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Study of EDM cell with coexisting ^{129}Xe/^{3}He

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Abstract

The ^{3}He comagnetometer which is capable of cancelling out long-term drifts in the external magnetic field is a strong tool in the EDM measurement of ^{129}Xe. In order to realize the ^{3}He comagnetometer for a glass cell with a double-cell geometry which enables us to suppress a frequency shift due to the contact interaction with polarized Rb atoms, the production and relaxation of spin polarization in the cell were studied. Through the developments, we achieved a polarization of 1.04(8)%, longitudinal spin relaxation time of 10.1(5) h, and transverse relaxation time of 2,340 s. This study found out that the performance of the cell is the key of an EDM measurement in ^{129}Xe atom, and solved the problems concerning the cell.

1. Introduction

A permanent electric dipole moment (EDM) of a particle, neutron or atom is an observable directly violating T-invariance, and its size sets limits on CP violating phases beyond the Standard Model through the CPT theorem. For diamagnetic atoms such as ^{129}Xe, an EDM would arise due to CP violating interaction among the nucleons. The present study aims at measuring the EDM in the ^{129}Xe atom 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], by one order of magnitude. The value of EDM is determined from the 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.

In the present EDM measurement system, 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. Using the spin-maser technique, the frequency precision for the spin precession is expected to improve rapidly by taking advantage of observing spin precession for an unlimitedly long time. The previous developments of the active nuclear spin maser have improved the precision of frequency determination to $\delta\nu = 9.3$ nHz for a one-shot measurement [4].

A comagnetometer using ^{3}He is incorporated into the active spin maser system in order to cancel out long-term drifts in the external magnetic field which may give rise to a systematic uncertainty in the frequency. The previous developments have realized the concurrent operation of ^{129}Xe and ^{3}He masers in a spherical gas cell [5]. However, the frequency shift due to contact interaction with polarized Rb atoms could not be removed because the strength of the ^{129}Xe-Rb coupling significantly differs from that of the ^{3}He-Rb coupling [6, 7]. In order to solve this problem,

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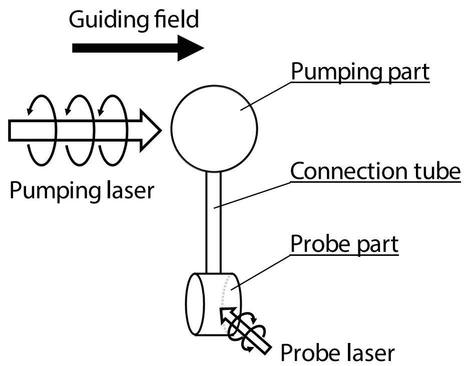

Figure 1: Schematic illustration of a double-cell geometry.

we decide to employ a double-cell geometry [1] in which the gas volume is divided into an optical pumping part and a probe part connected to each other with a connection tube, as shown in Fig. 1. The double-cell geometry reduces the Rb polarization in the probe part and thus suppresses the frequency shift due to contact interaction, because the longitudinal relaxation time of the Rb ($\sim 10^{-3}$ s) is much shorter than the typical diffusion time between a pumping part and probe part ($\sim$ 1 s). Previously we succeeded in the operation of the ^{129}Xe maser using the double-cell geometry [8].

In the present study, the ^{3}He comagnetometer with the double-cell geometry is developed. The amplitude of the maser oscillation operated with optimum feedback field is described as

$$V_{\mathrm{maser}} \propto P \times \sqrt{\frac{T_2}{T_1^*}} \tag{1}$$

where P is the polarization, T_1^* and T_2 are the effective longitudinal and transverse spin relaxation times, respectively. There are two main difficulties to realize the ^{3}He comagnetometer with the double-cell geometry. One is the low polarization P of ^{3}He because the spin-exchange rate between ^{3}He and Rb is lower than that between ^{129}Xe and Rb by several orders of magnitude. Another difficulty concerns T_2, which can be easily shortened due to inhomogeneities of the external magnetic field. In the case that T_2 is much shorter than T_1^*, the amplitude of the maser signal will be reduced. Furthermore, a possible reduction of the signal at the optical detection of spin precession with the double-cell geometry [8] should be taken care of. The improvements of P and T_2 brought by the design of the double-cell geometry are described in Section 2 and Section 3, respectively.

2. Polarization and longitudinal spin relaxation

In realizing the ^{3}He comagnetometer, the geometry and the fabrication method for the double cell are of key importance, because they affect the polarizations of both ^{129}Xe and ^{3}He. The polarization of ^{129}Xe at the probe part diminishes as it passes through the connection tube, since the longitudinal relaxation time for ^{129}Xe is rather short. On the other hand, the polarization of ^{3}He may be reduced because of a coating agent employed to suppress the ^{129}Xe relaxation. In order to find the best suited geometry and fabrication method for the cell, the polarization P and the longitudinal spin relaxation time T_1^* were studied by means of the adiabatic fast passage NMR (AFP-NMR) method.

