Optical magnetometry for the TUCAN nEDM experiment

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Motivation

• The Hamiltonian of the neutron:

\[ H = \hbar \omega = -\mu B \cdot S - dE \cdot S \]

• To measure d, take advantage of the behaviour of B, E, and S:

\[ h\omega_\uparrow = 2\mu_n B + 2d_n E \quad \text{Parallel} \]

\[ h\omega_\downarrow = 2\mu_n B - 2d_n E \quad \text{Anti-parallel} \]

• and solve for:

\[ d_n = \frac{\hbar(\omega_\uparrow - \omega_\downarrow)}{4E} \]

\[ d_n(\text{standard model}) \sim 1 \times 10^{-31}\text{e} \cdot \text{cm} \]

\[ d_n(\text{upper bound}) = 1 \times 10^{-26}\text{e} \cdot \text{cm} \]
The TUCAN experiment

- 2 chambers allows us to measure both values of $\omega$ simultaneously
- Working equation relies on identical E&B in both chambers, $B = 1 \mu T$
- Gradients in general, and vertical gradients especially will effect our measurement of $d_n$
Magnetometry: field decomposition

• In order to measure and control magnetic fields we need a sensible way to describe them

• Like Fourier decomposition, we can describe the field in terms of the relative contributions of orthogonal functions*

\[
\begin{pmatrix}
B_x (\vec{r}) \\
B_y (\vec{r}) \\
B_z (\vec{r})
\end{pmatrix} = \sum_{l,m} G_{l,m} \begin{pmatrix}
\Pi_{x,l,m} (\vec{r}) \cdot \hat{i} \\
\Pi_{y,l,m} (\vec{r}) \cdot \hat{j} \\
\Pi_{z,l,m} (\vec{r}) \cdot \hat{k}
\end{pmatrix}
\]

Fully describes the field up to order \( \ell \)

Magnetometry: measuring fields

\[ \begin{bmatrix} B_z(x_1, y_1, z_1) \\ \vdots \\ B_z(x_n, y_n, z_n) \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & y_1 & 0 & -\frac{1}{2} x_1 & z_1 & x_1 & 2x_1 y_1 & 2y_1 z_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & x_1 & z_1 & -\frac{1}{2} y_1 & 0 & -y_1 & x_1^2 - y_1^2 & 2x_1 z_1 \end{bmatrix} = \begin{bmatrix} G_{0-1} \\ G_{00} \\ G_{01} \\ G_{1-2} \\ G_{1-1} \\ G_{10} \\ G_{11} \\ G_{12} \\ G_{2-2} \\ G_{2-1} \end{bmatrix} \]

\[ \vec{B}_z = T_z \cdot \vec{g}. \]

\[ \vec{g} = \text{pinv}(T_z) \cdot \vec{B}_z \approx \text{pinv}(T_z) \cdot \vec{B}_{mod}. \]

Want to calculate

Measured by sensors

Known from positions of sensors
Optical magnetometry: NMOR
non-linear magneto-optical rotation

- Manifests in alkali vapour (Cs) excited by resonant light
- Atoms can be polarized by light
- Polarized atoms interact with magnetic fields
- Effectively couples magnetic field to light

Optical pumping rearranges the magnetic sub-level occupation
We use Cs atoms, we know precisely how fast they precess in a magnetic field.
Measuring fields at UofW

- Can clearly see drifts in the coil current generating the test field
- Well correlated with FID frequency measurement
Proof-of-concept performance

- sub-pT performance after 3-4 s integration
- Monte Carlo simulations indicate that this level of precision can adequately map our field
How to deploy sensors? Genetic Algorithm

- 20 sensors
- pT sensitive
- mm placement accuracy
- field map to 3\textsuperscript{rd} order
- field sim. to 5\textsuperscript{th} order
- F.O.M is error in identifying systematic
- histogram of 10,000 trials

Rings

Asymmetric rings

Helices

Random

Early Ferret run

Late Ferret run
Automatically optimizing parameters to maximize the amplitude of FIDs to characterize T2 for the custom made Cs cells. These cells get sent to SWS to be placed in the final sensors.

Current development

- Characterizing coated Cs cells for fibre coupled prototype
  - Automatically characterize T1, T2, Cs vapour pressure
- Going from free space coupled proof-of concept to fibre coupled prototype
  - prototype manufactured by SWS in Santa Fe

Fibre splitters being set up and tested at UofW
Questions?