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Co-magnetometry with ^{129}Xe/^{3}He dual active spin maser technique

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Abstract

The precision of our EDM search on ^{129}Xe using a technique of active spin maser is currently limited by drifts in the external magnetic field. Co-magnetometry using a ^{3}He spin maser provides conceptually the best suited scheme to eliminate systematic errors originating from the field drifts, but in practice shows a non-negligible shortcoming when the frequency shift due to longitudinal polarization of the coexisting Rb atoms is significant. In order to utilize the ^{3}He co-magnetometry by reducing the frequency-shift effects, a dual-species maser operation with ^{129}Xe and ^{3}He in a double-cell geometry is studied. An attempt is made to eliminate the longitudinal Rb polarization by irradiating the Rb atoms with a linearly polarized laser light. In the present article, the developments and the present status concerning the ^{129}Xe/^{3}He dual spin maser are reported.

1. Introduction

A permanent electric dipole moment (EDM) of a particle is defined as a polarization in the charge distribution of the particle along its spin axis. A non-zero EDM violates the time reversal symmetry and hence the CP symmetry under the CPT theorem. The size of EDM predicted within the Standard Model (SM) of elementary particles is nondetectably small. On the other hand, a number of theories beyond the SM predict sizable EDMs, which may be reachable by improved experiments. Therefore the search for EDM would constitute the exclusive means to shed light on physics beyond the SM.

The goal of our study is to search for the ^{129}Xe EDM in the region of 10^{-28} $e$cm, beyond the current upper limit of 4.1×10^{-27} $e$cm [1]. In the present study, the technique of active spin maser with an artificial feedback [2, 3] is used to elongate the spin precession permanently, which helps us reach the extremely high precision for the spin precession frequency. Previously, the precession frequency averaged over a 3×10^{4} s measurement time has been determined to a precision of $\delta\nu = 9.3$ nHz. A large systematic uncertainty, however, arises on the EDM value from the long-term drifts in the external magnetic field, setting a limit on the precision. For the magnetometry in our EDM study, a co-magnetometer using ^{3}He was employed. In order to implement the ^{3}He co-magnetometer, ^{3}He and ^{129}Xe are confined in the same volume of the gas cell. The ^{129}Xe precession frequency contains contributions from both the magnetic field and the EDM, while the ^{3}He one only contains the contributions from the magnetic field. Note that the EDM of ^{3}He is assumed to be negligible compared to that of ^{129}Xe because of the difference of the atomic numbers Z. The ^{129}Xe EDM is extracted from the observed difference in the phase evolutions between the ^{129}Xe and ^{3}He masers.

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It was found that there was another source of frequency uncertainty, which was caused by drifts in the frequency shift due to contact interactions between the ^{129}Xe/^{3}He spin and the longitudinally polarized Rb spin [4]. The frequency shift is proportional to the longitudinal polarization and number density of Rb atoms which exist in a form of vapor in the cell and assume indispensable roles in the optical pumping and in the optical detection of spin precession [5]. The drifts in the frequency shift, presumably arising from drifts in the cell temperature, can not be removed by the ^{3}He co-magnetometer alone, because there is a hundredfold difference between the strengths of Rb-^{129}Xe and Rb-^{3}He couplings [6, 7]. In order to reduce the effect arising from the longitudinal polarization of Rb atoms, a double-cell geometry was employed for the gas cell, where the cell is divided into two sections: the pumping section to polarize noble gases and the probe section for the maser operation. Although the double-cell geometry has proven to enable us reducing the Rb longitudinal polarization by factor of 10 or more from the case with a single-cell geometry, the shift still remains to be observed, which we consider to stem from the longitudinal repolarization of Rb atoms produced through collisions with the polarized ^{129}Xe or ^{3}He [5].

The present study proposes a scheme to operate the dual-species maser of ^{129}Xe and ^{3}He with the double-cell geometry, thus reducing the frequency shift duel to the polarized Rb. An attempt is made to reduce the longitudinal polarization of Rb atoms.

