Development of high-sensitivity NMOR magnetometry for an EDM experiment

T. Nanao\textsuperscript{a}, A. Yoshimi\textsuperscript{b}, T. Inoue\textsuperscript{a}, T. Furukawa\textsuperscript{a}, M. Tsuchiya\textsuperscript{a}, H. Hayashi\textsuperscript{a}, M. Uchida\textsuperscript{a}, K. Asahi\textsuperscript{a}

\textsuperscript{a}Department of Physics, Tokyo Institute of Technology
S5-412, 2-12-1, O-okayama, Meguro, Tokyo 152-8551, Japan

\textsuperscript{b}RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

E-mail:nanao@yap.nucl.ap.titech.ac.jp

Abstract. Developments are in progress aiming at the search for a permanent Electric Dipole Moment (EDM) in $^{129}$Xe atom using a low-frequency nuclear spin maser. In the EDM experiment, drifts in the applied static magnetic field in a long time scale are the dominating source of errors in frequency determination. The stability of the applied field and its monitoring by use of a high sensitivity magnetometer are thus the indispensable part of the EDM experiment. We are developing a magnetometer based on the Nonlinear Magneto-Optical Rotation (NMOR) effect in Rb atom. The sharp response to the magnetic field in this apparatus relies on a long relaxation time of the atomic spin alignment induced by linearly polarized laser light, and thus the suppression of the atomic decoherence should be essential for its sensitivity. Coating the inner walls of the cell with an antirelaxation layer, introducing a buffer gas in the cell and cancelling the transverse magnetic field should be effective in preventing atoms from depolarization. We obtained several NMOR spectra for Rb in cylindrical cells in such attempts. Up to now a sensitivity of $\delta B = 1.5 \times 10^{-5}$ G has been attained in the present setup.

1. Magnetometry for the EDM experiment
Permanent Electric Dipole Moment (EDM) of a particle, if non-zero, would be unavoidable evidence for the violation of time reversal symmetry, and hence of CP-symmetry through the CPT theorem. Predicted sizes of EDM in the standard model (SM) are too small to be detected, whereas measurable
values are predicted in theories beyond the SM. Thus, the EDM should constitute an exclusively useful tool to search for physics beyond the SM.

We attempt to search for an EDM in $^{129}$Xe atom by using a low-frequency nuclear spin maser [1]. In this method, a static magnetic field $B\sim 30$ mG and an electric field $E\sim 10$ kV/cm are applied, and precision measurements of the Larmor frequency are performed both with the $B$ and $E$ fields parallel and antiparallel to each other. A coupling of the spin to the $E$ field through an EDM shifts the frequency of the spin precession, and thus the EDM effect manifests itself as a difference in the Larmor frequency between these two configurations for $E$ and $B$ fields. In such a situation, slight drifts in the $B$ field strength may cause serious spurious signals, because the spin to $B$ field coupling through the magnetic dipole moment is enormously stronger. For example, a field drift of about 1 μG causes a 1 mHz change in the Larmor frequency. In order to pursue a high-sensitivity search for EDM in a 1 nHz level or better, such drifts must be avoided by carefully studying/monitoring the stability of the applied magnetic field.

We are developing a high-sensitivity magnetometer based on the Nonlinear Magneto-Optical Rotation (NMOR) effect [2]. The NMOR is a phenomenon in which the plane of polarization of a linearly polarized light is rotated during the passage through a Rb vapor under an external magnetic field. The advantages of this method are as follows: (1) it operates at room temperature, (2) it is applicable to fields in a ~10 mG level, and (3) it is easily adapted to the Xe maser system. In this paper, we report on the current status of the NMOR magnetometer under development by us.

![Figure 1](image-url). Illustration of the NMOR effect. Red arrow represents the axis of polarization plane for the laser light, while blue arrow shows the alignment of Rb atom.

