Ultracold neutrons
1. Neutrons and the precision frontier
2. Neutron optics, ultracold neutrons
3. Neutron detection
4. Fundamental physics with UCNs
   - Neutron lifetime
   - Electric dipole moment
   - Gravity with neutrons
Two frontiers of particle physics

**Energy frontier (LHC):** producing heavy unstable particles at colliders, e.g.
- W boson, $m_W = 80$ GeV
- Higgs boson, $m_H = 125$ GeV
- Dark matter particle?

**Precision frontier:** detecting the effect of virtual particles.
The neutron beta decay, lifetime of 15 minutes, proceeds via the exchange of the virtual W.
Fundamental structure of the Standard Model inferred from properties of the decay (e.g. parity violation).
New physics at the precision/intensity frontier

New particles could induce super-rare decays. Example: a new boson with $m_X = 10^{15}$ GeV could induce the proton decay with a lifetime of

$$\tau_p \approx \frac{M_X^4}{\alpha^2 m_p^5} \approx 10^{33} \text{ years}$$

It would violate the conservation of baryon and lepton number.

New particles could induce exotic couplings. An **electric dipole moment** (EDM) is an interaction of the spin of a particle with the electric field. This coupling **violates time reversal symmetry**, and is connected with the matter-antimatter asymmetry of the Universe.

The search for the EDM of the neutron is highly sensitive to interesting new physics.
Detecting the neutron electric dipole moment

$$\hat{H} = -d_n \vec{E} \cdot \vec{\sigma}$$

If the neutron EDM is $$d_n = 10^{-27} \text{ e cm}$$
And the electric field is $$E = 15 \text{ kV/cm}$$
The neutron spin will make one full turn in a time
$$\frac{\pi \hbar}{d_n E} = 1.4 \times 10^6 \text{ s} = 4 \text{ years}$$

In order to detect such a tiny coupling we need:
• The slowest possible neutrons to maximize the interaction time in the electric field
• An intense source of such neutrons to maximize the statistical sensitivity
**Large neutron factories**

**ILL high flux reactor**
since 1967
Grenoble, France

**Future European Spallation Source**
Scheduled 2025
Lund, Sweden

multi-disciplinary facilities

- Biology
- Chemistry
- Material sciences
- Magnetism
- Nuclear physics
- Particle physics

A typical neutron scattering experiment
Fission or Spallation sources

FISSION

- steady chain reaction
- \( \sim 2 \) neutron/fission
- Energy \( \sim 2 \) MeV

SPALLATION

- Accelerator driven
- Pulsed or steady
- \( \sim 20 \) neutrons/proton
- Energy \( \sim 20 \) MeV

About 20 Big neutron sources in the world

<table>
<thead>
<tr>
<th>Reactor</th>
<th>City</th>
<th>Country</th>
<th>Th. Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL</td>
<td>Grenoble</td>
<td>France</td>
<td>58 MW</td>
</tr>
<tr>
<td>HFIR</td>
<td>Oak Ridge</td>
<td>USA</td>
<td>85 MW</td>
</tr>
<tr>
<td>CARR</td>
<td>Beijing</td>
<td>China</td>
<td>60 MW</td>
</tr>
<tr>
<td>FRM II</td>
<td>Munich</td>
<td>Germany</td>
<td>20 MW</td>
</tr>
<tr>
<td>HANARO</td>
<td>Daejon</td>
<td>Korea</td>
<td>30 MW</td>
</tr>
<tr>
<td>WWR-M</td>
<td>Gatchina</td>
<td>Russia</td>
<td>18 MW</td>
</tr>
<tr>
<td>NIST</td>
<td>Gaithersburg</td>
<td>USA</td>
<td>20 MW</td>
</tr>
<tr>
<td>JRR-3M</td>
<td>Tokai</td>
<td>Japan</td>
<td>20 MW</td>
</tr>
<tr>
<td>BRR</td>
<td>Budapest</td>
<td>Hungary</td>
<td>10 MW</td>
</tr>
<tr>
<td>OPAL</td>
<td>Sydney</td>
<td>Australia</td>
<td>20 MW</td>
</tr>
<tr>
<td>BER II</td>
<td>Berlin</td>
<td>Germany</td>
<td>10 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spall. Source</th>
<th>City</th>
<th>Country</th>
<th>Beam Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINQ @ PSI</td>
<td>Villigen</td>
<td>Switzerland</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>SNS @ ORNL</td>
<td>Oak Ridge</td>
<td>USA</td>
<td>1.4 MW</td>
</tr>
<tr>
<td>JSNS @ KEK</td>
<td>Tsukuba</td>
<td>Japan</td>
<td>0.3 MW</td>
</tr>
<tr>
<td>ISIS @ RAL</td>
<td>Oxford</td>
<td>UK</td>
<td>0.2 MW</td>
</tr>
<tr>
<td>Lujan @ LANSCE</td>
<td>Los Alamos</td>
<td>USA</td>
<td>0.1 MW</td>
</tr>
</tbody>
</table>