2. Developments for ^{3}He co-magnetometry with double-cell geometry

In order to realize the ^{3}He maser in the double-cell geometry, increase of signal-to-noise ratio is necessary. This is achieved by the increase of the polarization and/or by the elongation of the transverse spin relaxation time of ^{3}He.

The amplitude of maser signal is proportional to the magnetization, i.e. the product of the partial pressure and polarization. The polarization of ^{3}He is reduced under the co-existence of ^{129}Xe. This is due to the interaction between the ^{129}Xe and ^{3}He spins and to the exhaustion of the laser power in polarizing the ^{129}Xe spins. Thus, the decrease of ^{129}Xe partial pressure leads to the increase of ^{3}He polarization. The magnetizations of ^{129}Xe and ^{3}He should be compromised. For example under a ^{3}He partial pressure of 425 Torr and a temperature of 80 °C, we found [8] that the decrease of the ^{129}Xe partial pressure from 10 Torr to 1 Torr brought about a factor of five increase of ^{3}He polarization from $P(\mathrm{He}) = 0.18(1)$ % to 1.0(1) %, thus realizing five times increased ^{3}He magnetization while keeping the ^{129}Xe magnetization at a level sufficient for maser operation.

In the operation of the maser, the precession signal is observed through the transverse component of the magnetization. In other words, for the stable maser operation, the magnetization should be tilted enough from the B_0 axis in an angle large enough for the precession to be detected. The angle of inclination is proportional to $\sqrt{T_2/T_1^*}$, where T_1^* is the effective longitudinal spin relaxation time and T_2 the transverse spin relaxation time. Since T_1^* of the ^{3}He is typically 10 hours, T_2 should be as close to T_1^* as possible, otherwise the observation of the transverse component of ^{3}He magnetization becomes difficult due to its small tilt angle. In order to improve the homogeneity of the magnetic field which will reduce T_2 of ^{3}He significantly, we newly constructed a magnetic shield and a B_0-field coil set [9]. The magnetic shield has a three-layer structure, each layer being a 2 mm-thick Permalloy cylinder with end caps each having a 15mm-diameter hole at the center. The sizes of the individual cylinders are 800-mmϕ × 1300 mm, 600-mmϕ × 1000 mm and 400-mmϕ × 680 mm. Residual field inside the shield was measured to be a few tens of μG, the shielding factor being larger than 10^4. The B_0-field coil set is composed of four short solenoid coils, and is installed inside of the innermost layer of the shield. The field gradient was measured to be 5 μG/cm within a spatial region of ±10 mm from the center when the coils are exited to produce a static field B_0 of 28.9 mG at the center.

In addition to the above improvement, an attempt to reduce the longitudinal polarization of Rb atoms is made, in which a linearly polarized laser light is used to irradiate the probe section of the double cell in the B_0 direction. The optical spin detection in the presence of the linearly polarized laser light should be checked.

In order to confirm the scheme of optical spin detection as well as to check T_2 of ^{3}He, free induction decay (FID) measurements for ^{3}He were performed. The schematic view of the experimental setup is shown in Fig. 1 (a). The cell used in the measurements was made of GE180 glass and had the following double-cell geometry, designed based on the results of Ref. [8]: a spherical pumping section of 20 mm in diameter, a cylindrical probe section of 15 mm in diameter and 10 mm in length, connected by a transfer tube 5 mm long and 8 mm in inner diameter. The cell contained 1 Torr of ^{129}Xe, 425 Torr of ^{3}He and 100 Torr of N_2. The cell was installed in a box inside of which the temperature was controlled to be 97 ± 1 °C at the pumping section and 85 ± 1 °C at the probe section by heated air blowing.

The box was placed at the central position of the coils. The coil generated a static magnetic field of $B_0 \sim 10$ mG. A 795 nm light beam from a TA-DFB laser, TA-100 (TOPTICA), was divided into two. One was circularly polarized and introduced to the pumping section in the B_0 direction with a power of 1.0 W, while another was linearly polarized and introduced to the probe section also in the B_0 direction with a power of 0.3 W. The probe light from a laser DL100, (TOPTICA, 795 nm, 10 mW), was transported to pass across the probe section in a direction orthogonal to B_0 and was detected by a photodiode. The signal from the photodiode was lock-in amplified with a reference signal set close to the ^{3}He precession frequency, and the resulting beat signal was recorded on a computer. The FID signal was observed even in the presence of the linearly polarized laser light, as shown in Fig. 1 (b). In this measurement, a T_2 of 2340 sec was achieved for ^{3}He, which was about 100 times better as compared to that obtained using the previous setup.

