Development of a novel comagnetometer for high-precision measurement of the electron's electric dipole moment using laser-cooled Fr atoms

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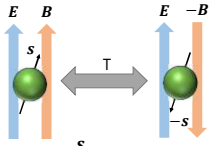
Introduction

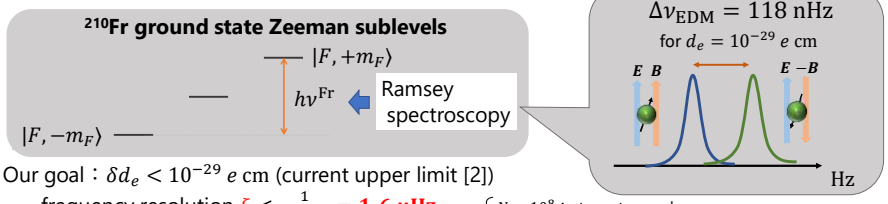
Electron's electric dipole moment (eEDM) : physical quantity of proof that time reversal symmetry is violated
Francium atoms (Fr) : good probe to measure the eEDM
- Large eEDM enhancement factor ($R_{\mathrm{Fr}} = 799$[1])

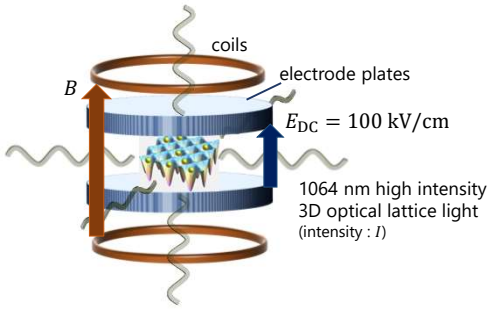
Our goal : detection of the energy shift caused by the eEDM
- The energy shift is detected as a change of the Larmor frequency
- We apply magnetic and electric fields in parallel and antiparallel and detect the frequency difference.



$$\mathcal{H} = -\mu \frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{B} - d_e \frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{E} \qquad \mathcal{H} = -\mu \frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{B} + d_e \frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot \boldsymbol{E}$$

Method of Fr-EDM measurement





Our goal : $\delta d_e < 10^{-29}$ e cm (current upper limit [2])
- frequency resolution $\xi < \frac{1}{2\pi T\sqrt{N}} = \mathbf{1.6\ \mu Hz}$
- shot noise limit $\Delta\nu < \frac{1}{2\pi T\sqrt{Nn}} = \mathbf{92\ nHz}$

$N = 10^8$: atoms trapped
$T = 10$ sec : coherence time
$n = 300$: the number of measurement

What we measure [3-5]

$$\nu^{\mathrm{Fr}} = \underbrace{g_F \Delta m_F \mu_B B/h}_{\text{Zeeman shift}} + \underbrace{\alpha(\lambda) U \Delta m_F \varepsilon_p}_{\text{vector light shift (VLC)} \propto I,\varepsilon_p} + \underbrace{\frac{g_F}{g_J}\Delta m_F R_{\mathrm{Fr}} \boldsymbol{d_e}\cdot \boldsymbol{E}_{\mathrm{DC}}/h}_{\text{Fr-EDM}} + (\text{collision shift}) + (\mathrm{m}_F^2 \text{ dependence term}) + (\text{higher order})$$

$\Delta P \times 30$ nHz for Cs [3] disappears for above scheme

dominant sources of systematic error

$$\delta B = \frac{h\xi}{g_F \Delta m_F \mu_B} < \mathbf{1.6\ pG} \qquad \Delta B = \frac{h\Delta\nu}{g_F \Delta m_F \mu_B} < \mathbf{93.2\ fG}$$

$$\delta(I\varepsilon_p) = \frac{\xi}{\beta \Delta m_F} < \mathbf{1.3\times 10^{-4}\ mW/cm^2} \qquad \Delta(I\varepsilon_p) = \frac{\Delta\nu}{\beta \Delta m_F} < \mathbf{7.6\times 10^{-6}\ mW/cm^2}$$

of stabilities are needed.
for $\Delta m_F = 4$

ΔP : population difference between $|F,\pm m_F\rangle$
U : trap depth
ε_p: polarization impurity of optical lattice laser beam
α : polarizability
$\beta = \alpha U/I$

Principle of dual-species comagnetometer

Atom **A** and atom **B** with small eEDM
Simultaneously measure each Larmor frequency

$$\begin{cases} \nu^{\mathrm{A}} = g_F^A \Delta m_F^A \mu_B B/h + \beta^{\mathrm{A}} \Delta m_F^A I\varepsilon_p \\ \nu^{\mathrm{B}} = g_F^B \Delta m_F^B \mu_B B/h + \beta^{\mathrm{B}} \Delta m_F^B I\varepsilon_p \end{cases}$$