High flux reactors with cold neutron source available for users (there are 246 operational research reactors worldwide)

High intensity spallation sources
Compare the flux

PWR power reactor 3 GW
Thermal neutron flux
\(\sim 10^{14} \text{ n/cm}^2/\text{s}\)

ILL high flux reactor 58 MW
Thermal neutron flux
\(\sim 1.5 \times 10^{15} \text{ n/cm}^2/\text{s}\)

SNS pulsed source (60 Hz)
Thermal neutron flux
Peak ~ \(3 \times 10^{16} \text{ n/cm}^2/\text{s}\)
Average ~ \(4 \times 10^{13} \text{ n/cm}^2/\text{s}\)
Thermalization of fast neutrons

Fast neutron
E = a few MeV

Moderator material with hydrogen or deuterium.
In heavy water the mean free path is about 2 cm and it takes about 35 collision to thermalize.

Thermal neutron
E = kT = 25 meV
ILL reactor

Heavy water moderator and reflector Ø2.5 m

Fuel: HEU (93.3% 235)

Hot source

Cold source: 20 L of Liquid D2 at 20K

Brightness (n/cm²/A/ster/s)

- Hot source
- Thermal source
- Cold source

wavelength (Å)
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Neutron spectrum

- **Fission ~ 2 MeV**
- **Resonant capture ~ 10 eV**
- **Thermal neutrons:** $kT = 25 \text{ meV} @ T = 300 \text{ K}$
- **Fermi potentials ~ 100 neV**

**Fast**
- $1 \text{ MeV}$
- $1 \text{ keV}$
- $1 \text{ eV}$
- $1 \text{ meV}$
- $1 \mu \text{eV}$
- $1 \text{ neV}$

**Epithermal**

**Cold**

**Ultrasound**

De Broglie wavelength

$$\lambda = \frac{2\pi \hbar}{\sqrt{2mE}}$$

$\lambda < 0.1 \text{ nm}$

“PARTICLE”

$\lambda > 0.1 \text{ nm}$

“WAVE”
Mirror effect at grazing incidence
Particles and waves
Neutron interaction with a single nucleus

Potential scattering described by non-relativistic quantum scattering theory. For nonrelativistic neutrons, nuclei look point-like ($kR_{\text{nucl}} \ll 1$):

- Isotropic scattering
- Energy-independent

Neutron wave function corresponding to the scattering process

$$\psi(r) = e^{i k x} - b \frac{e^{i k r}}{r}$$

scattering X-section

$$\sigma = 4\pi b^2$$

For a catalog, see www.ncnr.nist.gov/resources/n-lengths

Surprisingly, almost all nuclei have $b > 0$. 
Neutron interaction with a collection of nuclei

Incident neutron with energy $E = \frac{(hk)^2}{2m}$

Self consistency of the wave function

$$\psi(\vec{r}) = e^{ikx} - \sum_j \psi(\vec{R}_j) b \frac{e^{ik|\vec{r} - \vec{R}_j|}}{|\vec{r} - \vec{R}_j|}$$