As a result of above improvements, the polarization of the ^{3}He is increased by a factor of five and the T_2 of ^{3}He is elongated by a factor of hundred. Thus, the ^{3}He maser signal is expected to become 500 times larger than before, which should overwhelm noises and allow us to operate the maser.

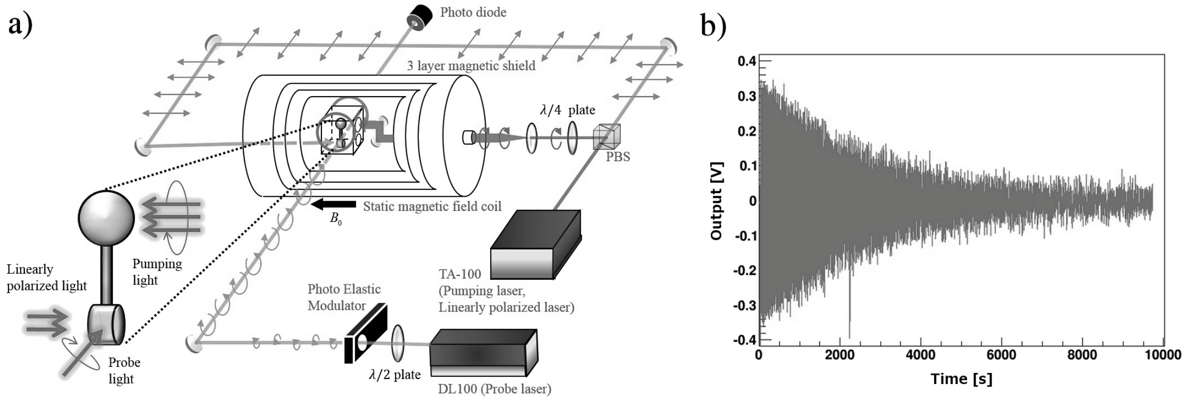

Figure 1: (a) Schematic view of the experimental setup. The presentation of the optical system is partly contracted. Laser light emitted from a TA-DFB laser is split by using $\lambda/2$ plates and PBSs. One of the two split light beams is converted to a circularly polarized light by a $\lambda/4$ plate so as to produce the Rb polarization in the pumping section. Another light beam is converted to a linearly polarized light by a Glan laser prism in order to reduce the longitudinal Rb polarization in the probe section. (b) FID signal for ^{3}He spin obtained with an irradiation of the probe section of the cell, with a 250 mW linearly polarized laser light.

3. ^{3}He/^{129}Xe dual spin maser with double-cell geometry

Using the improved static magnetic field and optimized maser cell described above, the first trial of the dual-species maser of ^{129}Xe/^{3}He was made. The experimental setup was the same as in the FID measurement except that a feedback circuit for the maser operation was added. In the operation of the active dual spin maser, the signal from the photodiode is divided into two, each being lock-in amplified with a reference signal close to the ^{129}Xe or ^{3}He precession frequency, and the resulting two beat signals are recorded and at the same time are processed individually to generate their feedback magnetic fields through two separate coils. In this measurement, the pumping section was irradiated with the circularly polarized pumping light with a power of 1.0 W. The probe section was irradiated with the linearly polarized light with a power of 0.2 W. Thus, we succeeded in operating the dual-species maser of ^{129}Xe and ^{3}He as shown in Fig 2. It should be noticed, however, that the maser signal amplitudes were not stable, presumably due to the low signal-to-noise ratio and instability of the cell temperature. This will be improved by refining the maser parameters such as the feedback field amplitudes, temperatures and gas partial pressures. Analysis on the correlation of frequencies between ^{129}Xe and ^{3}He is in progress.

