Introduction to the Ultracold neutron facility at TRIUMF

Beatrice Franke

WNPPC 2017, Banff

February 18, 2017

Outline

- Introduction to ultracold neutrons (UCN)
  and how to produce them
- The neutron electric dipole moment (nEDM):
  definition, motivation, history, and measurement method
- The UCN/nEDM facility at TRIUMF

Ultracold neutrons

- $E_{\mathrm{UCN}} \leqslant 300\,\mathrm{neV} \mathrel{\widehat{=}} 3.5\,\mathrm{mK}$ ("ultracold")

Ultracold neutrons

- $E_{\mathrm{UCN}} \leqslant 300\,\mathrm{neV} \mathrel{\hat{=}} 3.5\,\mathrm{mK}$ ("ultracold")
- Strong interaction results in pseudopotential
  $\hat{=}$ optical potential V_{Fermi}
- UCN undergo total reflection under *all angles of incidence*
  if $E_{\mathrm{UCN}} \leqslant V_{\mathrm{Fermi,\,material}}$
  $\Rightarrow$ UCN are storable, like a gas

Ultracold neutrons

- $E_{\mathrm{UCN}} \leqslant 300\,\mathrm{neV} \mathrel{\widehat{=}} 3.5\,\mathrm{mK}$ ("ultracold")
- Strong interaction results in pseudopotential
  $\widehat{=}$ optical potential V_{Fermi}
- UCN undergo total reflection under *all angles of incidence*
  if $E_{\mathrm{UCN}} \leqslant V_{\mathrm{Fermi,\,material}}$
  $\Rightarrow$ UCN are storable, like a gas
- Gravitational effects: $E_{\mathrm{UCN}}(1\,\mathrm{m}) \approx 100\,\mathrm{neV}$

Ultracold neutrons

- $E_{\mathrm{UCN}} \leqslant 300\,\mathrm{neV} \mathrel{\widehat{=}} 3.5\,\mathrm{mK}$ ("ultracold")
- Strong interaction results in pseudopotential
  $\widehat{=}$ optical potential V_{Fermi}
- UCN undergo total reflection under *all angles of incidence*
  if $E_{\mathrm{UCN}} \leqslant V_{\mathrm{Fermi,\,material}}$
  $\Rightarrow$ UCN are storable, like a gas
- Gravitational effects: $E_{\mathrm{UCN}}(1\,\mathrm{m}) \approx 100\,\mathrm{neV}$
- Magnetic fields depict a spin-dependent potential:
  $E_{\mathrm{UCN}}(1\,\mathrm{T}) \approx 60\,\mathrm{neV}$

Ultracold neutrons

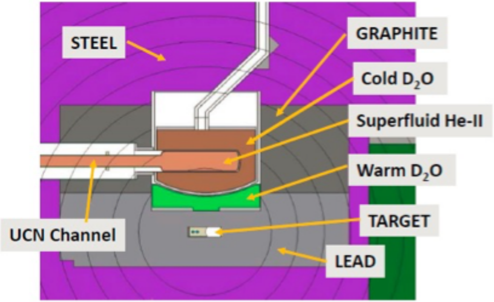
- $E_{\mathrm{UCN}} \leqslant 300\,\mathrm{neV} \mathrel{\widehat{=}} 3.5\,\mathrm{mK}$ ("ultracold")
- Strong interaction results in pseudopotential
  $\widehat{=}$ optical potential V_{Fermi}
- UCN undergo total reflection under *all angles of incidence*
  if $E_{\mathrm{UCN}} \leqslant V_{\mathrm{Fermi,\,material}}$
  $\Rightarrow$ UCN are storable, like a gas
- Gravitational effects: $E_{\mathrm{UCN}}(1\,\mathrm{m}) \approx 100\,\mathrm{neV}$
- Magnetic fields depict a spin-dependent potential:
  $E_{\mathrm{UCN}}(1\,\mathrm{T}) \approx 60\,\mathrm{neV}$
- Weak interaction: $\tau_{\mathrm{n}} \approx 900\,\mathrm{s}$

How to produce UCN: the TRIUMF source as example

Free n via spallation

Moderation
$E_{\mathrm{kin}} \propto T_{\mathrm{mod}} \gtrsim 10\,\mathrm{K}$

Conversion in superfluid He:
$E_{\mathrm{kin}} \rightarrow$ phonon/roton excitation



What to do with UCN

- Search for the neutron electric dipole moment
- Measure the neutron lifetime
- Investigate beta decay correlations
- Sensitivity to energies of down to peV allows to search for exotic interactions, fifth forces, axions, dark matter, quantized states in gravitational potential, etc.
- ...

