

論文 / 著書情報  
Article / Book Information

論題(和文)	
Title(English)	Performance test of improved magnetic field stabilization system for EDM measurement
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出典(和文)	, , , pp. 84-87
Citation(English)	Proceedings of 7th International Workshop on Fundamental Physics Using Atoms (FPUA 2014), , , pp. 84-87
発行日 / Pub. date	2015, 1

# Performance test of improved magnetic-field system for $^{129}\text{Xe}$ EDM measurement

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## Abstract

In  $^{129}\text{Xe}$  EDM experiment, the improvement of the amplitude of a nuclear spin maser is essential. The amplitude is proportional to the ratio of effective longitudinal relaxation time  $T_1^*$  and transverse relaxation time  $T_2$ . In particular, for the case of  $^3\text{He}$  spin for which  $T_1^*$  can be as long as 50 h,  $T_2$  is the most crucial parameter.  $T_2$  depends on the homogeneity of the magnetic field. Typical values of  $T_2$  for  $^3\text{He}$  in a spherical cell with a 10 mm radius in our setup range around 1,000 s. Thus in the present work we aim at improving  $T_2$  up to 10,000 s by developing a magnetic-field system where new coil to generate the static magnetic field with high homogeneity was introduced. As a result of the development,  $T_2$  of 11,000 s was achieved for  $^3\text{He}$ .

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## 1. Introduction

A permanent electric dipole moment (EDM) is an excellent probe of physics beyond the Standard model (SM). The typical magnitude of EDMs predicted by models beyond the SM are by many orders of magnitude larger than what is expected from the SM physics. An EDM is detected as a difference between the spin precession frequencies measured with an electric field applied parallel and antiparallel to the magnetic field. We aim to search for a  $^{129}\text{Xe}$  EDM with a sensitivity of  $d \sim 10^{-28}$  ecm by using a nuclear spin maser which enables to sustain the spin precession over a long measurement duration by an artificial feedback scheme [1, 2]. In the experiment,  $^{129}\text{Xe}$  which is the subject of our EDM search and  $^3\text{He}$  which acts as a co-magnetometer to remove a fluctuation of a magnetic field are enclosed in a glass cell which is a spherical cell of a 10 mm radius. The polarizations of these nuclear spins are generated through spin exchange with Rb atoms which are optically pumped. The nuclear spins thus polarized start precession immediately after they are tilted by the application of a resonant rf field pulse. The precession is detected by measuring the transmission of a probe laser light through a Rb vapor cohabiting the cell containing  $^{129}\text{Xe}$  and  $^3\text{He}$ . A feedback magnetic field to sustain the spin precession is generated returning to the obtained precession signal.

In this measurement, the improvement of the amplitude of the spin maser is essential. It is found that the amplitude is proportional to  $\frac{P_0}{2} \sqrt{\frac{T_2}{T_1^*}}$ , where  $P_0$  is the degree of polarization for the nuclear spin,  $T_1^*$  the effective longitudinal spin relaxation time and  $T_2$  the transverse spin relaxation time. Thus the ratio  $\frac{T_2}{T_1^*}$  and  $P_0$  are the key factors in the spin

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maser. In particular, for a  $^3\text{He}$  spin maser requires a long  $T_2$  since  $T_1^*$  is long and yet the polarization attained in  $^3\text{He}$  is low. The major cause of the transverse relaxation is a magnetic field gradient over the cell which encloses  $^{129}\text{Xe}$  and  $^3\text{He}$  gases, because the coherence is lost due to specially varying strength of the magnetic field as spins diffuse around in the cell. The  $T_2$  [3] is given as

$$\frac{1}{T_2} \sim \frac{1}{T_1} + \frac{8R^4\gamma^2|\nabla B_z|^2}{175D} \quad (1)$$

where  $R$  is the radius of the cell,  $\gamma$  the geomagnetic ratio,  $\nabla B_z$  the gradient of the z-component  $B_z$  of the magnetic field,  $D$  the diffusion constant, and  $T_1$  the longitudinal spin relaxation time. In the previous setup, observed  $T_2$  ranged around 1,000 s. In the present work, we aim to improve  $T_2$  value for  $^3\text{He}$  up to 10,000 s or better by improving homogeneity of the magnetic field over the cell. In order to achieve such a long  $T_2$ , the system was renewed to improve the field gradient in the cell region. Thus we redesign most carefully a coil generating a static magnetic field.