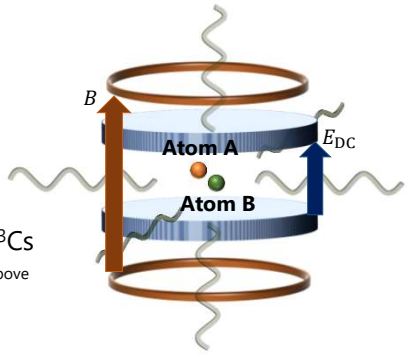
We can measure the effects of both independently.

$$\delta B = \mathbf{630\ fG} \qquad \Delta B = \mathbf{36.4\ fG}$$

$$\delta(I\varepsilon_p) = \mathbf{2.1\times 10^{-4}\ mW/cm^2} \qquad \Delta(I\varepsilon_p) = \mathbf{1.3\times 10^{-5}\ mW/cm^2}$$

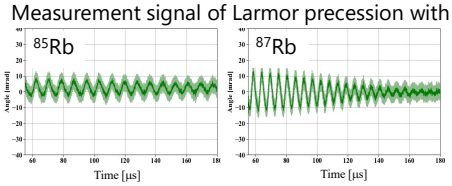
for ^{87}Rb-^{133}Cs

Assume that ξ and $\Delta\nu$ are equal to above



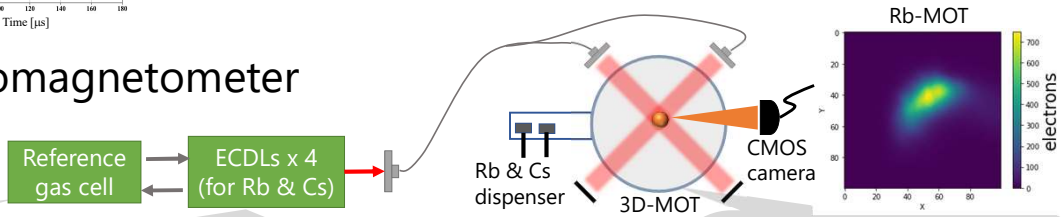
Prototype with ^{85}Rb-^{87}Rb at Tohoku Univ[6]

Measurement signal of Larmor precession with paramagnetic Faraday rotation[7].

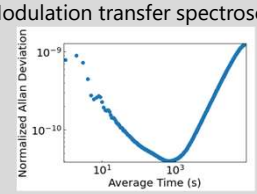


Achieved magnetic field sensitivity < 1 mG
Using Cs and Rb is better to divide Zeeman shift and VLS[6].

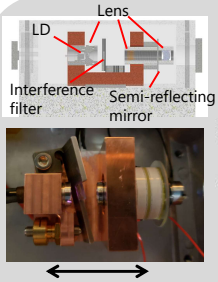
Status of ^{87}Rb-^{133}Cs comagnetometer



Modulation transfer spectroscopy

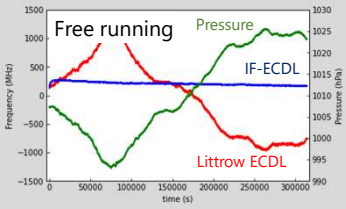


Achieved stable laser source



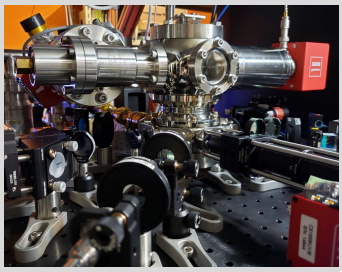
Cavity length ~50 mm

Homemade interference type external cavity diode lasers (IF-ECDL)



Reduce frequency drift with air-tight housing

Magneto-optical trap (MOT) chamber
Achieved ultra high vacuum ($< 1\times 10^{-11}$ Torr)



Conclusion

- The magnetic field fluctuation and the polarization and intensity fluctuation of the optical lattice laser beam are dominant sources of systematic error for EDM measurement.
- The basic idea of dual-species comagnetometer to eliminate these errors was introduced.
- Development of the Rb-Cs comagnetometer is ongoing.

[1] N. Shitara *et al.*, J. High Energy Phys. **2021**, 124 (2021).
[2] ACME Collaboration *et al.*, Nature **562**, 355 (2018).
[3] C. Chin, *et al.*, Phys. Rev. A, **63**, 033401 (2001).
[4] M. V. Romails, *et al.*, Phys. Rev. A, **59**, 6 (1999).
[5] K. Zhu, *et al.*, Phys. Rev. Lett. **111**, 243006 (2013).
[6] A. Uchiyama, PhD thesis, Tohoku Univ. (2018).
[7] T. Isayama, *et al.*, Phys. Rev. A, **59**, 6 (1999).