The neutron electric dipole moment d_n

Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field

$$\mathcal{H} = -\mu_\mathrm{n} \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{B}$$

The neutron electric dipole moment d_n

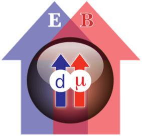
Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field and an electric field

$$\mathcal{H} = -\mu_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{B} - d_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{E}$$

The neutron electric dipole moment d_{n}

Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field and an electric field

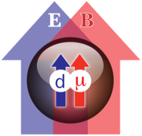
$$\mathcal{H} = -\mu_{\mathrm{n}} \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{B} - d_{\mathrm{n}} \frac{\vec{\sigma}}{|\vec{\sigma}|} \vec{E}$$



The neutron electric dipole moment d_n

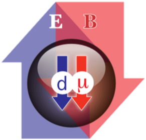
Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field and an electric field

$$\mathcal{H} = -\mu_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{B} - d_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{E}$$



Time reversal symmetry T is not conserved:

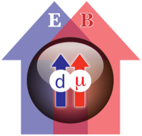
$$\mathrm{T}\mathcal{H} = -\mu_\mathrm{n}\frac{-\vec{\sigma}}{|\vec{\sigma}|}(-\vec{B}) - d_\mathrm{n}\frac{-\vec{\sigma}}{|\vec{\sigma}|}\vec{E} \neq \mathcal{H}$$



The neutron electric dipole moment d_n

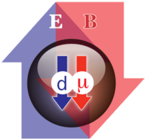
Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field and an electric field

$$\mathcal{H} = -\mu_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{B} - d_\mathrm{n}\frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{E}$$



Time reversal symmetry T is not conserved:

$$\mathrm{T}\mathcal{H} = -\mu_\mathrm{n}\frac{-\vec{\sigma}}{|\vec{\sigma}|}(-\vec{B}) - d_\mathrm{n}\frac{-\vec{\sigma}}{|\vec{\sigma}|}\vec{E} \neq \mathcal{H}$$



CPT theorem: T-violation ⇔ CP-violation.

The Baryon asymmetry of our universe (BAU)

In our universe matter is much more abundant than antimatter

$$\eta = \left(\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma}\right); \quad \eta(\mathrm{observed}) = (6.15 \pm 0.15) \cdot 10^{-10}$$

Standard model (SM) prediction:

$$\eta(\mathrm{SM}) \approx 10^{-18}$$

The Baryon asymmetry of our universe (BAU)

In our universe matter is much more abundant than antimatter

$$\eta = \left(\frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma}\right); \quad \eta(\text{observed}) = (6.15 \pm 0.15) \cdot 10^{-10}$$

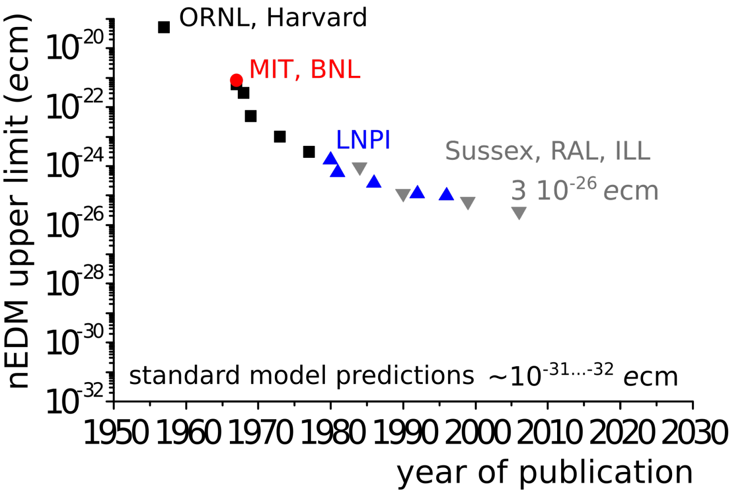
Standard model (SM) prediction:

$$\eta(\text{SM}) \approx 10^{-18}$$

Sakharov criteria (1967) necessary for BAU:

