**Double-cell Geometry For $^{129}$Xe/$^3$He Co-magnetometry**

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Comagnetometers play a key role in EDM experiments. They allow one to quantify, and subsequently correct for, any long-term drifts of the external magnetic field. In order to improve the performance of the $^3$He comagnetometer for our $^{129}$Xe EDM measurements, we have decided to incorporate a double-cell geometry which enables us to suppress a frequency shift due to contact interaction with polarized Rb atoms. In this study, the production and relaxation of $^3$He spin polarization in the double cell were studied. As a result, the followings were achieved: a polarization of 1.04(8)% and a transverse relaxation time of 2,340 s. With these improvements, concurrent operation of the $^{129}$Xe and $^3$He masers has been realized, and EDM measurement will be started in near future using a cell designed based on the results of this study.

**KEYWORDS:** EDM, Polarization, NMR

1. **Introduction**

According to the astrophysical study, the baryon asymmetry in the present universe is much larger than that predicted from the CP-violation in the Standard Model (SM). The permanent electric dipole moment (EDM) of a particle, neutron or atom has attracted much interest as a clear evidence for the possible existence of extra CP-violation. An EDM violates T-invariance, and its size sets limits on CP-violating phases beyond the SM. For diamagnetic atoms such as $^{129}$Xe, which is the target of our study, 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 \(|d| = 10^{-28}\) ecm, beyond the present upper limit of \(4.1 \times 10^{-27}\) ecm [1]. 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 \(|d| = 10^{-28}\) ecm requires an improvement in the frequency precision down to a level of 1 nHz under an electric field of 10 kV/cm.

A comagnetometer using \(^3\)He is incorporated into the active spin maser system [2, 3] in order to cancel out long-term drifts in the 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 cell [4]. 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 [5, 6]. In order to solve this problem, we employ a double-cell geometry [1], with a separate optical pumping cell connected to a probe cell by a narrow tube, as shown in Fig. 1. The double-cell geometry reduces the Rb polarization in the probe cell and thus suppresses the frequency shift due to contact interaction, because the longitudinal relaxation time of Rb (\(\sim 10^{-3}\) s) is much shorter than the diffusion time between a pumping cell and probe cell (\(\sim 1\) s).

Previously we succeeded in the operation of the \(^{129}\)Xe maser using the double-cell geometry [7]. In the present study, a \(^3\)He comagnetometer with the double-cell geometry is developed. The amplitude of the maser oscillation operated with optimum feedback field is described as

\[
V_{\text{maser}} \propto P \times \sqrt{\frac{T_2}{T_1^*}}
\]  

(1)

where \(P\) is the polarization, \(T_1^*\) and \(T_2\) are the effective longitudinal and transverse spin relaxation time, 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 for the optical detection of spin precession with the double-cell geometry [7] should be taken into account.

2. Improvement of \(^3\)He polarization

For the improvement of the \(^3\)He polarization, the geometry and the fabrication method for the double-cell are of key importance. The polarization of \(^{129}\)Xe at the probe cell 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 [8].

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 $^\circ$C. 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. Furthermore, we note that the inner surface of the 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 $^\circ$C, while the depolarization of $^3$He is more than 10 times enhanced by wall relaxation at the coated surface.

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 for 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.

3. Improvement of Transverse spin relaxation time of $^3$He

The transverse spin relaxation time $T_2$ was measured using the cell with a 15-mm long tube by means of free induction decay (FID) technique [9]. In the FID measurement, the static field was generated with a coil composed of four short solenoids [10], which was designed so that the gradient of the magnetic field $B_0 = 30$ mG was less than 30 $\mu$G/cm (i.e. a relative gradient of $10^{-3}$ cm$^{-1}$) in a region within 35 mm from the center position of the coil, corresponding to the center of the probe 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. [11]. The FID signals obtained in a measurement made at $B_0 = 10$ mG and $T = 90$ $^\circ$C are presented in Fig. 2. $T_2$ for the cell with a 15-mm long tube was measured to be 13 s, as shown in Fig. 2 (a).

The short $T_2$ is considered to be due to gradients in the magnetic field in the double-cell volume. The pumping cell of the cell with the 15-mm tube protrudes from the region where the gradient of the magnetic field is kept below 30 $\mu$G/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 cell and the probe 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 certificate the relative gradient of $10^{-3}$ 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. The FID signal was measured also for a cell with a tube length of 5 mm at $B_0 = 10$ mG and $T = 90$ °C, and $T_2$ was determined to be 2,340 s, as shown in Fig. 2 (b), achieving a two orders of magnitude improvement from the previous cell.

4. Summary and future perspective

The $^3$He comagnetometer with a double-cell geometry is expected to bring its primary potential to cancel out the long-term drifts in the external magnetic field without suffering from frequency shifts due to polarized Rb. In this study, the production and relaxation of spin polarization in the double cell containing both $^{129}$Xe and $^3$He were studied, in order to realize dual-species maser of $^{129}$Xe and $^3$He with a double-cell geometry. Through the AFP-NMR measurements, we found that the most 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 while keeping at the same time the $^{129}$Xe magnetization large enough to be detected. As a result, we achieved the polarization of 1.04(8)% and the longitudinal spin relaxation time of 10.1(5) h for $^3$He. It was also found out that the transverse spin relaxation time depends on detailed geometry of double cell. Using the cell whose volume fell into a region of good field homogeneity, we achieved the transverse spin relaxation time of 2,340 s, which is a two orders of magnitude improvement. Consequently, we have succeeded in a concurrent maser operation of $^{129}$Xe and $^3$He using the cell designed based on the results of this study [11, 12].

For the next step, the production and relaxation of spin polarization should be studied using a cell to which electrodes to apply an electric field in the EDM measurement are attached. The parameters of a cell equipped with electrodes such as bonding method and material of electrodes must be optimized for the $^{129}$Xe-EDM measurement to the order of $10^{-28}$ ecm.

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