2. NMOR magnetometry

Magnetometry using the NMOR effect has been pioneered by Budker et al. [2, 3]. Physical process involved in the NMOR can be divided into three stages (Fig. 1). In the first stage the Rb atoms are pumped into an alignment state by the incident linearly polarized laser light, with the alignment axis parallel to the polarization plane of the incident light. Then in the second stage, spins of Rb atoms execute precession around the external magnetic field, leading to a rotation of the alignment axis. As a result, in the third stage the polarization plane of the light is rotated because of the stronger absorption of the polarization component orthogonal to the alignment axis as compared to the parallel polarization component (linear dichroism).

The resulting rotation angle $\phi$ shows the following dependence on the magnetic field $B$.

$$\phi = \frac{l}{l_0} \frac{2g\mu B/h\Gamma}{(2g\mu B/h\Gamma)^2 + 1}$$

(1)

Here $g$ denotes the Lande’s $g$-factor, $\mu$ the Bohr magneton, $l$ the length of interaction area, $l_0$ a constant, called the absorption length, and $\Gamma$ the relaxation rate. According to Eq. (1), a significant change of the rotation angle $\phi$ takes place in a field region between $B = \pm h\Gamma/(2g\mu)$. In the vicinity of $B=0$. Within this region, $\phi$ may be approximated as:

$$\phi \approx \frac{2g\mu B}{h\Gamma}$$

(2)

Thus the sensitivity to the magnetic field $B$ is expressed as
\( \delta B = \left( \frac{d\phi}{dB} \right)_{B=0}^{-1} \delta \phi \)  \hspace{1cm} (3)

where \((d\phi/dB)_{B=0}\) denotes the slope of the \(B - \phi\) curve in the vicinity of \(B=0\), and \(\delta \phi\) the accuracy of the angle determination. The lower the relaxation rate is, the higher the attainable sensitivity to the magnetic field becomes. Thus it is of primary importance for a high sensitivity NMOR magnetometer to keep the spin alignment for as long time as possible by, for example, coating the inner walls of the cell with an antirelaxation layer.

3. Experiment

Experimental setup is shown in Fig. 2. The incident laser beam is separated at a beam splitter into two paths. The reflected laser beam is transmitted to a Rb vapour reference cell and a wavemeter, in order to monitor the laser beam properties with a wavemeter and a photodiode detecting the fluorescence light from Rb vapour in the reference cell. The laser frequency is tuned to the \(^{85}\text{Rb}\) D1 line \((F=3 \rightarrow F'=2)\). The light along the other path, non-reflected at the beam splitter, passes through a linear polarizer, and then enters the NMOR cell where the polarization plane is rotated by the NMOR effect. The intensity of the laser light entering the NMOR cell is \(\sim 100\mu\text{W/mm}^2\). The rotation angle \(\phi\) is determined by measuring the light intensity at a photodiode located downstream of a photo-elastic modulator (PEM) and a linear polarizer, by modulating the rotation angle using the PEM and lock-in detecting the photodiode signal.

![Figure 2. Experimental setup.](image)

A 3-axis Helmholtz coil is installed inside a 3-layer magnetic shield, in order to suppress effects of environmental field fluctuations. The \(z\)-axis is defined as the direction of laser beam, and the \(x\)- and \(y\)-axes are defined to be the horizontal and vertical directions. The NMOR cell is located at the center of the Helmholtz coil. The Helmholtz coil is used to vary the \(z\)-component of the magnetic field and to cancel the transverse component which is considered to destroy the alignment of Rb atoms. All cells used have cylindrical shapes, 25 mm in diameter and 25 mm long. According to ref. [4], the dependence of number density of Rb atoms, \([\text{Rb}]\), on the temperature \(T\) is as follows:

\[
[\text{Rb}] = \frac{10^{9.863-24215/T}}{kT^3} \hspace{1cm} (4)
\]

In our experimental conditions, \([\text{Rb}] = 1\times10^{10} \text{ atoms/cm}^3\) is obtained at 298 K. The current fed to the \(z\)-coil (being swept in time) is produced by a function generator, while the static currents flowing in the \(y\)- and \(z\)-coils are produced by current sources.
4. Result and discussion

The observed NMOR spectra are shown in Fig 3. The spectrum in Fig.3 (a) and (b) were obtained with the non-coated cell and paraffin-coated cell respectively. These observed spectra can be fitted with the Eq. (1), and the relaxation rates and slopes of the curves in vicinity of \( B=0 \) can be estimated. In the measurement with no-coat cell, the relaxation rate was determined as \( \Gamma=2\pi\times6.4\times10^4 \text{ s}^{-1} \), whereas \( \Gamma=2\pi\times6.3\times10^2 \text{ s}^{-1} \) was obtained for the paraffin-coated cell. The relaxation was suppressed to below 1/100 in the anti-relaxation coated cell, but the rotation angle turned to be 10 times smaller than in the non-coated cell.

