Experimental Search for atomic EDM in $^{129}$Xe using active nuclear spin maser

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Active spin maser
**EDM measurement of \(^{129}\text{Xe} \) atom**

- Stable isotope
  - Number density: \(10^{18} \sim 10^{19} \text{ cm}^{-3}\)
- Long coherence time
  - \(T_2 \sim 10^2 \text{ s}\)
- Nuclear spin: 1/2
  - Unique Zeeman splitting

Experimental upper limit:

\[ |d^{(129}\text{Xe})| < 4.1 \times 10^{-27} \text{ ecm} \]


\[ c.f. \, |d^{(199}\text{Hg})| < 3.1 \times 10^{-29} \text{ ecm} \]


EDM search under \(10^{-28} \text{ ecm}\)
**Principle of EDM measurement**

\[ H = -\mu \cdot B - d \cdot E \]

Energy level of spin \( \frac{1}{2} \) system

\( \mu > 0, \ d > 0 \)

\( m = -\frac{1}{2} \)

\( B = 0 \quad E = 0 \)

\( m = +\frac{1}{2} \)

\[ E = -\mu B - dE \]

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

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

\[ \Delta \nu = \nu_+ - \nu_- = \frac{4dE}{h} \]

\( d = 10^{-28} \) ecm, \( E = 10 \) kV/cm

\[ \Delta \nu = 1 \) nHz \]
How to improve frequency precision?

- Repeat of Free-induction decay (FID) measurements

![Graph of transverse spin]

\[
\delta v_{\text{final}} = \frac{\delta v_{\text{ind}}}{\sqrt{n}} \propto \frac{1}{\sqrt{n}} \frac{1}{T \sqrt{T}} = T^{-1/2} \frac{T_m^{-1/2}}{T_m} \\
T_m = n \times T \\
T_m : \text{measurement time}
\]

- Consecutive measurement of spin precession

![Graph of transverse spin]

\[
\delta v_{\text{final}} \propto \frac{\delta \phi}{T_m} = T_m^{-3/2} : \left[ \text{Fourier width} : \frac{1}{T_m} \right] \times \frac{1}{\left[ \text{data points} : T_m \right]^{1/2}}
\]

Long-term measurement
Nuclear-spin maser (spin-coil coupling)

Static magnetic field: $B_0 \sim G$

Feedback field

Induced current: $I \propto nPQ$

Feedback coil $L$

Capacitor $C$

Pumping light

Oscillation condition

$$\frac{1}{\tau_{RD}} = \frac{1}{2} \gamma^2 \eta \mu_0 \hbar I[n] P_0 Q > \frac{1}{T_2}$$

$\nu \sim \text{kHz} \ (B_0 \sim G)$

Strong coupling between nuclear spin and feedback coil

M. G. Richards et al., JPB 21 (1988) 655: $^3$He spin maser

T. E. Chupp et al., PRL 72 (1994) 2363: $^{129}$Xe spin maser
Transverse polarization transfer: \(^{129}\text{Xe}\) nuclei → Rb atoms (re-pol)
“Active” nuclear-spin maser

“Optically coupled” spin maser
with a feedback field generated by optical spin detection

Maser oscillation at low fields (\(\sim\) mG)
Suppression of drifts in \(B_0\) \(\rightarrow\) Suppression of drifts in \(\nu\)

Maser oscillation of $^{129}$Xe
Setup for maser

Solenoid coil for static field
\[ B_0 = 28.6 \text{ mG} \quad \text{(2.86 \mu T)} \]
\( \Leftrightarrow I_0 = 7 \text{ mA} \)

4-layer magnetic shield
Permalloy

Probe laser
Wave length: 794.76 nm
Width: \( \sim 10 \text{ MHz} \)
Power: 10 mW

Pumping laser
Wave length: 794.76 nm (Rb D1 line)
Width: \( \sim 10 \text{ MHz} \)
Power: 1 W

Gas cell
\(^{129}\text{Xe}, \, ^{3}\text{He}, \, \text{N}_2\)
Rb vapor
GE180 glass

Photo Diode

PEM

\( \frac{\lambda}{4} \) plate

20 mm
Setup for maser

4-layer magnetic shield

Compensation coil

Probe laser

Pumping laser
Long-term frequency drift

Determination precision of averaged frequency

$\Delta \nu \sim 10$ nHz

Long-term frequency drift

Long-term drift in mag. field at cell position

$\delta \nu \sim 1$ mHz

T. Inoue et al., Physica E 43 (2011) 847-850
$^3\text{He co-magnetometer}$
Principle of $^3\text{He}$ co-magnetometer

- Negligible EDM in $^3\text{He}$
- *in situ* magnetometry
- Correlation in phase: $\Phi_{\text{Xe}}(t) = \frac{\gamma_{\text{Xe}}}{\gamma_{\text{He}}} \Phi_{\text{He}}(t)$
Spin polarization of $^3$He