Using the relation

$$(\Delta + k^2) \frac{e^{ik|\vec{r} - \vec{R}_j|}}{|\vec{r} - \vec{R}_j|} = -4\pi \delta(\vec{r} - \vec{R}_j)$$

We find the wave equation

$$(\Delta + k^2)\psi(\vec{r}) = 4\pi b \sum_j \delta(\vec{r} - \vec{R}_j) \psi(\vec{r}) \approx 4\pi b n \psi(\vec{r})$$

$n$ is the nuclear density of the medium
Neutron Fermi potential

Defining the Fermi potential of a medium

\[ V_F = \frac{2\pi \hbar^2}{m} \]

The wave equation is a Schrodinger equation with the potential V

\[ \left( -\frac{\hbar^2}{2m} \Delta + V_F \right) \psi(\vec{r}) = E \psi(\vec{r}) \]

For cold neutrons, bulk matter is characterized by its Fermi potential. We expect wave phenomena (refraction, reflection, tunnel transmission..).

Solid matter characterized by the Fermi potential \( V_F \)

Condition for total reflection of neutrons of energy \( E \) (Fermi & Zinn 1946)

\[ E \sin^2 \theta < V_F \]
Exercises

1. Calculate the Fermi potential of Nickel
2. What is the maximum reflection angle on a Nickel surface for a cold neutron of wavelength 0.9 nm?

<table>
<thead>
<tr>
<th>Z-Symb-A</th>
<th>% or T1/2</th>
<th>I</th>
<th>bc</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-Ni</td>
<td></td>
<td></td>
<td>10.3 ± 0.1</td>
</tr>
<tr>
<td>28-Ni-58</td>
<td>67.88</td>
<td>0</td>
<td>14.4 ± 0.1</td>
</tr>
<tr>
<td>28-Ni-60</td>
<td>26.23</td>
<td>0</td>
<td>2.8 ± 0.1</td>
</tr>
<tr>
<td>28-Ni-61</td>
<td>1.19</td>
<td>3/2</td>
<td>7.6 ± 0.06</td>
</tr>
<tr>
<td>28-Ni-62</td>
<td>3.66</td>
<td>0</td>
<td>-8.7 ± 0.2</td>
</tr>
<tr>
<td>28-Ni-64</td>
<td>1.08</td>
<td>0</td>
<td>-0.37 ± 0.07</td>
</tr>
</tbody>
</table>
Application: neutron guides

ILL High Flux Reactor

Guide Hall
Neutron distribution channel at ILL
Many guides at the ILL, up to 100 m long
Neutrons with energy < 200 neV, are totally reflected by material walls.

They can be stored in material bottles for long times (minutes).

They are significantly affected by gravity.

**Ultracold neutrons (UCNs)**

- **Thermal neutrons**, $E=25 \text{ meV}$
- **Cold neutrons**, $E<25 \text{ meV}$
- **Ultracold neutrons**, $E<200 \text{ neV}$
UCNs are guided through evacuated stainless steel pipes (about 10 cm diameter) and bends.

Losses are generally percents/meter
Exercises

1. Calculate the velocity for an UCN with an energy of 200 neV

2. Calculate the De-Broglie wavelength of the same UCN

3. What is the proportion of UCNs (say E < 300 neV) in a Maxwell spectrum of thermal neutrons at 300 K?

4. A neutron is dropped at rest from a height of h = 1 m. What is the kinetic energy of that neutron when hitting the ground at h = 0?
UCNs feel gravity

\[ V(z) = mg \ z \]

\[ V(z = 1 \ m) = 102 \ \text{neV} \]

Very important for UCN techniques

- We accelerate UCNs to detect them (otherwise they would bounce off the detector window).
- Some UCN traps do not need a roof.
- Lifting an experiment by 50 cm can modify significantly the outcome!
Example: the “U” filter

