Magnetic Field Stabilization for \(^{129}\text{Xe}\) EDM Search Experiment

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Abstract. Magnetic field stabilization is a crucial condition parameter for many kinds of ultra-high precision measurements such as a search for an electric dipole moment (EDM). The instability of magnetic field strength often arises from the drift of current flow in a solenoid coil to generate the magnetic field. For our EDM search experiment with maser oscillating diamagnetic \(^{129}\text{Xe}\) atoms, we have developed a new stabilized current source based on a feedback system which is devised to correct the amount of current flow measured precisely with high-precision digital multimeter and standard resistor. Using this new current source, we have successfully reduced the drifts of coil current by at least a factor of 100 compared to commercially available current sources.

1. Introduction

Detection of a permanent electric dipole moment (EDM) is one of the most intriguing issues in recent physics studies [1, 2]. A finite value of the EDM along the spin axis is a direct evidence of violation of time-reversal symmetry. The T-violating symmetry would reveal the presence of new physics beyond the standard model. For this purpose, various EDM search experiments are proposed and tried intensively, e.g. in ref. [3-6].

1.1. Principle of EDM measurement

Many of the EDM search experiments proceed in the following way. Here we show the EDM search experiment in the case of diamagnetic atoms with nuclear spin \(I = 1/2\). The atom with spin \(I = 1/2\) in a static magnetic and electric fields \(B_0\) and \(E_0\) both in the same direction acquired an energy \(\varepsilon_{\pm 1/2}\) according to the magnetic substate \(m = \pm 1/2\) in the atom, as

\[
\varepsilon_{\pm 1/2} = \mp (\mu B_0 + dE_0),
\]

where \(\mu\) and \(d\) are the magnetic dipole and electric dipole moment, respectively. The energy splitting \(\Delta \varepsilon = |\varepsilon_{+1/2} - \varepsilon_{-1/2}|\) between the two spin states is measured as a precession frequency \(\nu\) as

\[
\nu = \Delta \varepsilon / \hbar = \frac{(2 \mu B_0 + 2dE_0)}{\hbar}.
\]
When the direction of $E_0$ is reversed, the frequency changes to $\nu' = \Delta \epsilon / h = (2\mu B_0 - 2dE_0) / h$. Then the EDM value $d$ is deduced from the measured difference between the two frequencies $\Delta \nu$ as

$$\Delta \nu = \nu - \nu' = \frac{4dE_0}{h}$$

(see Fig. 1).

When applying $E_0 = 10$ kV/cm, we find that in order to detect an EDM of size $d = 10^{-28} \text{ e cm}$, for example, the experiment should be able to distinguish a frequency change of $\Delta \nu = 1 \text{ nHz}$.

![Figure 1. Energy levels between $m = \pm 1/2$ substate.](image)

1.2. Nuclear Spin Maser Technique

To search for an EDM of a diamagnetic atom with a precision 10 times better than the present limit [3,4], we are developing a new experimental scheme with a precession of $^{129}$Xe atomic spin maintaining by “artificial” nuclear spin maser technique [6,7]. In the case of maser oscillating nuclear spins, the nuclear spins can precess continuously without losing their transverse polarization. Therefore we can measure the frequency of spin maser precession during extremely long period. The long term measurement with continuous precession of nuclear spin is a powerful tool for the search for EDM from the tiny shift of precession frequency. The evaluated frequency precision is improved as the measurement time $\tau$ becomes longer because the frequency uncertainty $\sigma_\nu$ is proportional to $\tau^{-3/2}$.

The experimental procedure of our measurement with the “artificial” nuclear spin maser is as follows. The $^{129}$Xe nuclei (a gas of 79% enriched $^{129}$Xe at 230 Torr) are enclosed in a Pyrex glass cell with Rb vapor (the density of $3.0 \times 10^{11}$ cm$^{-3}$ at the temperature of 333 K) and N$_2$ molecules (a gas of natural N$_2$ at 100 Torr). The $^{129}$Xe nuclei are polarized by spin exchange with spin-polarized Rb atoms [8]. The polarization of Rb atoms are produced by optical pumping with circularly polarized light from a diode laser tuned to the D1 absorption line of Rb atoms (794.7 nm). To prevent the spin relaxation of $^{129}$Xe nuclei due to the collision interaction, the inner wall of the glass cell is coated by SurfaSil [9].

The maser oscillation of nuclear spin arises as applying an oscillating transverse magnetic field to the spin polarized $^{129}$Xe. The phase of the oscillating transverse magnetic field is shifted by 90° to the transverse polarization component of atoms and the amplitude is proportional to the magnitude of the transverse polarization [6]. We have introduced an optical detection method for the $^{129}$Xe nuclear precession by utilizing the spin-exchange interaction between the $^{129}$Xe nucleus and the Rb atomic electron [7]. By feeding artificially the detected precession phase signal back to a coil which produces the oscillating magnetic field to operate the spin maser, continuous nuclear precession of the $^{129}$Xe can be realized. The spin maser with the optical-detection method can oscillate at a low frequency of the spin precession (low static field), contrary to the conventional spin maser which oscillates due to the spin–coil coupling [10,11]. The operation of the spin maser at low static field can be an advantageous
tool for the EDM experiment, because fluctuations and drifts in the applied magnetic field would be smaller for lower field [7].

