Search for electric dipole moment in ^{129}Xe atom using active nuclear spin maser

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Abstract. An experimental search for an electric dipole moment in the diamagnetic atom ^{129}Xe is in progress through the precision measurement of spin precession frequency using an active nuclear spin maser. A ^{3}He comagnetometer has been incorporated into the active spin maser system in order to cancel out the long-term drifts in the external magnetic field. Also, a double-cell geometry has been adopted in order to suppress the frequency shifts due to interaction with polarized Rb atoms. The first EDM measurement with the ^{129}Xe active spin maser and the ^{3}He comagnetometer has been conducted.

1 Introduction

A permanent electric dipole moment (EDM) of a particle, atom, or molecule is an observable directly violating time reversal symmetry, and hence is sensitive to CP-violating phases beyond the framework of the Standard Model. The EDM of a diamagnetic atom is induced by the Schiff moment of the nucleus, which arises due mostly to CP violation of the nucleon-nucleon interaction. Since the manner in which a nucleus acquires the Schiff moment depends strongly on its nuclear structure, the EDM of diamagnetic atoms should be studied for various nuclear species. The present study aims at measuring the EDM in the diamagnetic atom ^{129}Xe to a size of $|d| = 10^{-28}$ $e$cm, stepping into a domain below the present upper limit, $|d| < 4.1 \times 10^{-27}$ $e$cm [1]. The value of EDM is determined from difference between the frequencies of ^{129}Xe spin precession measured with the electric field applied parallel and antiparallel to a magnetic field. An EDM search to a size of $|d| = 10^{-28}$ $e$cm requires an improvement in the frequency precision down to a level of 1 nHz under an electric field of 10 kV/cm.
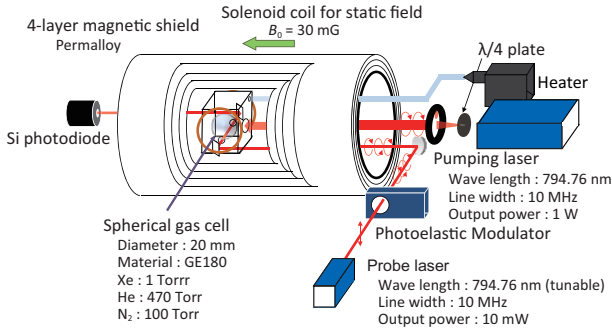
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Figure 1. Schematic view of experimental setup. A gas cell filled with 1 Torr of ^{129}Xe, 470 Torr of ^{3}He, 100 Torr of buffer N_2 gases, and Rb vapor, is contained in a box of which the temperature is monitored. The box is placed in a solenoid coil which generates a static magnetic field $B_0 = 30$ mG, and is enclosed in a 4-layer magnetic shield. A circularly polarized pumping laser is incident on the cell parallel to B_0. A probe laser passes through the cell in a direction orthogonal to B_0 and is detected by a photodiode.

In the present EDM measurement we employ an active nuclear spin maser [2, 3] which enables us to sustain the spin precession of ^{129}Xe over a long measurement duration. The active spin maser operates in the following manner: in an applied static field B_0 the ^{129}Xe spin is longitudinally polarized through spin exchange with Rb atoms which are optically pumped. Once the ^{129}Xe spin starts precession, the spin precession is detected optically through Rb atoms which are transversely polarized. By referring to the precession signal thus obtained, a magnetic field B_{FB} rotating in a plane transverse to the B_0 field is generated such that B_{FB} direction is kept orthogonal to the transverse component of spin. The B_{FB} thus prevents decay of the transverse magnetization. Previous developments of the active spin maser have achieved a determination precision of $\delta\nu = 9.3$ nHz for the average frequency of 36 Hz in a single-shot measurement of 3×10^4 s [3, 4].

2 ^{3}He comagnetometer

In an EDM measurement magnetometry is essential, because a large systematic uncertainty arises from long-term drifts in frequency. The main causes of the long-term drifts are drifts in the external magnetic field and drifts in the frequency shift due to contact interaction with polarized Rb atomic electrons. A comagnetometer using ^{3}He was incorporated into the nuclear spin maser system in order to cancel out the former drifts. By taking advantage of the fact that it directly measures the field that exerts on the ^{129}Xe precession, it is an *in situ* magnetometer.