If you want to remove UCNs with energy $E<80$ neV,
Just set $h = 80$ cm
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
Summary about UCN interactions

UCNs can be manipulated using

- The nuclear force (Fermi potentials ~ 100 neV)
- The gravitational force (1 m = 100 neV)
- Magnetic fields (1T = 60 neV)

They are used to study the fundamental interactions and symmetries

- Weak interaction (beta decay period 10 min)
- Electromagnetic properties of the neutron (EDM)
- Gravitational effects
Turbine with counter rotating blades to decelerate the neutrons
Superthermal production of UCNs in superfluid He

Input: intense beam of cold neutrons with a wavelength of 8.9 Å

The superfluid Helium needs to be cooled down to 0.7 K
UCN source at the Paul Scherrer Institute

pulsed UCN source
One kick per 5 min
online since 2011

600 MeV
2.2 mA
Worldwide comparison of UCN sources

3 techniques

• selection out of a thermal flux
  ILL PF2 source

• Superthermal production and accumulation in superfluid He
  ILL SUN-2, ILL GRANIT, TRIUMF

• Superthermal production in solid deuterium
  PSI, Los Alamos, Mainz (TRIGA)
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Importance of neutron detection

• Monitoring in nuclear reactors
• Radiation safety
• Detection of special nuclear materials (233U and 239Pu)
• Cosmic ray detection, monitoring the flux

• Neutrino detectors $\nu + p \rightarrow e^+ + n$
• Most serious background in WIMP direct searches
  WIMP-induced nuclear recoil $\chi + N \rightarrow \chi + N$
  similar to fast neutron – induced recoil $n + N \rightarrow n + N$

Remember: You can’t directly detect neutrons...
Neutrons should be converted in a detectable particle first.
Neutron inelastic reactions

- Neutron capture \( n + {}^A X \rightarrow {}^{A+1}X^* + \gamma \) a.k.a. \( X(n, \gamma) \)
- Charged reactions \( n + {}^A X \rightarrow p + {}^A Y \) a.k.a. \( X(n,p)Y \)
  \[ n + {}^A X \rightarrow \alpha + {}^{A-3}Y \quad \text{a.k.a.} \quad X(n, \alpha)Y \]
- Fission \( n + {}^{235}U \rightarrow PF_1 + PF_2 + \nu n \) a.k.a. \( U(n, f) \)

**THE 1/\(v\) LAW**

\[
\sigma(v) = \sigma(v_0) \frac{v_0}{v}
\]

One finds in tabulated neutron data the thermal cross sections

\[
\sigma^{\text{th}} = \sigma(2200 \, \text{m/s})
\]
(n,γ) capture: \( n + \frac{A}{Z}X \rightarrow \gamma + A+1 \frac{1}{Z}X \)

All stable nuclei have \( Q > 0 \) EXCEPT for \( ^4\text{He} \).
Thus, \( ^4\text{He} \) is the only stable element with zero capture cross section for slow neutrons.

Energy release \( Q = (m_X + m_n - m_W)c^2 \)
a.k.a. the neutron separation energy of the nucleus W.
(n,p) reaction \( n + \frac{A}{Z}X \rightarrow p + z \frac{A}{Z-1}Y \)

Energy release \( Q = (m_X + m_n - m_p - m_Y)c^2 \)
Slow neutrons undergo (n,p) reaction only if \( Q > B_c \)

Only one possibility
\( n + ^3\text{He} \rightarrow p + t \)
(n,α) reaction  \( n + \frac{A}{Z}X \rightarrow \alpha + \frac{A-3}{Z-2}Y \)

Coulomb barrier \( B_c = \alpha \frac{\hbar c}{R_0} \frac{2(Z-2)}{4^{1/3} + (A-3)^{1/3}} \)

Energy release \( Q = (m_x + m_n - m_\alpha - m_z)c^2 \)

Slow neutrons undergo (n,α) reaction only if \( Q > B_c \)

