Development of high-sensitivity magnetometer for EDM experiment with $^{129}$Xe spin oscillator

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RIKEN Nishina Center (~ 2011.9)
Okayama University (2011.10 ~ )

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**EDM measurement**

\[ B = 0 \quad E = 0 \]

\[ B \neq 0 \quad E \neq 0 \]

\[ E \parallel B \quad E \parallel -B \]

\[ \hbar \omega_+ \]

\[ \hbar \omega_- \]

\[ v_+ = \frac{2\mu B + 2dE}{h} \]

\[ v_- = \frac{2\mu B - 2dE}{h} \]

**Frequency shift of 1 nHz**

\[ \delta B = 1 \text{ pG} = 0.1 \text{ fT} \]

\[ \frac{1}{1 \text{ nHz}} = 10^9 \text{ s} \approx 31 \text{ years} \]

**Phase measurement**

\[ \delta \nu = \frac{\delta \phi}{2\pi T} \]

\[ \delta \phi = 1 \text{ mrad} (0.06^\circ), \quad T = 1,000 \text{ s} \]

\[ \delta \nu = 160 \text{ nHz} \]

**Repeating measurements**

\[ \delta \nu_{\text{total}} = \frac{\delta \nu_i}{\sqrt{n}} \]

10 month = 25,920 ksec: \[ \delta \nu_{\text{total}} = \frac{\delta \nu_i}{\sqrt{n}} = \frac{160 \text{ nHz}}{\sqrt{25920}} = 1 \text{ nHz} \]

**Frequency shift of** \[ 1 \text{ nHz} \]

\[ \Delta \nu = \frac{4dE}{h} = \frac{4 \times 10^{-28} \text{ [ecm]} \times 10^4 \text{ [V cm}^{-1}] }{4.136 \times 10^{-15} \text{ [eV s]}} \]

\[ = 0.97 \times 10^{-9} \text{ [s}^{-1}] \approx 1 \text{ [nHz]} \]
Nuclear Spin Maser with Polarized $^{129}$Xe at low field

**Maser signal**

- Signal (V)
- Time (s)

**Frequency precision**

- $\delta v_0 = 7.9$ nHz ($T_m = 30,000$ s)
- $\delta B = 50-100$ μG
- $\delta B = 50-100$ nG

**Environmental field**

- $\delta B = 50-100$ μG
- Field fluctuation due to change in the magnetic shield
Comagnetometer with $^3$He - Michigan Univ. -

Rosenberry and Chupp, PRL (2001)

$B_0 = 3.0 \text{G}$

129Xe precession: locked with reference oscillator

No drift

$\delta \nu_{\text{locked-Xe}} \approx 20 \text{nHz}$

2000 s - Run

Feedback to solenoid current

$\delta B \approx 17 \text{pG}$

Measuring $^3$He maser frequency

$\rightarrow$ EDM signal

Long term fluctuation

$\delta \nu_{\text{free-He}} \approx \mu\text{Hz} \Rightarrow \approx \text{nG}$

$T_{\text{maser}} = 120 \degree \text{C}$

$[\text{Rb}] \approx 2.0 \times 10^{13} / \text{cm}^3$

$P_{\text{Rb-maser}} \approx 0.68$

$T_{\text{maser}} = 40 \degree \text{C}$

$[\text{Rb}] \approx 5.2 \times 10^{10} / \text{cm}^3$

$P_{\text{Rb-maser}} < 0.0001$
Frequency stability in Dual noble gas spin maser

Sources of frequency drift

- Drift of the applied magnetic field $B_0$
- Magnetic field generated from polarized atoms
  - Other species: Longitudinal (7mHz, 8.2 mHz), Transverse (58 pHz, -81 pHz)
  - Same species: Longitudinal (23mHz, 2.5 mHz), Transverse (-18mHz, -5.5mHz)
  - From Rb atoms (40 nHz, 2μHz)
- Maser Position: (30mHz)
- Cavity pulling: (20μHz)
- Field gradient (100nHz, 36nHz)