First, the reduction of the ^{129}Xe polarization in the connection tube was evaluated using a double cell with the following geometrical parameters: a sphere 20-mm in diameter for the pumping, a cylinder 15-mm in diameter, 10-mm in length for the probe part, and a tube 15 mm long and 6 mm in inner diameter connecting the two parts. The double cell was enclosed in a box in which the temperature is controlled by hot air blowing. A circularly polarized laser light from a taper-amplified DFB laser with a power of 0.7 W, a mean wavelength of 794.76 nm, and a line width of 10 MHz, illuminated the pumping part of the double cell through a transparent window of the box. An rf field with a frequency of 34.2 kHz was applied using a couple of coils surrounding the box. The static magnetic field applied by a solenoid was swept, with the AFP condition being kept satisfied. The NMR signals of ^{129}Xe were obtained both at the pumping part and at the probe part, using pickup coils installed around the respective parts of the double cell. The spin relaxation time T_1^* was also measured, from which evaluation was made of the spin relaxation taking place during the diffusion in gas. The reduction factor for the ^{129}Xe polarization in this geometry was evaluated to be 0.6 by comparing the above two NMR signals with correction for the spin relaxation. We note that the inner surface of the

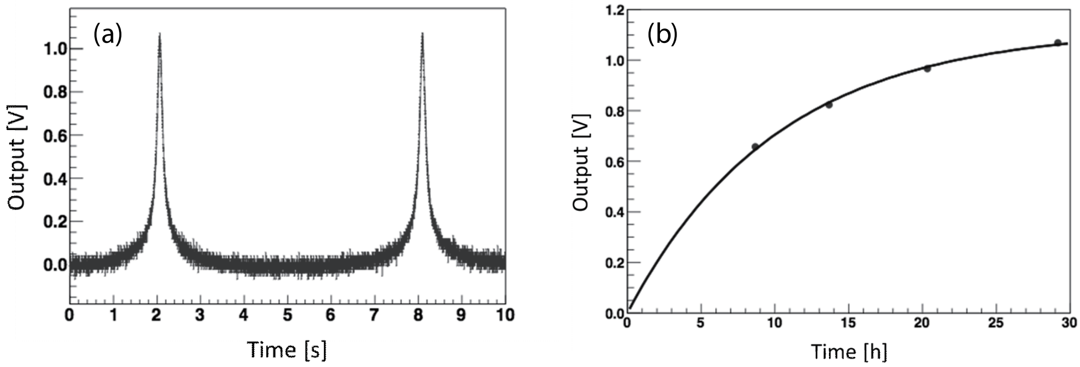

Figure 2: (a) AFP-NMR signal for ^{3}He. (b) Production Build-up of the ^{3}He spin polarization produced by the spin-exchange optical pumping method. Both data were obtained with a cell containing 1 Torr of ^{129}Xe, 425 Torr of ^{3}He and 100 Torr of N_2.

cell was not coated with any agent, because the depolarization of ^{129}Xe is dominated by contact with unpolarized Rb vapors but not by wall relaxation under temperatures around 80 °C, while the depolarization of ^{3}He is more than 10 times enhanced by wall relaxation at the coated surface.

Next, the polarization of ^{3}He achievable under various partial pressures of ^{129}Xe was studied. A spherical single cell of 20 mm in diameter was used, because T_1^* of ^{3}He is in any case much longer than the diffusion time, resulting in a very homogeneous distribution of P over the cell. The results obtained for the polarization and spin relaxation time for ^{3}He are: $P = 1.04(8)\%$ and $T_1^* = 10.1(5)$ h for a cell containing 1 Torr of ^{129}Xe; $P = 0.18(1)\%$ and $T_1^* = 4.63(1)$ h for a cell containing 10 Torr of ^{129}Xe; both of which contained 425 Torr of ^{3}He and 100 Torr of N_2, at 80 °C. The NMR singal and the build-up curve for the spin polarization obtained with the 1-Torr cell are shown in Fig. 2 (a) and (b), respectively. Although the wall relaxation changes cell by cell, the difference in the obtained T_1^* may imply possible importance of the interaction between ^{129}Xe and ^{3}He spins. The small polarization P obtained in the 10-Torr cell is presumably due both to the short T_1^* and to the laser power exhaustion in polarizing ^{129}Xe. Indeed, the Rb polarizations were measured to be 95(1)% and 66(1)% for the 1-Torr and 10-Torr cells, respectively.

By taking into account the above results of the AFP-NMR measurements, details of the double cell and partial pressures should be determined in order to achieve ^{129}Xe and ^{3}He polarizations high enough for the concurrent maser operation. In terms of the ^{3}He polarization, the partial pressure of ^{129}Xe should be suppressed down to a level of 1 Torr. The length of the connection tube suited for 1-Torr ^{129}Xe was evaluated to be less than 15 mm, by considering the NMR pulse height, reduction of polarization in the tube, and the expected diffusion time.

