Abstract

The development of a nuclear spin oscillator system, namely a spin maser with an external feedback, for use in the search for $^{129}$Xe atomic EDM is presented. By introducing a new current source for the $B_0$ field solenoid, drifts in the maser frequency were remarkably suppressed. This in turn clearly brought out the correlation between the maser frequency and the environmental field. Correcting for the effect of the environmental field, the frequency precision of 5 nHz in the measurement time of 45,000 s was attained. Origins of the remaining drifts in the maser frequency are now under investigation.

Keywords: Nuclear spin maser, Spin precession, Frequency precision, Electric dipole moment, Optical pumping

1. Introduction

A permanent electric dipole moment (EDM) of a particle violates the time reversal symmetry, and signifies CP violation because of the CPT theorem. Detection of a finite EDM value would provide a clear evidence of physics beyond the standard model (SM) of elementary particles, because EDMs predicted in the SM are extremely small, being practically undetectable [1]. Theories beyond the SM, on the other hand, contain a variety of new CP violating phases allowing for EDM to acquire values within the experimental reach [2]. Thus, an experimental search for EDMs constitutes a crucial test discriminating between the SM and theories beyond it. The EDMs of diamagnetic atoms such as $^{199}$Hg and $^{129}$Xe are considered to stem from P, T-violating components of nucleon-nucleon interactions, and poses on theoretical models a constraint which is different from those from EDMs of neutron and paramagnetic atoms [3, 4]. The latest experimental upper limits for EDMs of the neutron [5], $^{129}$Xe atom [6], and $^{199}$Hg atom [7] are, $|d_n| < 2.6 \times 10^{-26}$ e cm, $|d(^{129}\text{Xe})| < 4.0 \times 10^{-27}$ ecm, and $|d(^{199}\text{Hg})| < 3.1 \times 10^{-29}$ ecm, respectively. So far, the experimental $d(^{199}\text{Hg})$ poses the most stringent constraint on the theories. However, the Xe atomic EDM has a potential of significant improvement in the experimental limit by utilization of a nuclear spin maser technique.

The EDM $d$ is deduced from a frequency shift observed upon the reversal of the electric field $E_0$ along the magnetic field $B_0$, namely

$$ d = \frac{\hbar (\nu_+ - \nu_-)}{4E_0}, $$

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where \( \nu_+ (\nu_-) \) represents the frequency of Xe spin precession measured with \( E_0 \) parallel (antiparallel) to \( B_0 \). For example, an EDM of a size \( |d| = 10^{-29} \) cm with \( E_0 = 10 \) kV/cm gives \( \Delta \nu = \nu_+ - \nu_- = 0.1 \) nHz. Thus, high precision in the frequency determination, and hence long measurement time of the spin precession, is essential for EDM searches. We are now developing a nuclear spin maser with an external feedback, a mechanism to sustain the nuclear spin precession for unlimitedly long duration and thereby to realize long measurement times [8].

The principle of the present spin maser is outlined as follows. The nuclear spin precession is optically detected by using a probe laser light. A feedback field is generated according to the detected signal, with its phase arranged such that the feedback field is always orthogonal to the transverse component of the spin. The feedback field is applied with a coil wound around a Xe containing cell. The detection sensitivity for spin precession using a probe light is by far higher than that with a pick-up coil, and consequently the present spin maser can operate even at considerably lower static field. In this way, the absolute size of field fluctuations becomes smaller and consequently the fluctuation in the precession frequency is substantially suppressed. Until present, the spin maser is operated under \( B_0 = 30.6 \) mG, and the frequency precision of 9.3 nHz has been obtained [9]. Detailed studies of maser operation have revealed that the main factor limiting the present frequency precision is drifts in a solenoid current for the static field [10].

2. Correlation between the maser frequency and environmental field

In order to suppress the drift in the solenoid current, we developed a new current source with stabilization by means of a feedback system, which is devised to correct the current measured precisely by using a high precision digital multimeter and a standard resistor [11]. Thus a stability of better than 1 ppm at \( I_0 = 7 \) mA was achieved, which corresponded to the \( B_0 \) field fluctuation below 30 nG.