Laser properties
- Temperature
- Environmental field
- Shield drift, noise
- Mechanical instability

Diagram:
- $\Delta B_{sol}$
- $\Delta B_{ext}$
- $\Delta B_{atoms}$
- $\mu_{Xe}$
- $B_T$
- $B_{FB}$
- $B_{T–atoms}$
- $B_{T–grad}$
- Maser posi.
- Cavity pul
Magnetometer for Low freq-Spin maser EDM experiment

(1) High sensitivity magnetometers
- Not comagnetometer
- Rb magnetometer near maser cell
- Only Xe and Rb (small, and not pol)

$$\delta B = 10^{-11} \text{ G/}\sqrt{\text{Hz}}$$

100 s -run (if constant):

$$\delta B = 10^{-12} \text{ G}$$

(2) Rb comagnetometer
- Comagnetometer of Rb
- Only Xe and Rb (small, and not pol)
- Problem of Rb – Xe interaction?
  (→ Low density Xe gas?)
- Polarizability problem

(3) 3He comagnetometer
- Comagnetometer of 3He
- S/N for He precession for laser probing.
Precise magnetometer with Rb atoms using NMOR

Resonant optical rotation in Rb vapor
(NMOR; Nonlinear Magneto-Optical Rotation)

Incident laser beam
Transmitted laser beam

Atomic alignment

Incident laser beam

(b)

|\rangle = \frac{1}{\sqrt{2}} \left( |m_F = +1\rangle + |m_F = -1\rangle \right)

|\rangle = \frac{1}{\sqrt{2}} \left( |m_F = +1\rangle - |m_F = -1\rangle \right)

\[ |0\rangle = |m_F = 0\rangle \]

\[ \varphi = \frac{2 g_F \mu_B B_z}{\gamma_0} \frac{l}{1 + \left( \frac{2 g_F \mu_B B_z}{\gamma_0} \right)^2 \frac{2l_0}{2l_0}} \]

\[ \Delta B \approx 1 \mu G \]

Narrow line width  (reducing spin relaxation)
Operation at room temperature
Operation at geophysical field range (mG~G)
(by using modulation of laser property)
NMOR setup

- 4-layer magnetic shield
- Photo diode
- Linear polarizer
- Photo elastic Modulator (PEM)
- 3-axis coil
- Rb cell
- Beam splitter
- External Cavity Diode Laser (20mW, FWHM 1MHz)
- Linear Polarizer-1
- Rb reference cell
- Wavemeter
- PEM driver&controller
- Lock-in amplifier
- Oscilloscope
- Reference (50kHz)
- Signal
- 85Rb
- 87Rb
- 87Rb
- 15 GHz
Setup, Rb cell

Rb cell with Paraffin coating: commercial paraffin mixture (Paraflint) \((\text{CH}_2)_n\)

Field coil (3-axis)

ECDL

\(\phi\ 25 – 30\ mm\)
NMOR spectrum

Wide-field scan

Dispersive function

\[ \varphi = \frac{2g_F \mu_B B_z / \hbar}{\gamma} \left( 1 + \frac{2g_F \mu_B B_z / \hbar}{\gamma} \frac{l}{2I_0} \right) \]

\[ \gamma = 2\pi \times (6.43 \pm 0.03) \times 10^4 [s^{-1}] \]

\[ \Delta t = 1.25 \times 10^{-5} \text{ s} \]

Preservation of atomic spin coherence at wall-collision

\[ \left( \frac{\gamma}{2\pi} \right)^{-1} = \frac{1}{1.65 \times 10^2 [s^{-1}]} = 6.1 [\text{ms}] \]
NMOR width (Cell dependence and residual field)

ΔB = 4.04 mG

ΔB = 1.99 mG

Residual magnetic field

\[
\begin{align*}
B_x &= -235 \, \mu G \\
B_y &= -237 \, \mu G \\
B_z &= -13 \, \mu G \\
\end{align*}
\]

