Atomic Magnetometry for neutron EDM experiment


The University of Winnipeg
Neel for Precision Magnetometry

\[ H = -\hat{\mu} \cdot \hat{B} - \hat{d} \cdot \hat{E} \]

- The EDM \((d)\) term violates CP.
- New sources of CP violation required in e.g. electroweak baryogenesis.

\[ h\nu = 2\mu B \pm 2dE \]

- Precision goal \(\delta d_{\text{stat}} = 10^{-25} \text{ e-cm / 100 s.}\)
- Requires average \(B\) known to \(\delta B < 16 \text{ fT}\), operating field \(B = 1 \mu\text{T}\).
We have been studying NMOR-based magnetometers at U. Winnipeg (as well as Xe-129, Fluxgates, GMI, and SQUID’s but that’s not in this talk)
Magneto-optical rotation (Faraday rotation)

Circular components of linear polarization

Circular birefringence \( (n_{\pm}) \) rotates plane of polarization

\[
\phi = \pi (n_+ - n_-) \frac{l}{\lambda}
\]

Linear effect from Zeeman splitting

\[
\phi = \frac{2g\mu_B B\Gamma}{\hbar \Gamma} \frac{l}{1 + (2g\mu_B B/\hbar \Gamma)^2 l_0}
\]

Doppler width \( \Gamma \sim \text{GHz} \)

\( F' = 0 \)

\( F = 1 \)

\( M = -1 \)  \( M = 0 \)  \( M = +1 \)
Nonlinear Magneto-Optical Rotation (NMOR)

Nonlinear = light modifies the medium

1. Hole burning:
   Light depletes ground-state velocity distribution.

2. Coherent dark state:
   Linearly polarized light $\Delta M = \pm 1$ selection rule creates coherent dark state.

\[
\frac{1}{\sqrt{2}} (|M = 1\rangle + |M = -1\rangle)
\]

\[
\frac{1}{\sqrt{2}} (|M = 1\rangle - |M = -1\rangle)
\]

\[B = 0\]

Atomic velocity

Number of atoms

\[F' = 0\]

\[F = 1\]

\[g\mu B\]
NMOR

- Medium becomes linearly dichroic
- Axis of alignment rotates by Larmor precession in the magnetic field
- Net result: again, circular birefringence.

\[ \phi = \frac{2g\mu B/\hbar\gamma_{rel}}{1 + (2g\mu B/\hbar\gamma_{rel})^2 l_0} l \]

\[ \Delta B \sim 400 \text{ G} \]

\[ 400 \text{ G} \rightarrow 2 \text{ } \mu \text{G} \]

\[ 40 \text{ mT} \rightarrow 200 \text{ pT} \]
Removing Limitation on the Dynamic Range: AM/FM NMOR

- Axis of alignment in the vapour rotates at \( \omega_L = \gamma B \),
  \( \gamma = 4.7 \text{ kHz/\( \mu \text{T} \)} \) (\(^{85}\text{Rb}\))
- Stroboscopic effect: flash the laser light at \( 2\omega_L \)
- Displaces the resonance from zero field to \( B \).

Previous Work of Others

2.8 $\mu$G = 280 pT

15 $\mu$G = 1.5 nT

$\delta B_{SNL} \approx \frac{1}{g_F \mu_0} \sqrt{\frac{\gamma_{rel}}{N T}} = 2$ fT/rtHz

$(T=35^\circ C)$

D.F. Jackson-Kimball, et al.,

D. Budker, et al.,
PRL 81, 5788 (1998)
Our Work - Apparatus
Results from 2013-14 school year


NMOR results @ zero field

Direct Measurement of Relaxation of Axis of Alignment

Clear indicator of issues with cell/coating quality (paraffin)

Us: $\tau = 2.1 \text{ ms} = 1/\gamma_{\text{rel}}$

Graf: $\tau = 0.4 \text{ s} = 1/\gamma_{\text{rel}}$
New Cell (borrowed from D. Budker)

Dear Dima and Brian,

Your cell works great!

- NMOR width ~ 1.5 μG = 150 pT
- $\gamma_{rel} \sim 1/0.36 \text{ s} = 2.8 \text{ Hz}$

Consistent with Budker’s best results!

“Dear Dima and Brian, Your cell works great!”

New cells from Balabas expected.
Measuring small fields

± 46 fT steps in applied magnetic field.
1 Hz filter applied to optical rotation signal.
Probe power 13 uW.
Application: Measurement of very large magnetic shielding factors

Green: internal field (calibration, ±500 fT)
Red: external field (applied ±2 μT, unknown shielding factor)
Conclusion: The shielding factor is $1.5 \times 10^7$, couldn’t have been measured otherwise.
AM NMOR

• Width ~ 1 nT Consistent with Jackson-Kimball.
• Larmor frequency consistent with fluxgate calibration 0.21 μT

Noise ~ pT
Still working to make it better.
Room temperature.
Quantifying existing magnetic noise, field quality.

\[ \omega_{\text{mod}} = 2 \text{ kHz} = 2 \omega_L \]
Conclusions

• Precision magnetometry below 1 pT is critical for nEDM measurement.
• AM NMOR is studied as a solution for fT-level magnetometry.
• System developed at U. Winnipeg approaches this goal
  • NMOR widths consistent with best published values.
  • ~30 fT/rtHz noise @ 1 Hz for zero field
  • ~pT/rtHz noise @ 1 Hz for 0.22 uT applied field – we are working hard to understand and make it better.
• Method already applied to measurements of very large axial magnetic shielding factors with very small applied fields.
Future

• Make the best magnetometer we can based on this system and use it to study magnetic shielding, generation of magnetic fields.
• Using this system will make us experts capable of employing a Cs-based fiberized system for the eventual nEDM experiment.
• New: B. Patton et al “All-Optical Vector Atomic Magnetometer” arXiv:1403.7545!!!
• Developing collaboration with Budker, Balabas. A big thank you to D. Budker, B. Patton, and M. Solarz for the use of their cell.

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