Only two possibilities
\[
\begin{align*}
n + ^6\text{Li} & \rightarrow \alpha + t \\
n + ^{10}\text{B} & \rightarrow \alpha + ^7\text{Li}
\end{align*}
\]
Validity of the $1/v$ law

\[ \sigma(v) = \sigma(v_0) \frac{v_0}{v} \]
Three possible neutron convertors

<table>
<thead>
<tr>
<th></th>
<th>$^3\text{He} \ (n,p)$</th>
<th>$^6\text{Li} \ (n,\alpha)$</th>
<th>$^{10}\text{B} \ (n,\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>0.014 %</td>
<td>7.6 %</td>
<td>19.9 %</td>
</tr>
<tr>
<td>$\sigma^\text{th}$</td>
<td>5330 barn</td>
<td>937 barn</td>
<td>3837 barn</td>
</tr>
<tr>
<td>Kinetic energy of products</td>
<td>$p$ 764 keV</td>
<td>$\alpha$ 2.056 MeV</td>
<td>$\alpha$ 1.47 MeV</td>
</tr>
<tr>
<td></td>
<td>$t$ 191 keV</td>
<td>$t$ 2.728 MeV</td>
<td>Li 0.84 MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma$ 0.48 MeV</td>
<td></td>
</tr>
</tbody>
</table>

**Gaseous detectors**
proportional counters filled with $^3\text{He}$ or $\text{BF}_3$

**Solid detectors**
scintillators $\text{LiF}$
silicon detectors with Boron solid conversion layer
1. Calculate the kinetic energy of the products for the reaction $n + ^3\text{He} \rightarrow t + p$

2. Consider a 1 cm thick multiwire proportional chamber filled with 1 bar of 3He. What is the detection efficiency for thermal neutrons?

3. The same detector is filled with 10 mbar of 3He, what is the detection efficiency for UCNs? For thermal neutrons?

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>nat. ab.</th>
<th>atomic mass [u]</th>
<th>neutron mass</th>
<th>Planck conversion constant</th>
<th>Avogadro constant</th>
<th>Boltzmann constant</th>
<th>Atomic mass unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>99.99%</td>
<td>1.0078250322</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$mc^2 = 939.565379(21)$ MeV</td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td>0.015%</td>
<td>2.0141017781</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\hbar c = 197.3269718(44)$ MeV fm</td>
</tr>
<tr>
<td>$^3\text{H}$</td>
<td></td>
<td>3.0160492779</td>
<td></td>
<td></td>
<td>$N_A = 6.02214129(27) \times 10^{23}$ mol$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>$10^{-4}%$</td>
<td>3.0160293201</td>
<td></td>
<td></td>
<td></td>
<td>$k_B = 1.3806488(13) \times 10^{-23}$ J/K</td>
<td></td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>100%</td>
<td>4.0026032541</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$u = 931.494028(23)$ MeV/c$^2$</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>7.5%</td>
<td>6.0151228874</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>92.5%</td>
<td>7.0160034366</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$^{10}\text{B}$</td>
<td>20%</td>
<td>10.012936949</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}\text{B}$</td>
<td>80%</td>
<td>11.009305355</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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The neutron beta decay lifetime

\[ n \rightarrow p + e^- + \bar{\nu}_e + 782 \text{ keV} \]

Free neutron lifetime

\[ \tau_n = 880.0(9) \text{ s} \]

[PDG 2013]

- **Particle physics**
  Extracting CKM matrix element

- **Astrophysics and Neutrinos**
  Calculating weak semi-leptonic processes like
  \[ p + p \rightarrow d + e^+ + \nu_e \]
  \[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

- **Cosmology**
  Predicting the yields of the Big Bang Nucleosynthesis
Two complementary experimental methods

**Counting the dead neutrons: BEAM METHOD**

A detector records the decay products in a well defined part of a neutron beam. A neutron beam is indeed radioactive due to beta decay.

\[- \frac{dN}{dt} = \frac{N}{\tau_n}\]