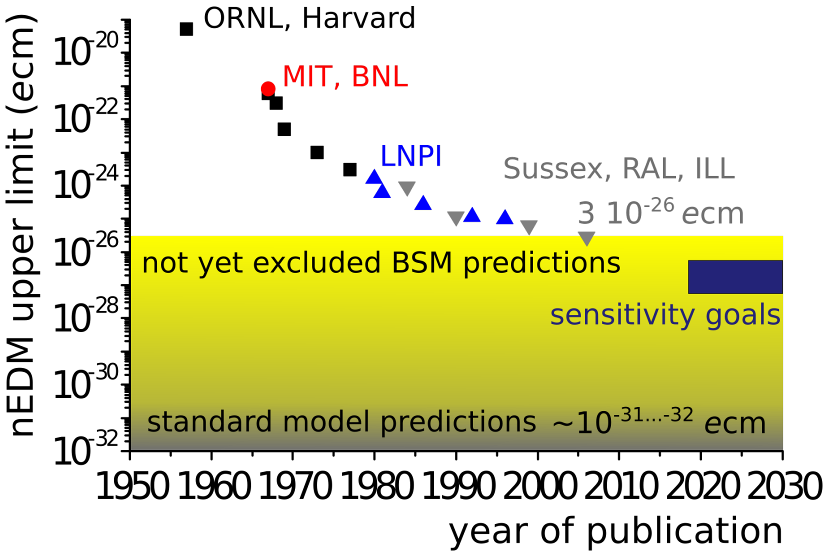
- Baryon number violation
- C- and CP-violation
- thermal non-equilibrium

Limits on the nEDM



TRIUMF

Limits on the nEDM



How to measure an nEDM?

- Apply a magnetic field $\vec{B}$

$$hf_{\mathrm{n}} = 2\mu_{\mathrm{n}} B$$

How to measure an nEDM?

- Apply a magnetic field $\vec{B}$ and an electric field $\vec{E}$ $\uparrow\uparrow$ or $\uparrow\downarrow$

$$hf_{\mathrm{n}} = 2\mu_{\mathrm{n}}B \pm 2d_{\mathrm{n}}E$$

How to measure an nEDM?

- Apply a magnetic field $\vec{B}$ and an electric field $\vec{E}$ $\uparrow\uparrow$ or $\uparrow\downarrow$

$$h f_{\mathrm{n}} = 2\mu_{\mathrm{n}} B \pm 2 d_{\mathrm{n}} E$$

- Extract nEDM d_{n} from *the difference* of Larmor precession frequencies in $\uparrow\uparrow$ or $\uparrow\downarrow$ fields:

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}$$

How to measure an nEDM?

- Apply a magnetic field $\vec{B}$ and an electric field $\vec{E}$ $\uparrow\uparrow$ or $\uparrow\downarrow$

$$hf_{\mathrm{n}} = 2\mu_{\mathrm{n}} B \pm 2 d_{\mathrm{n}} E$$

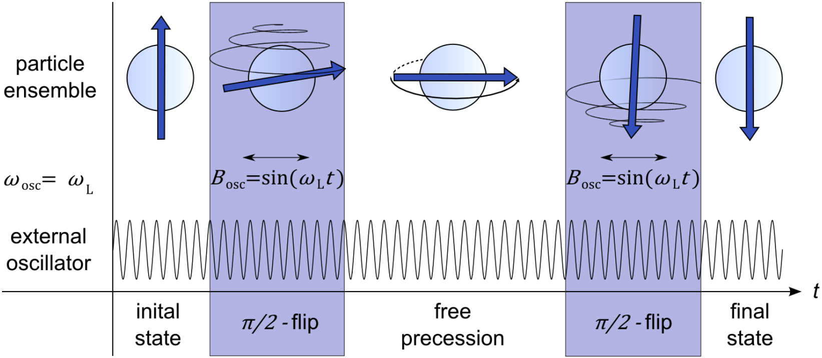
- Extract nEDM d_{n} from *the difference* of Larmor precession frequencies in $\uparrow\uparrow$ or $\uparrow\downarrow$ fields:

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}$$

- How to measure the neutron Larmor precession frequency?

The Ramsey method of separated oscillatory fields

f_n is extracted by a clock comparison between the neutrons and an external, precise (10^{-11} relative), oscillator.