Degaussing...
Magnetic sensitivity

\[ \Delta B = 0.37 \, \text{mG} \]

\[ \left( \frac{\partial \phi}{\partial B_z} \right)_{B_z=0} = 16.1 \, \text{rad/G} \]

\[ \delta B = \frac{7.5 \times 10^{-7}}{16.1} = 4.7 \times 10^{-8} \left[ \text{G} / \sqrt{\text{Hz}} \right] \approx 50 \, \text{nG} / \sqrt{\text{Hz}} \]

NMOR spectrum

Noise spectrum

\[ \delta V = 0.002 \, \text{V/}\sqrt{\text{Hz}} \]

\[ \delta \phi \approx 0.75 \, \mu\text{rad/}\sqrt{\text{Hz}} \]
The cell made by Prof. M.V. Balabas: φ60 mm, T1 ~ 2s.

Thanks to Prof. Hatakeyama (Tokyo Univ. Agri. Tech.)

\[ \Delta B = 0.37 \text{ mG} \]
\[ (\gamma / 2\pi)^{-1} = 40 [\text{ms}] \]
\[ \left( \frac{\partial \phi}{\partial B_z} \right)_{B_z=0} = 16.1 \text{ rad/G} \]

\[ \Delta B = 0.28 \text{ mG} \]
\[ (\gamma / 2\pi)^{-1} = 50 [\text{ms}] \]
\[ \left( \frac{\partial \phi}{\partial B_z} \right)_{B_z=0} = 37.8 \text{ rad/G} \]

No large difference in NMOR width → Wall performance does not limit the width → residual field...
Modulated NMOR - measurement at $B_0 = 10$ mG -

NMOR: measurement around $B=0$ G

At higher magnetic field, optical rotation does not appear

$\omega_{Rb} > \gamma_{rel}$

Modulated NMOR

Low field: $\omega_{Rb} < \gamma_{rel}$
High field: $\omega_{Rb} > \gamma_{rel}$

Production of alignment

$\omega_{mod} = \frac{1}{2} \times \omega_{Rb}$

- Frequency modulated
- Amplitude modulated

Setup - measurement at $B_0 = 10$ mG -

Amplitude modulation by using
AOM:(Acousto-Optical Modulator)
Spectrum - measurement at $B_0 = 10 \text{ mG}$ -

Modulation frequency: 9 kHz (AM) corresponds to twice the Larmor freq. at $B_0 = 9.645 \text{ mG}$

Magnetic field sweep: $-11 \text{ mG} \rightarrow +11 \text{ mG}$

Magnetic sensitivity (at present)

Slope $= 53.5 \text{ V/mG}$

$$\delta B = \left( \frac{d\phi}{dB} \right)^{-1}_{B=0} \delta \phi = \frac{2 \times 10^{-3}}{53.5 \times 10^3} \approx 40 \frac{\text{nG}}{\sqrt{\text{Hz}}}$$

$$\nu_F = \frac{g_F \mu_B}{\hbar}$$

$= 461.7 \text{ [kHz/G]}$

$\Rightarrow 4.5000 \text{ [kHz]} @ 9.7466 \text{ mG}$

$\delta \phi = 2 \text{ mV/} \sqrt{\text{Hz}}$
Summary and Future

- High sensitive magnetometer is inevitable for atomic EDM experiments because main source of frequency stability comes from drifts of magnetic field (applied $B_0$ or environmental field).

- We have developed the Rb NMOR spectrometer for the operation of magnetometer.

- Operation of modulated NMOR for measurements at $B_0 = 10$ mG.

- Improving NMOR-magnetometer performance;
  
  Optimization of degaussing procedure, cancelling field (to $<< \Delta B_z$)
  
  Improving cell-coating procedure.
  
  Measurement of $T_1$ for the Rb cells

- Noise studies; detection method, electronics, experimental room…

- Introduction to spin maser setup