**Counting the surviving neutrons: BOTTLE METHOD**

UCNs are stored in a bottle, the number of neutrons remaining in the bottle after a certain storage time \(t\) is measured.

\[N(t) = N(0)e^{-t/\tau_n}\]
Early beam method: counting the electrons

Christensen et al. (1972)
Modern beam method: counting the protons

Nico et al. (2005)

Protons produced almost at rest (endpoint energy = 800 eV) are accumulated in a Penning trap.
**Principle of a bottle UCN measurement**

Typical sequence

1. Switch moved to FILL position, Valve OPEN for 20 s
2. Close Valve, Switch moved to EMPTY position
3. Wait period $T$
4. OPEN Valve, count neutrons

Repeat the sequence with different $T$
Example: measured storage curve in the 20 L chamber of the EDM experiment.

Problem: UCN losses at wall reflection are not negligible.

\[
\frac{1}{\tau_{st}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}}
\]
Estimating the wall losses

The probability for a UCN to be lost at a wall collision can be of the order of \( \mu \approx 10^{-4} \).

The mean free path between collisions is of the order of \( \lambda \approx 30 \text{ cm} \).

The frequency of wall collisions for a velocity of 3 m/s is of the order of \( f = \frac{v}{\lambda} \approx 10 \text{ Hz} \).

The partial lifetime due to wall losses is thus of the order of \( \tau_{wall} = \frac{1}{f\mu} \approx 1000 \text{ s} \).
Useful Clausius law

Consider a bottle with arbitrary shape, of volume $V$ and surface $S$.

When mechanical equilibrium is achieved (isotropic velocity distribution) the mean free path between wall collisions is

$$\lambda = \frac{4V}{S}$$

Results valid without gravity!

$$\lambda = \frac{2d}{3}$$

$$\lambda = \frac{dh}{d/2 + h}$$

$$\lambda = \frac{2abh}{ab + ah + bh}$$
More on wall losses (complicated topic)

- The wall loss probability is energy-dependent
  \[ \mu(E) = 2\eta \left( \frac{V}{E} \arcsin \sqrt{\frac{E}{V}} - \sqrt{\frac{V}{E} - 1} \right) \]

- It depends on temperature (the colder the better)

- Losses can be calculated from absorption and inelastic scattering cross section data. But measured losses are generally higher, due to surface impurities (hydrogen, in particular)
The trap geometry is varied, one extrapolates the storage time to infinite mean free path.
Current status on the neutron lifetime

The current situation
There is a 3.8 $\sigma$ discrepancy between the bottle method combination and the beam method combination.

To be continued...
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Electric and Magnetic Dipoles

\[ \hat{H} = -\mu_n B \hat{\sigma}_z - d_n E \hat{\sigma}_z \]

Spin precession due to the magnetic dipole \( \mu_n \)

Spin precession due to the electric dipole \( d_n \)?
Electric dipole violates time reversal invariance!
Hunting the neutron Electric Dipole Moment

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, Ø47 cm, H12 cm.
**CP violation and baryogenesis**

Sakharov’s Baryogenesis recipe (1967)
- Baryon number not conserved
- Universe out of equilibrium
- **Violation of CP symmetry** $> nEDM$

Current nEDM bound constrains many scenarios of BSM electroweak baryogenesis

- **symmetric phase** $\phi = 0$
- $T = 300 \text{ GeV}$
- Boiling
- $T \approx 100 \text{ GeV}$
- Broken phase $\phi \neq 0$
- $T = 20 \text{ GeV}$

10^{15} \text{ GeV}
- Inflation ends?

100 \text{ GeV}
- Electroweak transition

1 \text{ MeV}
- Decoupling of CMB

1 \text{ eV}
- Today

1 \text{ meV}
- Today

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Free precession in $E$ and $B$ fields ...

A: spin polarizer
C: Apply RF pulse
$\pi/2$ spin-flip...

