Storage of polarized ultracold neutrons
Hunting the neutron Electric Dipole Moment (EDM)

One measures the neutron Larmor precession frequency $f_L$ in weak Bagdetic and strong Electric fields

$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi \hbar} d_n E$$

The most sensitive experiments use Ramsey’s method with polarized ultracold neutrons stored in a “precession” chamber. Here a cylinder, Ø50 cm, H12 cm.
Scheme of the apparatus at PSI during EDM data-taking 2015-2016

High voltage, $E = \pm 132 \text{ kV/12 cm}$

4 layers mu-metal shield

UCN source

5T polarizer (SC magnet)

Magnetized iron analyser

Adiabatic Spin Flipper
Importance of neutron polarization

Statistical sensitivity:

$$\sigma d_n = \frac{\hbar}{2 \alpha E T \sqrt{N}}$$

- Neutron counts
- Precession time $T = 180 \text{ s}$
- Electric field strength $E = 132 \text{ kV/12 cm}$

$\alpha = \text{"visibility"} = \text{"contrast"} = (\text{final polarization}) \times (\text{analyzing power})$

$\alpha = 0.77$ in average in 2015-2016 PSI nEDM data.
2 modes to study the depolarization in nEDM

**Cycle to measure the longitudinal polarization, **$T1$** mode**

<table>
<thead>
<tr>
<th>Filling polarized UCNs</th>
<th>Storage period of duration $T$, UCN spins aligned with $\hat{B}$</th>
<th>Emptying neutrons, counting $N_+$ and $N_-$</th>
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**Cycle to measure the transverse polarization, **Ramsey mode**

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<th>Filling polarized UCNs</th>
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<tr>
<td>(2 s)</td>
<td></td>
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\[time\]
Longitudinal depolarization curve

- The initial polarization 0.85 gives the **analyzing power** of the detection system.

- The UCN longitudinal polarization decays due to depolarization at wall collisions.

\[ \frac{1}{T_1} = \nu \beta \]

Rate of wall collisions \( \approx 50/s \)

Depolarization probability \( \approx 3 \times 10^{-6} \)

No magnetic gradient applied

\[ A(T) = A(0)e^{-T/T_1} \]

\[ A(0) = 0.854 \pm 0.003 \]

\[ T_1 = 5705 \pm 509 \text{ s} \]
We scan the vertical field gradient

Precession chamber

\[
\frac{\partial B_z}{\partial z} [\text{pT/cm}]
\]

UCN polarization after \( T = 180 \) s storage

- Longitudinal polarization
- Ramsey
Due to gravity, different energy groups have different mean height $\bar{z}(E)$ in a cell $H = 12$ cm.

Low energy groups accumulate a phase difference rel. to high energy groups in a vertical gradient.

Theory for small phases:

$$\Delta \alpha = -\frac{1}{2} \gamma_n^2 \left( \frac{\partial B_z}{\partial z} \right)^2 \text{Var}[\bar{z}] T^2$$
# 3 modes to study the depolarization in nEDM

## T1 mode

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## Ramsey mode

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## Spin-echo cycles

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<td>(2 s)</td>
<td>(4 s)</td>
<td>(2 s)</td>
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9/22
Principle of the spin-echo method

**Ramsey cycles**

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**Spin-echo cycles**

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In the rotating frame

- **“early spins”**
- **“late spins”**

Flip!  

$B_0$

Time
We scan the vertical field gradient

Spin echo cancels the gravitational depolarization.

Precession chamber

UCN polarization after $T = 180$ s storage

\[ \frac{\partial B_z}{\partial z} \text{[pT/cm]} \]

\[ \text{Var}[z] = 0.09(2) \text{ cm}^2 \]
We scan the horizontal field gradient

\[ \frac{\partial B_z}{\partial x} \] [pT/cm]

Precession chamber

UCN polarization after T = 180 s storage

- spin echo
- Ramsey
Elements of spin-relaxation theory

**Intrinsic depolarization** =
polarization decay within an energy group due to random motion in a static but non-uniform field.

This is an **irreversible process**

Longitudinal “noise” seen by a neutron $b(t) = B_z(t) - \langle B_z \rangle$. The spin-relaxation theory says:

$$\frac{1}{T_2} = \gamma^2 \int_0^\infty \langle b(t)b(t+\tau) \rangle d\tau := \gamma^2 \langle b^2 \rangle \tau_c$$

- Autocorrelation function of the field
- Correlation time, defined by this equation
MC calculation of the correlation time

We calculate $\tau_c = \frac{1}{\langle x^2 \rangle} \int_0^\infty \langle x(0)x(\tau) \rangle d\tau$

correlation function for $v = 4 \text{ m/s}$

Data:
- $\tau_c = 86 \text{ ms}$
- $\tau_c = 30 \text{ ms}$

UCN polarization after $T = 180 \text{ s}$ storage

Data:
- $\tau_c = 90 \text{ ms}$

$\partial B_z / \partial x \ [\text{pT/cm}]$
Summary:
UCN transverse depolarization
(during precession)

Wall collision
\[ T_{\text{wall}} = T_1 \approx 5000 \text{ s} \]

Intrinsic depolarization
due to random trajectories in a non-uniform magnetic field