GE180 spherical cell:
Low magnetic impurity
Low leakage of $^3$He

Checked by AFP-NMR measurement

Typically
$P(^3\text{He}) = 3\%$
$T_1(^3\text{He}) = 50\text{ hours}$

at $100\,^\circ\text{C}$
Concurrent operation of $^{129}$Xe/$^{3}$He masers

- Spherical GE180 cell ($^{129}$Xe: 1 Torr, $^{3}$He: 470 Torr, N$_2$: 100 Torr)
- Simultaneous spin detection & individual feedback of $^{129}$Xe/$^{3}$He
- Succeeded in concurrent maser oscillation
- Determination precision of averaged frequencies for $^{129}$Xe/$^{3}$He are both $\sim$100 nHz in $10^6$ sec
- No correlation between $\nu(^{129}\text{Xe})$ and $\nu(^{3}\text{He})$
- Larger drift in $\nu(^{129}\text{Xe})$ than $\nu(^{3}\text{He})$
- Correlated with cell temperature

\[ \frac{\gamma_{\text{He}}}{\gamma_{\text{Xe}}} \sim 3 \]
Frequency shift due to polarized Rb

Frequency shift of $^{129}$Xe/$^3$He
due to contact interaction with polarized Rb

$$\Delta \nu \propto \kappa [\text{Rb}] P_{\text{Rb}}$$

Rb number density  \hspace{1cm} Rb Polarization

Two-body factor $\kappa_0$

$$\begin{cases} \kappa_0 \text{Xe–Rb} = 493(31) \ [1] \\ \kappa_0 \text{He–Rb} = 4.52 + 0.00934T \ [2] \end{cases}$$


Frequency shift due to polarized Rb atoms
can not be removed by $^3$He co-magnetometer
**Double-cell geometry**

Cell is divided into Pumping section & Probe section

\[ \Delta \nu_{\text{Rb}} \propto \kappa [\text{Rb}] P_{\text{Rb}} \]

- Rb number density
- Rb polarization

**Advantages**
- Reduce \( P_{\text{Rb}} \) at probe section
- Different temperature at pumping part & probe part

**Difficulties**
- \( T_1(^{129}\text{Xe}) \) vs diffusion
- Deterioration of maser signal due to reduced \( P_{\text{Rb}} \)
Maser oscillation with double cell

GE180 SurfaSil coated

Xe: 10 Torr/1.33 kPa
He: 470 Torr/62.65 kPa
N$_2$: 100 Torr/13.33 kPa
Rb

1$^{29}$Xe maser oscillation

- $^{129}$Xe maser + $^3$He FID measurements
- Frequency shift is reduced < 1/10 (90 mHz -> 8 mHz)
- Remaining shift due to Rb longitudinal repolarization
EDM measurement
Electric-field application test

- Gas pressure
  - $^{129}$Xe : 1 Torr
  - $^3$He : 470 Torr
  - $\text{N}_2$ : 100 Torr
- GE180
- SurfaSil coated

$^{129}$Xe maser signal @ $E = 5 \text{ kV/cm}$ (Leak current : 70 pA)

![Graph showing sinusoidal waveform for $^{129}$Xe maser signal](image)
First run of EDM measurement using $^{129}$Xe active spin maser + $^3$He co-magnetometer has been conducted.
Future Perspective
To be improved

- Improvement in $^3$He polarization
- Improvement in $T_2$ for $^3$He
- Reduction of Rb longitudinal polarization
Reduction of Rb longitudinal polarization

Linearly polarized laser light is introduced into probe section

- Destroy Rb longitudinal polarization
- Monitor [Rb] through transmission

- Rb transverse polarization survives
Summary

- **Active spin maser**
  - Optical spin detection + artificial feedback
  - Determination precision of averaged frequency: \(~10\ nHz\)

- **Incorporation of \(^3\)He co-magnetometer**
  - Concurrent \(^{129}\)Xe/\(^3\)He maser oscillation
  - Frequency shift due to polarized Rb
  - Double-cell geometry

- **EDM measurement**
  - First trial using active \(^{129}\)Xe maser + \(^3\)He co-magnetometer

- **Future perspective**
  - Improvement in \(^3\)He polarization
  - Improvement in \(T_2\)
  - Reduction of Rb longitudinal polarization