C': Second RF pulse

A': spin analyzer
D: counter

First EDM experiment with a neutron beam

Smith, Purcell and Ramsey,

$d_n = (-0.1 \pm 2.4) \times 10^{-20} \text{ e cm}$

Vary the RF frequency and measure the resonance curve to extract $f_L$. Do it for parallel and antiparallel $E$ and $B$ fields.

Statistical sensitivity:

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

$T \approx 1 \text{ ms}$
The slower, the better...
UCN nEDM apparatus (Sussex/RAL/ILL)

Apparatus installed at the ILL reactor Grenoble (1986-2009)

Best limit: \( d_n < 3 \times 10^{-26} \) e cm obtained with 1998 – 2002 data

Scheme of the apparatus at PSI

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

4 layers mu-metal shield

Mercury lamp

photomultiplier

Iron analyser

Switch

5T polarizer (SC magnet)

Spin flipper

UCN source
Problem: the analyzing foil

What is the optimal height of the analysing foil in the nEDM experiment?

The analyzing foil consists of a thin layer of magnetized iron. The precession chamber, situated at height \( H \) above the analyzing foil, stores neutrons in the energy range \( 0 < E < 120 \text{ neV} \). Calculate the Fermi potential of non-magnetized iron. Suppose now that the foil is magnetized to a saturation field of \( B_s = 2 \text{ T} \). Neutrons with spin aligned with the magnetic field are dubbed low field seekers, those with spin anti-parallel with the magnetic field are dubbed high field seekers.

• Calculate the Fermi potential of the magnetized foil for high and low field seekers.
• Discuss the optimal height \( H \) to maximize the spin-analysis efficiency.
• Estimate the transmission of the foil.

<table>
<thead>
<tr>
<th>material</th>
<th>( \rho ) [g/cm(^3)]</th>
<th>( M ) [g/mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum</td>
<td>2.70</td>
<td>27.0</td>
</tr>
<tr>
<td>boron</td>
<td>2.34</td>
<td>10.8</td>
</tr>
<tr>
<td>iron</td>
<td>7.87</td>
<td>55.8</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>nat. ab.</th>
<th>( b ) [fm]</th>
<th>( \sigma_{th} ) [barn]</th>
<th>atomic mass [u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{27})Al</td>
<td>100%</td>
<td>3.449</td>
<td>0.231</td>
<td>26.981538531</td>
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<tr>
<td>(^{54})Fe</td>
<td>5.8%</td>
<td>4.2</td>
<td>2.25</td>
<td>53.9396105</td>
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<tr>
<td>(^{56})Fe</td>
<td>91.7%</td>
<td>9.94</td>
<td>2.59</td>
<td>55.934936326</td>
</tr>
<tr>
<td>(^{57})Fe</td>
<td>2.2%</td>
<td>2.3</td>
<td>2.48</td>
<td>56.935394</td>
</tr>
</tbody>
</table>
Typical measurement sequence at PSI, 1 cycle every 5 minutes

The **mercury co-magnetometer** compensates for the residual magnetic field fluctuations.
1. Neutrons and the precision frontier
2. Neutron optics, ultracold neutrons
3. Neutron detection
4. Fundamental physics with UCNs
   • Neutron lifetime
   • Electric dipole moment
   • Gravity with neutrons
Bouncing neutrons

The vertical motion is a simple quantum well problem

\[-\frac{\hbar^2}{2m_i} \frac{d^2\psi}{dz^2} + mgz \psi = E \psi\]

We want to test Enstein’s equivalence principle for a quantum particle in a classical gravity field.
Discovery of the quantum states at ILL

Nesvizhevsky et al
Problem: micrometric position sensitive detector

1. Calculate the Fermi potential of (i) natural boron (ii) pure $^{10}$B. Why do we have to use isotopically pure boron?

2. We choose a boron layer thickness of 200 nm. Discuss this choice in terms of neutron conversion efficiency (for UCNs of velocity 3 m/s), Si detector efficiency and spatial resolution.