By-products of nEDM searches

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Introduction to 'exotic physics' searches
Notes on (co-)magnetometry
...using 'old' graphics from PSI/my thesis

Example: exotic interaction mediated by axion-like particles
Other examples of scientific results (in brief)
Some questions...

- What does ‘by-product’ mean in this context?
- Why would one want to put effort into a detour?
- Where do these ideas come from?
- How does it work?
A 'by-product' can be a measurement or scientific result/finding/limit performed with an apparatus that was intended for something else.

High precision experiments often take years for the data taking to be completed. Interim measurements can provide knowledge gain, past time, publications, new ideas, etc...

Hardware downtime can maybe be used meaningfully.

Suggestions of theoreticians, phenomenologists or other smart and creative people need to include a potential observable;

The observable has to be accessible with the apparatus at hand, and maybe be a variable of some setting or property of the setup (the 'knob' to turn).

In case of nEDM, this can be stored neutrons, neutron precession frequency, magnetic field, ...

⇒ (Co-) magnetometry plays a huge role
"The neutron magnetometer"

Ingredients to extract $f_n$ via the Ramsey method:

- 100% polarized ensemble
- Magnetic field, ideally on single homogeneous component
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- Magnetic field, ideally on single homogeneous component
- Very precise external clock
- Count neutrons depending on polarization state

\[
\omega_{osc} = \omega_L
\]

\[
B_{osc} = \sin(\omega_L t)
\]
Magnetic field sensitivity requirements

nEDM measurement:
Observe Larmor precession in a magnetic field $\vec{B}$ and an electric field $\vec{E}$ ↑↑ or ↑↓

$$hf_n = 2\mu_n B \pm 2d_n E$$
$$d_n = \frac{\hbar (f_n^{↑↑} - f_n^{↑↓}) - \mu_n (B^{↑↑} - B^{↑↓})}{2 (E^{↑↑} + E^{↑↓})} = \frac{h\Delta f - \mu_n \Delta B}{4E}$$

- Ideally, $\Delta B \to 0$, but has finite size in reality
- Statistical sensitivity to $d_n$ determines required sensitivity to $\Delta B$
  (reminder: we want to reach $\sigma(d_n) \leq 1 \cdot 10^{-27} e\text{cm}$; how well do I need to know $B$ to get there?)

$$\sigma(d_n)_{\text{stat}} = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

$$\Rightarrow \sigma(\Delta B)_{\text{cycle}} \ll \mathcal{O}(4)pT \quad \& \quad \sigma(\Delta B)_{\text{run}} \ll \mathcal{O}(200)fT$$

- $B_0 \equiv B^{↑↑} = B^{↑↓} \approx 1 \mu T \quad \sigma(\Delta B)/B_0 < 10^{-6}!$
Spin-polarized mercury atoms are filled into the UCN precession chamber. A $\pi/2$-pulse causes the spins to precess freely in the transverse plane ($\sim 8$ Hz). Precession frequency is proportional to $\vec{B}$-field and read out via optical means. Precision of $^{199}$Hg co-magnetometer: $\sim 10^{-7} \Leftrightarrow \sim 100$ fT.
The mercury co-habiting magnetometer

Precision of $^{199}$Hg co-magnetometer: $\sim 10^{-7} \leftrightarrow \sim 100$ fT

Crucial difference in behaviour of UCN and $^{199}$Hg atoms:
Difference in the center-of-mass height!

UCN mercury

UCN center-of-mass offset: $h \sim O$(mm).

Beatrice Franke, Fundamental Neutron Physics Summer School, NCSU, July 17, 2018
Precision of $^{199}$Hg co-magnetometer: $\sim 10^{-7}$ $\Leftrightarrow \sim 100$ fT
The mercury co-habiting magnetometer

- Crucial difference in behaviour of UCN and $^{199}$Hg atoms: Difference in the center-of-mass height!

- UCN center-of-mass offset: $h \sim \mathcal{O} \text{ (mm)}$. 
Scalar (or maybe even vector) magnetometers provide magnetic field information at various positions.

- Allows to extract a vertical magnetic field gradient, and possibly transverse field info.
Most neutron EDM measurements apply a Hg co-habiting magnetometer. The ratio of Larmor precession frequencies

\[ R = \frac{f_n}{f_{\text{Hg}}} \]

is used to correct for magnetic field changes. 

\( R \) is measured at high precision and can also be used to perform other experiments than the neutron EDM search.
The ratio $R$ of Larmor precession frequencies

- UCN and $^{199}\text{Hg}$ precess together in the same volume
- The following ratio is used to measure the magnetic field

$$ R = \frac{f_n}{f_{\text{Hg}}} $$

- Do both species sample the magnetic field in the same way?

$$ R = \frac{f_n}{f_{\text{Hg}}} = \frac{\gamma_n B_n}{\gamma_{\text{Hg}} B_{\text{Hg}}} ? \frac{\gamma_n}{\gamma_{\text{Hg}}} $$
UCN have a center of mass offset $h \approx 2$ mm.

