- topology unchanged
- bigger coil distances
- less coils 44 ⇒ 28
- max. field in conductor 6.1 ⇒ 5.5 T
- storage potential 74 ⇒ 115 neV
- proton collection 70 ⇒ 68 %
- detector size 0.3 ⇒ 0.23 m²
- central current in warm bore
Instability of UCN tracks – physics or numerics?

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Instability of UCN tracks – physics or numerics?

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Reactions similar to neutron decay

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

Solar astrophysics: p-p chain in the sun

\[ p + p \rightarrow ^2D + e^+ + \nu_e \]

\[ p + e^- + p \rightarrow ^2D + \nu_e \]

\[ \Rightarrow \text{long life of stars} \]

Reactions similar to neutron decay

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

\[ \Rightarrow \text{long life of stars} \]

neutron star formation

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

\[ \Rightarrow \text{long life of stars} \]

neutrino detection

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

Big Bang nucleosynthesis

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

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

\[ \Rightarrow \text{He abundance} \]

W,Z production

\[ p\bar{p} \rightarrow W + X \rightarrow e^- \bar{\nu}_e \]

\[ p\bar{p} \rightarrow Z + X \rightarrow \nu\bar{\nu}, l^+ l^- \ldots \]

\[ \Rightarrow \text{He abundance} \]

© NASA

KamLAND detector

© Ohio State

Z: UA1 experiment @SPS, CERN

Dubbers 1991

Byrne 2005
the particle data group (PDG) reviews all major particle properties annually [http://pdg.lbl.gov/](http://pdg.lbl.gov/)

- PDG “world” averages of the neutron lifetime for the last 50 years

⇒ PENeLOPE
   - Precision Experiment on the Neutron Lifetime Operating with Proton Extraction
   - Combination of magnetic storage of ultra-cold neutrons and in-situ proton detection

"Exponential fit" of averages:

\[
\tau_n(t) = \tau_{n0} + Ne^{-\frac{t}{\tau_{PDG}}}
\]

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\tau_{n0} = 880.4 \pm 1.4 \text{ s}
\]

\[
\tau_{PDG} = 11.6 \pm 1.5 \text{ years}
\]