The ^{3}He comagnetometer has been developed using a gas cell of spherical shape made of GE180 glass with a diameter of 20 mm. The inner surface of the cell is not coated. Using this cell, we typically achieved 3% polarization and over 50 hours of the longitudinal spin relaxation time for ^{3}He at a temperature of 100 °C.

The experimental setup used to test the ^{3}He comagnetometer is shown in Fig. 1. In the operation of the active spin maser with the ^{3}He comagnetometer, the signal from the photodiode is divided into two, each being lock-in-amplified with ^{129}Xe or ^{3}He precession frequency, and the resulting two beat signals are stored in a disk in a computer and at the same time are processed individually to generate their feedback magnetic fields B_{FB} through two separate coils. We succeeded in operating the masers of ^{129}Xe and ^{3}He concurrently, as shown in Fig. 2. The individual determination precisions of the average frequencies for ^{129}Xe and ^{3}He achieved in 10^6 seconds are both ~100 nHz.

The drifts in the frequencies for ^{129}Xe and ^{3}He are shown in Fig. 3 (a) and (b), respectively. There is not seen any correlation between the ^{129}Xe and ^{3}He frequencies. The drifts for ^{129}Xe is dominated by drifts in the frequency shift due to the contact interaction with polarized Rb atoms. The magnitude of the frequency shift is proportional to the product of the Rb polarization and the Rb number density, the latter being given as a function of the temperature. The drifts in the frequency shift could not be
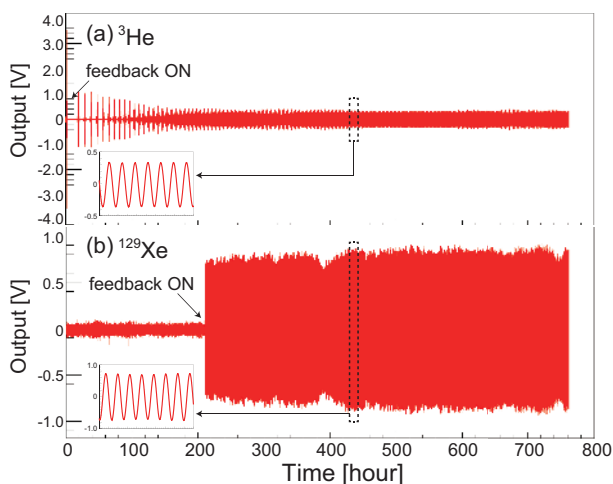
Figure 2. Concurrent maser oscillation of (a) ^{129}Xe and (b) ^{3}He, operated at a temperature of 100 °C. The beat signals lock-in-amplified for ^{129}Xe and ^{3}He were generated upon the reference frequencies of 33.04 Hz and 92.28 Hz, respectively. First the ^{3}He maser was operated. After it went to a steady oscillation mode through a transient mode, the feedback for ^{129}Xe was turned on thus the ^{129}Xe maser oscillation started. Insets in (a), (b) show the steady maser oscillations over a typical period of 100 s.
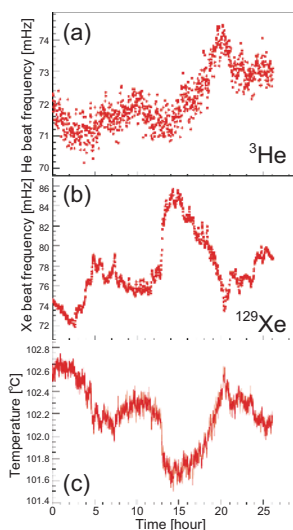

Figure 3. (a) Drifts in beat frequency for ^{129}Xe. (b) Drifts in beat frequency for ^{3}He. In both figures the frequency is obtained by averaging over 100 s. Although the drifts in external magnetic field should be seen in (a) with a magnitude of ~1/3 compared to that in (b) because of the ratio of gyromagnetic ratios, the drifts in (b) is dominated by drifts in the frequency shift due to contact interaction with polarized Rb atoms. (c) Temperature in the box containing the gas cell monitored using a platinum resistance thermometer. Since the Rb number density is given as a function of the temperature, the drifts in the temperature cause drifts in the frequency shift which is proportional to the product of the Rb polarization and the Rb number density.