- If a vertical magnetic field gradient $G$ is present, both species will effectively sample different fields.

- $\bar{v}_{\text{UCN}} \sim 4 \text{ m/s}$

- $f_{\text{Hg}} = |\gamma_{\text{Hg}} B / 2\pi| \approx 30 \text{ Hz} @ 1 \mu T$

- travel 0.1 m during Larmor period (adiabatic)

- $\text{sgn} \gamma_{\text{Hg}} < 0$

- $\bar{v}_{\text{Hg}} \sim 170 \text{ m/s}$

- $f_{\text{Hg}} = |\gamma_{\text{Hg}} B / 2\pi| \approx 8 \text{ Hz} @ 1 \mu T$

- travel 20 m during Larmor period (non-adiabatic)

- $\text{sgn} \gamma_{\text{Hg}} > 0$
How do UCN and Hg atoms sample magnetic fields?

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The ratio $R$

$$R = \frac{f_n}{f_{\text{Hg}}} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 \pm \frac{Gh}{B_0} \pm \delta_{B \perp} \uparrow \downarrow \mp \delta_{\text{Hg,Light}} \uparrow \downarrow \mp \delta_{\text{Earth}} \right)$$

Assuming $G = 100 \text{ pT/cm}$,

$$R^\uparrow \approx 3.8 \left( 1 - 2 \cdot 10^{-5} + 3.7 \cdot 10^{-6} + 1.3 \cdot 10^{-6} - 5.3 \cdot 10^{-6} \right).$$

Measure $R$ as function of $G$ for $B_0 \uparrow$ and $\downarrow$
\[ f_n = \left| -\frac{\gamma_n B_0}{2\pi} \pm f_{\text{Earth}} \sin(\lambda) \right| = \left| -\gamma_n B_0 \pm \omega_{\text{Earth}} \sin(\lambda) \right| \quad (1) \]

\[ f_{\text{Hg}} = \left| \frac{\gamma_{\text{Hg}} B_0}{2\pi} \pm f_{\text{Earth}} \sin(\lambda) \right| = \left| \gamma_{\text{Hg}} B_0 \pm \omega_{\text{Earth}} \sin(\lambda) \right| \quad (2) \]

\[ \frac{f_n}{f_{\text{Hg}}} = \frac{\left| -\gamma_n B_0 \pm \omega_{\text{Earth}} \sin(\lambda) \right|}{\left| \gamma_{\text{Hg}} B_0 \pm \omega_{\text{Earth}} \sin(\lambda) \right|} \approx \frac{\gamma_n}{\gamma_{\text{Hg}}} \left( 1 \mp \frac{\omega_{\text{Earth}} \sin(\lambda)}{B_0} \left( \frac{1}{\gamma_n} + \frac{1}{\gamma_{\text{Hg}}} \right) \right) \quad (3) \]

[Try at home; easy homework using \((\omega_{\text{Earth}} \sin(\lambda)/\gamma_{\text{Hg}} B_0) \ll 1\) and \(\frac{1}{1 \pm \epsilon} \approx 1 \mp \epsilon\) for \(\epsilon \ll 1\), or look up in my thesis;)\]
'Linear' function of gradient G (measured with magnetometer array), offsets through constant terms in R (nonlinearity mentioned later). Zero gradient could mean/require current in gradient correction coil...
Most neutron EDM measurements apply a Hg co-habiting magnetometer. The ratio of Larmor precession frequencies

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'Starting position':
- Fundamental particle (n), spin polarized
- Precession frequency of both species measured precisely
- Close to high density of unpolarized nucleons (wall material)

Very well suited to look for a dipole-monopole interaction: spin-dependent & CP-violating, like the potential suggested by Moody & Wilczek in 1984:

\[
V(\vec{r}) = g_s g_p \frac{(\hbar c)^2}{8\pi mc^2} (\vec{\sigma} \cdot \hat{r}) \left( \frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda}}
\]
- Short-range spin dependent interaction
- Dark matter candidates
- Solution to the strong CP problem [Peccei & Quinn 1977]

$$\mathcal{L}_{\text{QCD}}^{\text{CPodd}} \propto \bar{\theta} \leq 10^{-10}$$

- Axion window:
  $$10 \mu \text{eV} \leq m_A \leq 10 \text{meV}$$

generic bosons no relation between mass and interaction strength is given, as compared to the genuine axion. The origin of such particles can be symmetries other than Peccei-Quinn symmetry, which are broken at very high energies and often postulated in theories beyond the Standard Model of particle physics, such as e.g. String Theory. Axions and axion-like particles, are intriguing dark matter candidates and BSM probes
Spin-dependent interaction results in a pseudomagnetic field $b$ normal to the surface. Pseudomagnetic field alters $f_n$ and thus also $R$.