3. Transverse spin relaxation

The transverse spin relaxation time T_2 was measured using the cell with a 15-mm long tube by means of the observation of free induction decay (FID) after application of an RF pulse. In the FID measurement, the static field was generated using a coil composed of four short solenoids [9], which was so designed that the gradient of the magnetic field $B_0 = 30$ mG was less than 30 μG/cm (i.e. a relative gradient of 10^{-3}) in a region within 35 mm from the center position of the coil, corresponding to the center of the probe part of the cell. The coil was surrounded by a triple-layer magnetic shield with a shielding factor larger than 10^4. The optical setup was the same as that described in Ref. [10]. The FID signals obtained in a measurement made at $B_0 \approx 30$ mG and $T = 90$ °C are presented in Fig. 3. T_2 for the cell with a 15-mm long tube was measured to be 13 s, as shown in Fig. 3 (a).

The short T_2 is considered to be due to gradients in the magnetic field in the double-cell volume. The pumping part of the cell with the 15-mm tube extends out from the region where the gradient of the magnetic field is kept below 30 μG/cm. Since $T_1^* \sim 10$ h for ^{3}He is much longer than the time scale for ^{3}He to travel between the pumping part and the probe part of the double cell, the coherence of ^{3}He spin will be destroyed during the travel in a region of larger field inhomogeneities. Therefore the double-cell geometry should be designed with special care taken for the field gradients over the whole volume of the double cell. The coil was designed to assure the gradient better than 30 μG/cm in a region within 35 mm from the center along the radial direction as mentioned above. Thus the length of the connection tube should be shorter than 5 mm, a more demanding requirement than that discussed in Sec. 2. The FID signal was measured also for a cell with a 5-mm long tube, where B_0 was changed to approximately 10 mG.

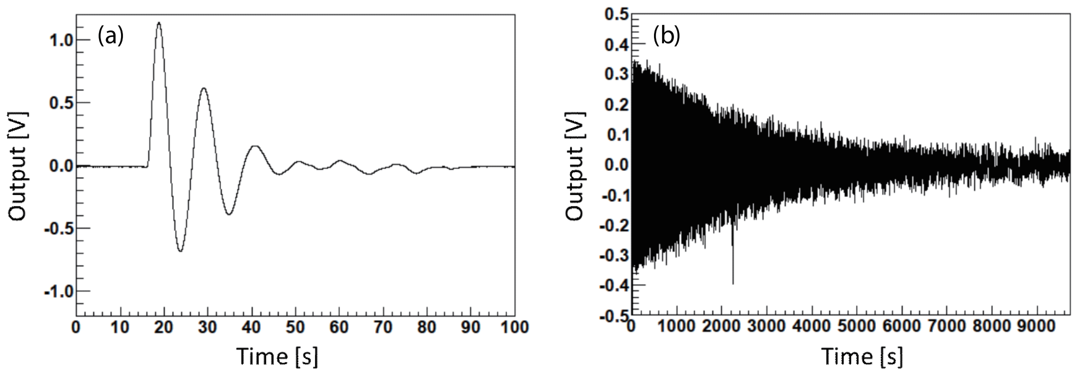

Figure 3: (a) FID signal of ^{3}He obtained for a cell with 15-mm long tube. (b) FID signal of ^{3}He obtained for a cell with 5-mm long tube.

T_2 was determined to be 2,340 s, as shown in Fig. 3 (b), achieving a two orders of magnitude improvement from the previous cell.

4. Summary and future perspective

In order to realize the ^{3}He comagnetometer with a double-cell geometry, the production and relaxation of spin polarization in the double cell containing both ^{129}Xe and ^{3}He were studied. Through the AFP-NMR measurements, we find that the appropriate partial pressure of ^{129}Xe lies around 1 Torr, which allows suppression of the ^{3}He spin relaxation arising from possible interaction with ^{129}Xe spin and at the same time keep the ^{129}Xe magnetization large enough to be detected. We achieved the polarization of 1% and the longitudinal spin relaxation time of 10 h for ^{3}He. It was also found out that the double-cell geometry was important to improve the transverse spin relaxation time T_2. Using the cell whose volume fell into a region of good field homogeneity, we achieved the transverse spin relaxation time of 2,340 s. The results of this study indicate that the performance of the cell is of key importance in the EDM measurement. Indeed, we have succeeded in a concurrent maser operation of ^{129}Xe and ^{3}He using the cell developed in the present study [10, 11]. The ^{3}He comagnetometer with a double-cell geometry is expected to bring its primary potential into play in cancelling out the long-term drifts in the external magnetic field without suffering from frequency shifts due to polarized Rb. In future, the production and relaxation of spin polarization will be studied for a cell to which electrodes to apply an electric field in the EDM measurement are attached. The EDM measurement will be started shortly using a cell designed based on the result of this study.

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