The two different widths obtained in the NMOR spectra are understood with known phenomena, which are called transit effect and wall-induced Ramsey effect, detailed in [5]. In the spectrum with the non-coated cell, only the transit effect is observed, where the alignment state in atoms collapse in collision with the inner wall of cell. In this case, the coherence time is given by the time that atoms transit through the laser beam region. In the paraffin-coated cell, the wall-induced Ramsey effect is observed in which the alignment state can survive often many atom-wall collisions. The atoms re-enter the laser beam area after this many non-depolarizing wall collisions, so that the reduced relaxation rate is observed. Decreasing the rotation angle in wall-induced Ramsey effect is the result of the difference of the number of Rb atoms which interact with the laser light between transit and wall-induced Ramsey effect. The transit effect occurs also in the coated cell. This is seen as the background slope in Fig. 3 (b).

![Figure 3](image)

**Figure. 3** NMOR signals. (a) Without anti-relaxation coating, and (b) with paraffin coating.

Other two efforts for suppressing the relaxation were made. The cells with helium buffer gas at three different pressures (1, 5 and 50 Torr) were prepared. In gas cells with 1 and 5 Torr helium, slightly sharper spectra compared to that in Fig. 3 (a) were obtained. In the 5 Torr gas cell, however the rotation angle was smaller and the S/N ratio was worse. In the 50 Torr gas cell, the NMOR signal was not obtained. This may indicate that the alignment of atoms was destroyed during collisions with helium atoms in the 50 Torr cell. However, the buffer gas at some appropriate pressures would be helpful for prolonging the coherent time. Secondly, we cancelled the residual transverse magnetic field of a few milligauss, which induces transverse relaxation. In this case, the applied transverse field along the \( x \)-axis was \( B_x=0.096 \text{ mG} \), and that along the \( y \)-axis was \( B_y=-0.641 \text{ mG} \). The smaller relaxation rate by factor 0.8 was observed in this measurement.

Finally, the sharpest NMOR signal was obtained in a paraffin coated cell after cancelling the transverse magnetic field. The obtained slope of the curve is \( (d\phi/dB)_{B=0}=1.77\times10^3 \text{ mrad G}^{-1} \). The background noise in the rotation signal was \( \delta\phi=0.026 \text{ mrad} \), which was observed as the signal fluctuation without applying the magnetic field of the 3-axis Helmholtz coil in a 20 s period. The angle \( \delta\phi \) is defined as a root-mean-square of the noise which includes the fluctuation of the magnetometer.
and residual magnetic field. Thus we conclude that sensitivity to the magnetic field is better than $\delta B = 1.5 \times 10^{-5}$ G in a time scale of 20 s, an estimation from Eq. (3).

5. **Further developments**

Present performance of the magnetometry should be improved by several approaches. Firstly the noise power spectrum should be studied in order to estimate the sensitivity more accurately. In order to improve the magnetometer, the systematic investigation of the cell size, laser beam radius, the intensity of laser light, the procedure for the cell coating and the buffer gas introduction is needed. Experiments to improve the performance are under way.

In addition, we will start to develop a frequency (or amplitude) modulated NMOR system to utilize the magnetometer in the range of $B = 30$ mG under which the spin maser operates. This method has been recently studied [6, 7], and is expected to provide means to precisely measure the magnetic fields of the geophysical-scale. We are also planning to fabricate a small-size magnetometer with polarization-conserving optical fibers. A module of such a magnetometer would be suitable for use in variety of experimental arrangements.

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