$$R = \frac{f_n}{f_{Hg}} \xrightarrow{\text{corrections}} \frac{\gamma_n}{\gamma_{Hg}}$$
Pseudomagnetic field & gyromagnetic ratio

\[ V(\vec{r}) = g_s g_p \frac{(\hbar c)^2}{8\pi mc^2} (\vec{\sigma} \cdot \hat{\vec{r}}) \left( \frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda}} \]

Spin-dependent interaction results in a pseudomagnetic field \( b \) normal to the surface. Pseudomagnetic field alters \( f_n \) and thus also \( R \).

\[ R = \frac{f_n}{f_{Hg}} \xrightarrow{corrections} \frac{\gamma_n}{\gamma_{Hg}} \xrightarrow{exotic\ interaction} \frac{\gamma_n}{\gamma_{Hg}} \left( 1 \pm \frac{b}{B_0} \right) \]

Integrate over all nucleons & UCN density distribution:

\[ g_S g_P \hat{\phi} = b \frac{H^2\gamma^\phi m^\phi}{6\hbar h N\lambda^2} \left( 1 - e^{-\frac{H}{\lambda}} \right)^{-1} \left( 1 - e^{-\frac{a}{\lambda}} \right)^{-1} \]

Measurement yielded: \( b = (0.28 \pm 0.53) \) pT

\( \Rightarrow g_S g_P \lambda^2 < 2.2 \cdot 10^{-27} \) m\(^2\) for \( 1 \mu m < \lambda < 5 \) mm at 95 % CL
Results from a clock comparison

\[ \gamma_n / \gamma_{\text{Hg}} = 3.842457(3) \]

[Afach et.al., PLB 739, 128 (2015)]
Results from a clock comparison

[Afach et al., PLB 745, 58 (2015)]
More example of exotic physics searches:
prerequisite: stored UCN; observable: UCN losses

- possibility of recoil energy detection down to UCN energy of roughly $100 \text{ neV} \approx 10^{-7} \text{ eV}$
- Earth moves through dark matter

$\Rightarrow$ UCN experience recoil on collision and get upscattered

- neutron is not 'ultracold' anymore and leaves trap, resulting in additional loss mechanism $\tau_{\text{dark matter}}^{-1}$ in lifetime measurement
- this loss mechanism is not present in neutron beam experiments

$$(\tau_n^{-1})_{\text{UCN}} - (\tau_n^{-1})_{\text{beam}} = \tau_{\text{dark matter}}^{-1}$$

- can be translated to an interaction probability between UCN and dark matter of a certain density

prerequisite: stored UCN, tunable $B$; observable: UCN losses

- In "mirror world" a complete copy of known particle spectrum would exist, but weak interaction would be $V+A$
- Parity would be restored in a global sense
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Neutron to mirror-neutron oscillations

prerequisite: stored UCN, tunable $B$; observable: UCN losses

- In "mirror world" a complete copy of known particle spectrum would exist, but weak interaction would be V+A
- Parity would be restored in a global sense
- New interactions could lead to mixings between neutral particles: $nn'$ oscillations
- Ordinary and mirror state are degenerate for $B \approx 0$ or $B \approx B'$
- $\tau_{nn'} > 448$ s for $B \approx 0$ at 90 %CL
- Look for a resonance in UCN losses as function of $B$
- $\tau_{nn'} > 12$ s at 95 %CL for any $0 \mu T < B' < 12.5 \mu T$
Anisotropy of the Universe, Lorentz Invariance Violation

prerequisite: spin precessing UCN; observable: siderial modulations

- Propose electromagnetic field resulting from fundamental anisotropy of the Universe [Kostelecki, Pospelov]
- Potential of stored neutrons is modified by additional term $V' = b_i \sigma_i$
- Look for an interaction between particle spin and $b$ "cosmic axial field" in energy units
- No siderial modulation observed at a level of $\sim 10^{-24} \, \text{cm}$
- Can be translated to a limit on Lorentz violation energy scale of $\mathcal{E}_{LV} > 10^{10} \, \text{GeV}$

Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

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We report on a search for ultralow-mass axionlike dark matter by analyzing the ratio of the spin-precession frequencies of stored ultracold neutrons and 199Hg atoms for an axion-induced oscillating electric dipole moment of the neutron and an axion-wind spin-precession effect. No signal consistent with dark matter is observed for the axion mass range $10^{-21} \leq m_a \leq 10^{-17}$ eV. Our null result sets the first laboratory constraints on the coupling of axion dark matter to gluons, which improve on astrophysical limits by up to 3 orders of magnitude, and also improves on previous laboratory constraints on the axion coupling to nucleons by up to a factor of 40.
Some results

Gravitational enhanced depolarization and associated frequency shift


Some results

Spin-echo spectroscopy

See poster by G. ZSIGMOND

Physical review letters 115 (16), 162502 (2015)
Thank you for your attention!