Gravitational depolarization
different energy groups have different height \( z \)

\[ \frac{d\alpha}{dT} = -\frac{\alpha}{T_{\text{wall}}} - \frac{\alpha}{T_{2,\text{mag}}} + \dot{\alpha}_{\text{grav}} \]

- In nEDM@PSI we obtained \( \alpha = 0.77 \) after \( T = 180 \text{ s} \) of precession
- It is important to understand the magnetic depolarization for the design of n2EDM because we want to increase the size: diameter 47 cm in nEDM -> diameter 80 cm in n2EDM
We also store polarized mercury atoms

\[ T_2 \approx 100 \text{ s} \]

Depolarization at wall collisions.

\[ \frac{1}{T_1} = \nu \beta \]

Rate of wall collisions \[ \approx 1000/\text{s} \]

Depolarization probability \[ \approx 10^{-5} \]
The co-magnetometer equation is given by:

\[
R = \frac{f_n}{f_{Hg}} = \gamma_n \gamma_{Hg} \left( 1 + \frac{2E}{\pi \hbar f_{Hg}} (d_n^{\text{true}} + d_n^{\text{false}}) + \frac{G(z)}{B_0} + \frac{B_T^2}{2B_0^2} + \ldots \right)
\]

This equation describes the relationship between the frequencies of two magnetometers, one with a different magnetic susceptibility. The graphs show the gravitational shift and transverse shift as functions of the magnetic field strength. The gravitational shift is indicated by a linear decrease in the parameter R with respect to the magnetic field strength G_{1,0}, while the transverse shift is shown as a non-linear curve with respect to G_{1,2}. The graph for G_{1,0} shows a decrease in R with increasing G_{1,0}, with a noted shift of \( \langle z \rangle = -0.36(3) \) cm. The graph for G_{1,2} shows a more complex behavior, with an initial decrease and then a peak, possibly indicating a nonlinear effect.
Magnetic depolarization of mercury?

The mercury is less sensitive to gradients because the correlation time is shorter, $\tau_c = 2 \text{ ms}$.
Frequency shift induced by magnetic noise

\[ \delta \omega = \frac{\gamma^2}{2} \int_0^\infty \text{Im} \left[ e^{i\omega \tau} \langle b^*(t)b(t+\tau) \rangle \right] d\tau \]

\[ b(t) = \left( \vec{B}(t) + \frac{1}{c^2} \vec{E} \times \vec{v}(t) \right) \cdot (\vec{e}_x + i\vec{e}_y) \]

**SIMULATION FOR Hg ATOMS**

- motional field
- mercury

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**Graph:**
- Red line: motional field \( E_{y}(t)/c^2 \), \( E = 11 \text{ kV/cm} \)
- Blue line: gradient field \(-1/2Gz(t)\), \( G = 50 \text{ pT/cm} \)

**Axes:**
- Y-axis: field / pT
- X-axis: t / ms

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19/22
False motional EDM of mercury

Linear false EDM:

\[ d^\text{false}_{\text{Hg}} = \frac{\hbar \gamma^2_{\text{Hg}}}{8c^2} R^2 G_{1,0} \]
\[ \approx \frac{G_{1,0}}{1 \text{pT/cm}} \times 1.15 \times 10^{-27} e \text{ cm}, \]
Final remarks on field uniformity
To measure nEDM at the $10^{-27}$ e cm level

- **B must be uniform**
  otherwise the UCN depolarize too fast
  the requirement on the *field production* is $< 10$ pT/cm

- **B non-uniformities must be controlled**
  otherwise we get a false EDM due to the mercury motional field
  the requirement on the *field measurement* is $< 0.1$ pT/cm
Credits to the n2EDM collaboration

50 physicists
10 PhD students
7 countries
13 laboratories
thank you,
the rest are backup slides
UCNs and magnetic fields

Neutron magnetic moment

\[ \mu_n \times (1 \text{ T}) = 60 \text{ neV} \]

Magnetic fields act on the spin ½ neutron

\[ V = -\hat{\mu}_n \vec{B} \]

Input: unpolarized UCNs

Magnetized foil

Output: polarized UCNs
Storing Ultracold neutrons in the nEDM apparatus

$N(T) = \frac{N(0)}{2} \left( e^{-T/T_f} + e^{-T/T_s} \right)$

$T_f = 40 \pm 4 \text{ s}$

$T_s = 252 \pm 4 \text{ s}$

$N(0) = 32669 \pm 856$
\[ d_{n}^{\text{false}} = \frac{\hbar \gamma_n \gamma_{Hg}}{2c^2} \int_0^\infty \langle B_x(0)\psi_x(\tau) + B_y(0)\psi_y(\tau) \rangle \cos \omega \tau \, d\tau. \]

FIG. 3. False motional EDM \( d_{n}^{\text{false}} \) induced by a linear gradient of \( G_1 = 1 \text{ pT/cm} \) as a function of the magnitude of the holding field \( B_0 \) in a cylindrical chamber of height 12 cm and diameter 47 cm (dashed line) or 100 cm (plain magenta line). The vertical lines labeled “magic field” indicate the values of \( B_0 \) for which \( d_{n}^{\text{false}} = 0 \).