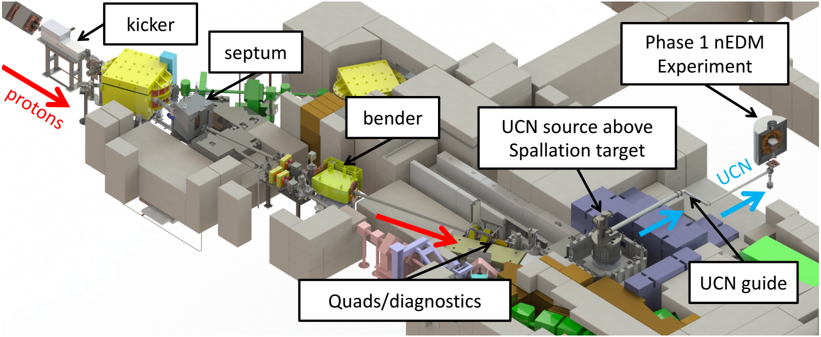


The UCN facility at TRIUMF

Collaborating institutions:
KEK, RCNP, University of Osaka
UBC, UNBC, SFU, University of Winnipeg, University of Manitoba
Goals:

- Build UCN source with world leading densities ($\sim 100/\mathrm{ccm}$ at experiment)
- Measure the nEDM at $10^{-27}\,e$cm precision
  - Phase 1: "old" RCNP equipment used at TRIUMF (Vertical UCN source & nEDM apparatus)
  - Phase 2: upgrade UCN source (Horizontal geometry) and install new next generation nEDM apparatus
- Establish UCN user facility via second UCN port and attract international scientific community

The UCN facility at TRIUMF

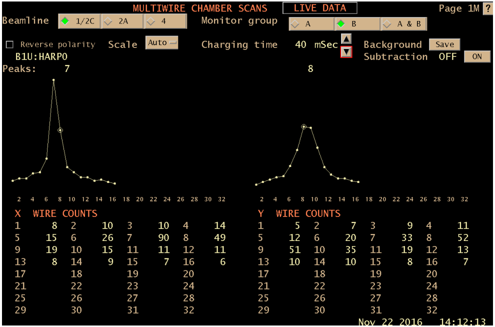


The UCN facility at TRIUMF

The UCN facility at TRIUMF

Commissioned!

First beam on target ⇒ production of thermal and cold neutrons

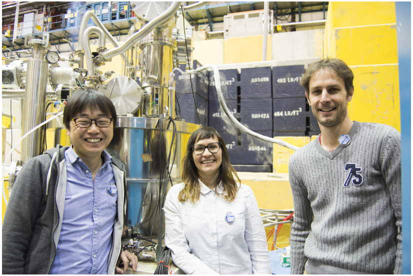


The UCN facility at TRIUMF

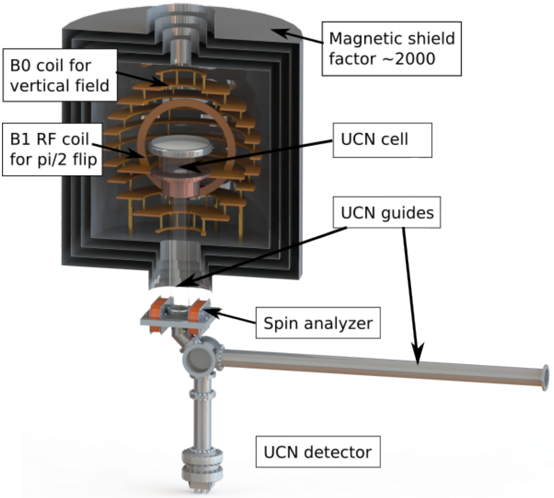
Commissioned!
First beam on target ⇒ production of thermal and cold neutrons