The introduction of the new current source indeed suppressed the main part of the observed drifts in the maser frequency, and as a consequence revealed a clear correlation between the maser frequency \( \nu_0 \) and an environmental field \( B_{\text{env}} \), as shown in Fig. 1 (the correlation coefficient \( r = 0.98 \)). The maser frequency \( \nu_0 \) and its precision are deduced from a linear \( \chi^2 \)-fitting procedure on the phase values deduced from the lock-in amplifier outputs whose, phases are different by \( \pi/2 \) from each other [12]. The environmental field \( B_{\text{env}} \) was sensed with a flux gate magnetometer placed outside a 4-layer cylindrical magnetic shield. The deduced \( \nu_0 \) is plotted as a function of the measured \( B_{\text{env}} \) in Fig. 1. The slope \( d\nu_0/\text{dB}_{\text{env}} \) was determined from the linear fitting to the data in Fig. 1. The result is

\[
\frac{d\nu_0}{\text{d}B_{\text{env}}} = 1.289956 \pm 0.000011 \text{ Hz/G.}
\]

Noting that the gyromagnetic ratio of \(^{129}\text{Xe} \) nucleus is \( \gamma/2\pi = 1.17779 \times 10^3 \) Hz/G, the obtained slope indicates that the shielding factor of the magnetic shield is about \( 10^3 \). The rather low value of shielding factor may be limited by the
Figure 2: Time variation of the maser frequency averaged over 100 s duration. The raw values (open circles) and the values corrected for drifts in $B_{\text{env}}$ (closed circles) are plotted.

Figure 3: Measurement of the time dependence of the maser frequency precision before and after the correction for drifts in $B_{\text{env}}$. The dashed line represents the expected precision $\delta \nu \propto t^{-3/2}$.

existence of a wide opening at one of the two ends of the cylindrical shield and also by some unintended magnetization due to mechanical stress.

3. Correction for environmental field effect

Making use of the above known dependence of $\nu_0$ upon $B_{\text{env}}$, the precession phase at time $t_i$, $\phi_{\text{raw}}(t_i)$ was corrected for the effect of drifts in $B_{\text{env}}$,

$$\phi_{\text{corr}}(t_i) = \phi_{\text{raw}}(t_i) - 2\pi \frac{d\nu_0}{dB_{\text{env}}} \sum_i [B_{\text{env}}(t_i) - B_{\text{env}}(t_i = 0)] \Delta t,$$

where $\phi_{\text{corr}}(t_i)$ denotes the phase value at time $t_i$ after the correction, $B_{\text{env}}(t_i)$ the environmental field at time $t_i$, and $\Delta t = 0.05$ s a time bin width for the data acquisition.

By the correction made above for drifts in the environmental field $B_{\text{env}}$, gross structures in the time variation of $\nu_0$ disappeared, as shown in Fig. 2 in which the time deviations of maser frequency both before and after the correction are plotted as functions of time. Before the correction, the improvement of frequency precision ceased at around 10,000 s, as shown in Fig. 3. After the correction, the frequency precision continued to improve beyond 10,000 s,
and reached $\delta \nu \sim 5\text{nHz}$ at 45,000 s. The obtained frequency precision would correspond to an expected sensitivity for EDM of $\delta d \sim 5 \times 10^{-28}\text{cm}$, when the application of an electric field $E_0 = 10\text{kV/cm}$ will be realized. However, beyond 2,000 s, a deviation from the expected precision $\delta \nu \propto t^{-3/2}$ and a structure appeared, suggesting that drifts of other factors which caused the frequency drift still remain. Origins of these drifts are being investigated. In an EDM measurement, the Allan standard deviation $\sigma_{\text{Allan}}$ also is an important parameter. The Allan deviation evaluated for a time interval $\tau = 500\text{s}$, for example, was $\sigma_{\text{Allan}} = 22\text{\mu Hz}$ even after the above correction was made for the $B_{\text{env}}$ variation. This indicates that in an actual stage for EDM search a kind of co-magnetometer will be needed. We are developing a high sensitivity magnetometer by utilizing the nonlinear magneto-optical rotation (NMOR) \cite{13, 14}, in order to monitor variations in the applied and ambient magnetic fields.