removed even by the incorporation of the ^{3}He comagnetometer because the strengths of the Rb-^{129}Xe and Rb-^{3}He contact interaction are different from each other [5, 6]: the enhancement factor due to this effect for ^{129}Xe is greater by a factor of ~100 than that for ^{3}He. Actually the drifts in the ^{129}Xe frequency is correlated to the drift in the temperature in the cell box, as shown in Fig. 3 (c).

In order to suppress the frequency shift attributed to the polarized Rb, we then replaced the cell with a new-type one, in which the gas volume is divided into a part for the optical pumping and a part for the optical detection. Such a double-cell geometry enables us to reduce the Rb polarization in the optical detection part and thus to suppress the frequency shift. The inner surface of the double cell was coated by an agent SurfaSil, in order to suppress the spin relaxation of ^{129}Xe at the inner wall and to let the ^{129}Xe atoms pass through the connecting tube with their spin kept polarized. As a result, the active spin maser oscillation of ^{129}Xe with the double cell has been successfully achieved, suppressing the frequency shift down below 1/10 of that obtained with the spherical cell. Details of the development of the active spin maser with the double cell is presented elsewhere [7].

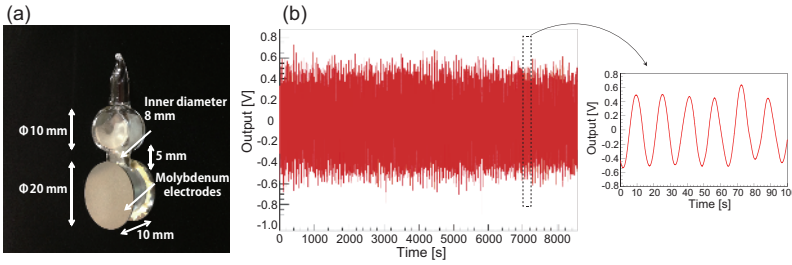**Figure 4.** (a) Double cell used for the EDM measurement. (b) Maser oscillation of ^{129}Xe using the double cell, under an electric field of 1.5 kV/cm. The beat frequency was obtained upon the reference signal of 33.46 Hz.

3 EDM measurement

With the success of the aforementioned development, our EDM measurement for ^{129}Xe using the active spin maser with the ^{3}He comagnetometer has started. For the double cell used in the EDM measurement, electrodes made of Mo for application of an electric field were installed to both sides of the probe part of the double cell, as shown in Fig. 4 (a). For gluing the electrodes, Torr Seal was used. The active maser of ^{129}Xe was operated under an electric field of 1.5 kV/cm with a measured leak current of 620 pA, as shown in Fig. 4 (b). In the present status, because the polarization of ^{3}He in the cell for the EDM measurement is not sufficient, the first EDM measurement has been carried out with maser oscillation of ^{129}Xe and free induction decay of ^{3}He.

4 Summary and outlook

As the first step to employ the ^{3}He comagnetometer in the ^{129}Xe EDM measurement, we have succeeded in operating the active double-species spin masers of ^{129}Xe and ^{3}He. Although drifts in the frequency shift attributing to the polarized Rb atoms is not compensated even by the ^{3}He comagnetometer, the frequency shift has been reduced by a factor of 10 or more by employing the double-cell geometry. Further reduction is expected by introducing a linearly polarized laser into the probe part to destroy the longitudinal repolarization of Rb. Incorporation of the ^{3}He comagnetometer into the double cell may bring out its primary potential to cancel out the long-term drift in the frequency. Consequently a dramatic improvement in the frequency precision is expected by taking advantage of the long measurement duration using the active spin maser. In this work, the first trial of the EDM measurement has been conducted using the ^{3}He comagnetometer. In order to implement an ideal concurrent maser operation with a cell equipped with electrodes, the improvement in the polarization of ^{3}He is necessary. [This work was partly supported by the JSPS KAKENHI (No.21104004 and No.21244029).]

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