4. Summary and future aspect

The co-magnetometry based on the dual-species maser of ^{129}Xe and ^{3}He was developed in order to reduce systematic uncertainty arising from the drifts in the external magnetic field. The optimization of the partial pressure

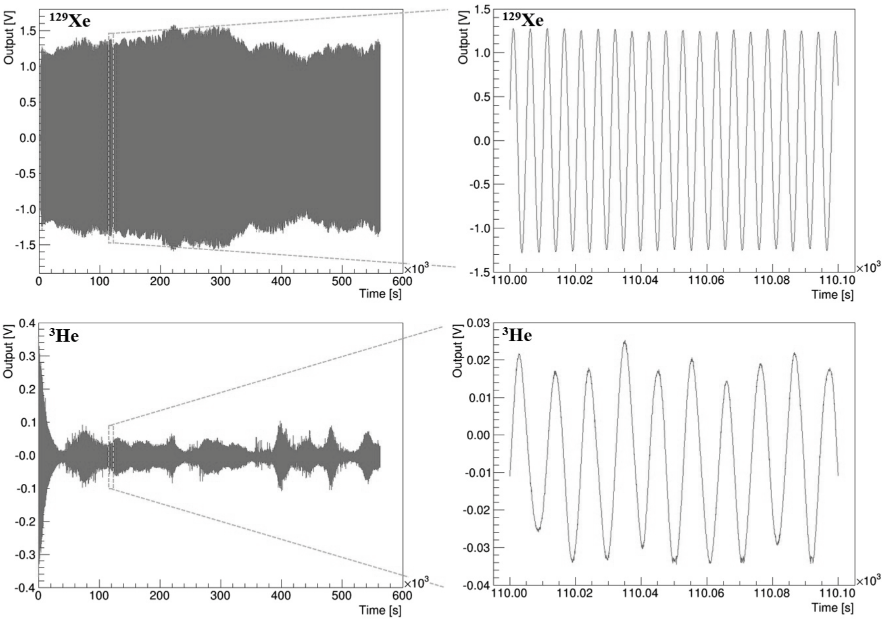

Figure 2: Maser oscillations of ^{129}Xe (upper panels) and ^{3}He (lower panels), operated at a temperature of 84 °C. The reference frequencies for the lock-in amplifiers were 11.38 Hz for ^{129}Xe and 31.39 Hz for ^{3}He. Right two panels show closeups of the maser oscillations from a typical 100 sec period.

of ^{129}Xe was studied in order to improve the polarization of ^{3}He. A three-layer magnetic shield and coils for the static magnetic field were developed in order to elongate the transverse spin relaxation time of ^{3}He. In addition, a linearly polarized laser light was introduced to the probe section in order to reduce the longitudinal polarization of Rb atoms. Combining these improvements, the FID signal of ^{3}He was observed. The amplitude of the FID signal and the transverse relaxation time of ^{3}He were significantly improved. As a result, the first trial of the dual-species maser of ^{129}Xe and ^{3}He with double-cell geometry was successfully made. Further stable operation of the dual-species masers will be achieved by refining the maser parameters. For the next step, validity of the ^{3}He co-magnetometer should be examined. This will be done by analysis of frequencies of the dual-species maser.

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References

[1] M. A. Rosenberry *et al.*, Phys. Rev. Lett. **86**, 22 (2001).
[2] A. Yoshimi *et al.*, Phys. Lett. A **304**, 13 (2002).
[3] A. Yoshimi *et al.*, Phys. Lett. A **376**, 1924 (2012).
[4] Y. Ichikawa *et al.*, EPJ Web of Conf. **66**, 05007 (2014).
[5] E. Hikota *et al.*, EPJ Web of Conf. **66**, 05005 (2014).
[6] Z. L. Ma *et al.*, Phys. Rev. Lett. **106**, 193005 (2011).
[7] M. V. Romalis *et al.*, Phys. Rev. A **58**, 3004 (1988).
[8] Y. Ohtomo *et al.*, Proceedings of FPUA2014 (this proceedings).
[9] Y. Sakamoto *et al.*, Proceedings of FPUA2014 (this proceedings).