4. Summary and future

The spin maser with external feedback was operated incorporating a newly developed current source for the $B_0$ solenoid. Owing to the improved stability of the $B_0$ field, a clear correlation between the maser frequency and the environmental field $B_{\text{env}}$ was observed. The correction for drifts in $B_{\text{env}}$ drastically removed the gross variation of the maser frequency, and yielded a frequency precision that was improved by a factor of 2 from before. However, the remaining drifts whose origins have not been clarified so far seem to limit the current frequency precision. We are investigating the origin of the remaining drifts. In addition, the designing of correction coils to compensate the drift in the environmental field is under way.

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6. References

[1] I.B. Kriplovich, S.K. Lamoreaux, 1997, CP Violation Without Strangeness, Springer Verlag.
[2] M. Pospelov, A. Ritz, 2005, Electric dipole moments as probes of new physics, Ann. Phys. 318. 119.
[3] J.S.M. Ginges, V.V. Flambaum, 2004, Violations of fundamental symmetries in atoms and tests of unification theories of elementary particles, Phys. Rep. 397. 63.
[4] K. A. Olive, M. Pospelov, A. Ritz, and Y. Santoso, 2005, CP-odd phase correlations and electric dipole moments, Phys. Rev. D. 72. 075001.
[5] C. A. Baker, D. D. Doyle, P. Geltenbort, K. Green, M. G. D. van der Grinten, P. G. Harris, P. Iaydjiev, S. N. Ivanov, D. J. R. May, J. M. Pendlebury, J. D. Richardson, D. Shiels, and K. F. Smith, 2006, Improved Experimental Limit on the Electric Dipole Moment of the Neutron, Phys. Rev. Lett. 97. 131801.
[6] M. A. Rosenberry and T. E. Chupp, 2001, Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of $^{129}\text{Xe}$ and $^{3}\text{He}$, Phys. Rev. Lett. 86. 22.
[7] W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, and E. N. Fortson, 2009, Improved Limit on the Permanent Electric Dipole Moment of $^{199}\text{Hg}$, Phys. Rev. Lett. 102. 101601.
[8] A. Yoshimi, K. Asahi, K. Sakai, M. Tsuda, K. Yogo, H. Ogawa, T. Suzuki, M. Nagakura, 2002, Nuclear spin maser with an artificial feedback mechanism, Phys. Lett. A. 304. 13.
[9] A. Yoshimi, K. Asahi, T. Inoue, M. Uchida, N. Hatakeyama, M. Tsuchiya, and S. Kagami, 2009, Nuclear Spin Maser at Highly Stabilized Low Magnetic Field and Search for Atomic EDM, AIP. Conf. Proc. 1149. 249.
[10] T. Inoue, M. Tsuchiya, T. Furukawa, H. Hayashi, T. Nanao, A. Yoshimi, M. Uchida, Y. Matsuus, and K. Asahi, Frequency characteristics of a nuclear spin maser for the search for the electric dipole moment of $^{129}\text{Xe}$ atom, Physica E, in press.
[11] T. Furukawa, T. Inoue, T. Nanao, A. Yoshimi, M. Tsuchiya, H. Hayashi, M. Uchida and K. Asahi, Magnetic Field Stabilization for $^{129}\text{Xe}$ EDM Search Experiment, to be published.
[12] T.E. Chupp, R.J. Hoare, R.L. Walsworth, and Bo Wu, 1994, Spin-Exchange-Pumped $^{3}\text{He}$ and $^{129}\text{Xe}$ Zeeman Masers, Phys. Rev. Lett. 77. 3971.
[13] D. Budker, D.F. Kimball, S.M. Rochester, V.V. Yashchuk, and M. Zolotorev, 2000, Sensitive magnetometry based on nonlinear magneto-optical rotation, Phys. Rev. A. 62. 043403.
[14] V. Acosta, M.P. Ledbetter, S.M. Rochester, D. Budker, D.F. JacksonKimball, D.C. Hovde, W. Gawlik, S. Pustelny, J. Zachorowski, and V.V.Yashchuk, 2006, Nonlinear magneto-optical rotation with frequency-modulated light in the geophysical field range, Phys.Rev. A. 73. 053404.