The UCN facility at TRIUMF

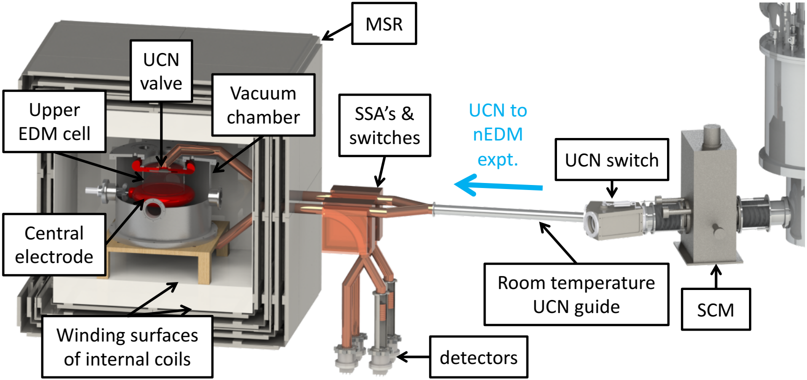
Ongoing work: Installation of converter cryostat for UCN production in superfluid He



The nEDM experimental setup; Phase 1



The nEDM experimental setup; Phase 2



Thank you for your attention!

Backup slides

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 611, Issues 2–3, 1–11 December 2009, Pages 318–321

Particle Physics with Slow Neutrons

Q-BOUNCE—Experiments with quantum bouncing ultracold neutrons

Tobias Jenke[a, b, 1], David Stadler[b], Hartmut Abele[a, b, 1], Peter Geltenbort[c]

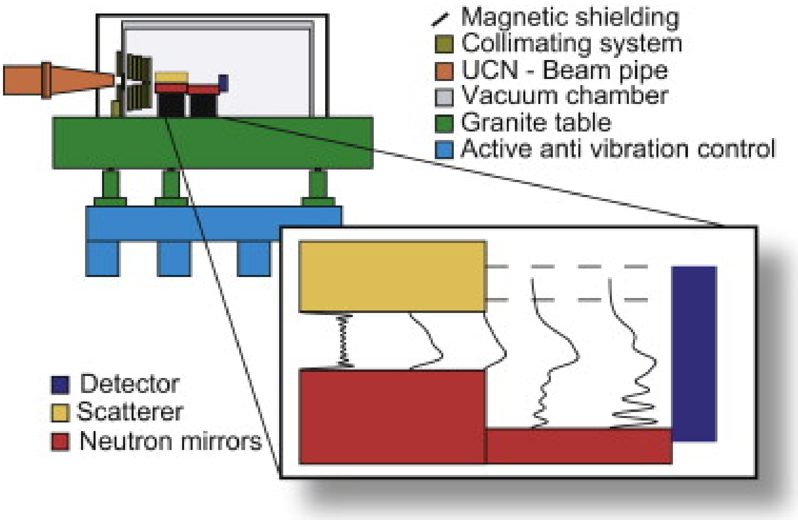
[a] Physik-Department E18, Technische Universität München, Garching, Germany

[b] Physikalisches Institut, Heidelberg, Germany

[c] Institut Laue-Langevin, 6 rue Jules Horowitz, 38042 Grenoble Cedex 9, France

Available online 6 August 2009

Set up of the Q bounce experiment



Required sensitivity

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}$$

Required sensitivity

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)} = \frac{h\Delta f - \mu_{\mathrm{n}}\Delta B}{4E}$$

Required sensitivity

$$d_n = \frac{h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) - \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)} = \frac{h\Delta f - \mu_n \Delta B}{4E}$$

- Cancel magnetic field changes ΔB?
- Sensitivity $\sigma(d_n)$ determines required sensitivity to ΔB

Required sensitivity

$$d_\mathrm{n} = \frac{h\left(f_\mathrm{n}^{\uparrow\uparrow} - f_\mathrm{n}^{\uparrow\downarrow}\right) - \mu_\mathrm{n}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)} = \frac{h\Delta f - \mu_\mathrm{n}\Delta B}{4E}$$

- Cancel magnetic field changes ΔB?
- Sensitivity $\sigma(d_\mathrm{n})$ determines required sensitivity to ΔB

$$\sigma(d_\mathrm{n})_\mathrm{stat} = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

Required sensitivity

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)} = \frac{h\Delta f - \mu_{\mathrm{n}}\Delta B}{4E}$$

- Cancel magnetic field changes ΔB?
- Sensitivity $\sigma(d_{\mathrm{n}})$ determines required sensitivity to ΔB

$$\sigma(d_{\mathrm{n}})_{\mathrm{stat}} = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

$$\Rightarrow \sigma(\Delta B)_{\mathrm{cycle}} \ll 2.4\mathrm{pT} \quad \& \quad \sigma(\Delta B)_{\mathrm{run}} \ll 160\mathrm{fT}$$