2. Stabilization of maser frequency with suppressing the fluctuation of magnetic field strength

One of the most essential points to achieve such accuracies is the stability of the magnetic field. In many cases, the instability of maser frequency arises from the fluctuations and drifts of magnetic field strength. As shown in Sect. 1, the precession frequency $\nu$ depends strongly on the applied magnetic field $B_0$. In the case of $^{129}$Xe maser precession, $\nu$ is approximately 35 Hz with $B_0$ of 2.95 $\mu$T. Then the shift of $B_0$ only less than 0.1 pT induces the frequency shifts of 1 $\mu$Hz, which is much larger than the shift of 1 nHz due to effect of EDM (see Sect. 1).

The stability of magnetic field strength is directly governed by drifts of current flow in a solenoid coil to generate the magnetic field. In general, the magnetic field fluctuation is mostly caused by two reasons: a) the drift of current flow in a solenoid coil to generate the magnetic field, and b) the fluctuation of environmental magnetic field. In the case of our maser experiment, the drift of maser frequency caused by the drift of coil current was clearly observed as shown in Fig. 2.

To suppress large drifts of coil current due to the fluctuation of surrounding environments such as room temperatures, we have developed a new stabilized current source based on a feedback system which is devised to correct the amplitude of current flow measured precisely. In this paper, we describe the details of this new current supply system and discuss the stability of it compared to the previous current source.

We used the stabilized current source (Emac Co.Ltd., PSE-1101) for applying the current of 7 mA to the solenoid coil. The coil current was measured with a high precision digital multimeter as a current meter (Keithley Co. Ltd., DMM-2002). The current source has a good stability during a few tens thousands seconds. However, we often observed a large current drift after driving a few tens of thousands seconds. This drift is due to many reasons, such as the drift of environmental temperature. Because this long-term drift reduces the stability of precession frequency, the precision of frequency...
measurement is limited by the stability of current source. So far we have achieved the frequency uncertainty $\sigma_\nu = 10$ nHz with the drift of coil current of 100 nA during 30,000 s measurement [13]. From this result, we estimated that the stability of current source of 50 nA during 1,000,000 s is required for our purpose, specifically the search for the EDM with $d = 1.0 \times 10^{-29} \text{ cm}$ precision.

3. A new stabilized current supply system

Figure 3(a) and (b) shows the schematics of electric circuits in the previous and new current supply system, respectively. Our new stabilized current supply system contains two stabilized current sources (ADC Co. Ltd., Model 6161), a high precision digital multimeter (Keithley Co. Ltd., Model 2002) and a 1 k$\Omega$ standard resistor (Alpha Electronics Co. Ltd., CSR-102). The current sources and the digital multimeter are controlled by a computer. We apply the current to the circuit with the two current sources placed in parallel. One of the current sources [source 1 in Fig. 3(b)] is used to apply the coarse current flow and the other [source 2 in Fig. 3(b)] is used for fine tuning of current flow with the minimum range of current setting. In the current feedback we control the setting value of only the source 2 for reducing the setting range error. The amplitude of current flow is measured as voltage between both ends of the standard resistor using the digital multimeter.

The procedure of current feedback to obtain the required current $I_{\text{req}}$ with the new current source is as follows. The measurement of current flow is carried out at once with each 5 seconds, continuously. After 10 times measurements, the new setting current $I_{\text{set, new}}$ are set up for closing the current flow to the required current $I_{\text{req}}$ as,

$$I_{\text{set, new}} = I_{\text{set, prev}} + (I_{\text{req}} - I_{\text{ave}}),$$

where $I_{\text{set, prev}}$ the previous setting current and $I_{\text{av}}$ an averaged current taken over 10 times measurements. The operation of current feedback mentioned above is carried out by a computer with LabVIEW programming.

Figure 3. a) the schematics of the electric circuit with the previous current supply system, b) that with the new current supply system, c) the time variation of current flow with the previous current source, and d) that with the new current applying system. In c) and d) we shows the time variation during 340,000 s ( ~ 4 days) .
The time variations of current flow with the previous and new system are shown in Fig. 3(c) and (d), respectively. Note that the current fluctuation of approximately 10 nA is mainly due to the fluctuation of the measurement with the digital multimeter. It is also to be noted that in this result we do not take into account the relative accuracy of the digital multimeter itself of less than 50 nA. Even allowing for the large uncertainty of the digital multimeter, one can clearly see the improvement of current stability with the new current supply system. The new current supply system shows the stability of 10 nA fluctuation and less than 1nA (+ less than 50 nA uncertainty from the digital multimeter) drift during longer than 1,000,000 s. This performance is sufficient for our EDM search experiment with the precision of \( \Delta = 1.0 \times 10^{-29} \) em as mentioned in Sect. 2. Note that the performance can be improved by using more accurate current measurement because the performance is limited dominantly by the uncertainty of the digital multimeter.

4. Summary

In summary, we have developed the new stabilized current supply system for the EDM search of diamagnetic \(^{129}\text{Xe}\) atoms. The basis of the current supply system is that; the current flow is measured precisely by the standard resistor and high-precision digital multimeter, and the drift of current flow is corrected by the feedback control with a computer. Using the new current apply system, the fluctuation of current flow is reduced approximately two orders of magnitude than previous current source.

In near future, we will confirm the stability of maser precession frequency of \(^{129}\text{Xe}\) atoms with the new current supply system, and will search for the EDM of \(^{129}\text{Xe}\) atoms precisely, specifically with the precision of \( \Delta = 1.0 \times 10^{-29} \) em or higher.

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