## 2. Magnetic-field system

We constructed a new magnetic-field system placing emphasis on the high field homogeneity. The system consists of a triple layer magnetic shield and a coil generating a static magnetic field. The triple layer magnetic shield is made of permalloy with the relative permeability higher than 90,000. The individual layers of the shield are cylinders of 2 mm wall thickness, and their sizes are, from the innermost to outermost ones, 40 cm in diameter and 68 cm in length, 60 cm in diameter and 100 cm in length, and 80 cm in diameter and 130 cm in length, respectively. The magnetic shield is designed so that the gaps between the two consecutive layers are larger than those in the previous shield, in order to enhance the magnetic flux absorbency. On the left and right side of each cylindrical wall, three holes each are open to allow a probe laser light to pass through. The shield is demagnetized by AC demagnetization method [5]. After the demagnetization, the residual magnetic field was measured to be  $\sim 20 \mu\text{G}$  (the shielding factor, higher than  $10^4$ ) and the gradient of the residual field was determined to be  $3.5 \pm 0.5 \mu\text{G}/\text{cm}$  in a region within 10 mm from the center.

## 3. New coil design

A set of coils was designed to realize improved field homogeneity in the cell region within 10 mm from the common center of the three cylinders of the shield. The coil set, shown Fig. 1, consists of two split-pair solenoids, and located at the center of the shield. The coil set has five parameters : Location  $z_1$  and width  $w_1$  of the inner coil pair, location  $z_2$  and width  $w_2$  of the outer coil pair, and coil radius  $a$ . In order to achieve the target  $T_2$ , these parameters are tuned to eliminate z- and  $\rho$ -dependences of the magnetic field order by order in  $z$  and  $\rho$ . The magnetic field is expressed as

$$B_z(z, \rho) = f_0 + f_2(-2z^2 + \rho^2) + f_4(8z^4 - 24z^2\rho^2 + 3\rho^4) + \dots \quad (2)$$

where we use a cylindrical coordinate system  $(\rho, z)$ , and coefficients  $f_0, f_2$ , and  $f_4$  each being a function of the coil parameters  $z_1, w_1, z_2, w_2$ , and  $a$ , represent the 0th, 2nd and 4th order terms, respectively. Thus a homogeneous field is obtained by tuning the coil parameters to eliminate the 2nd and 4th order terms,  $f_2, f_4 = 0$ , yielding the selected values of  $z_1 = 26.65$  mm,  $z_2 = 142.00$  mm. Also  $w_1 = 10.47$  mm and  $w_2 = 40.44$  mm are selected so that the coil widths correspond to multiples of the wire diameter, 0.81 mm, which includes a 0.03 mm thick coating film on the wire. The numbers of turns for the inner and outer coils are 13 turns and 50 turns, respectively. Radius  $a$  is selected to be 100.00 mm.

We measured the magnetic field generated by the new coil-shield system, and compared the results with a computer simulation. In the simulation, we used a magnetic field simulation software Opera-3D [6] which simulates a magnetic field by means of a finite element method. The simulation includes permeability of materials, geometrical structure of the shield and holes on the individual layers. Calculation was made for the magnetic field generated by the coils at positions along the z- and  $\rho$ -axes. The measurement results are found to suffer from the systematic error due to field changes at removal or re-attachment of the endcaps on the cylinder ends. The measured values of the field typically showed changes by  $0.8 \mu\text{G}$  after a six times repetition of the removal-reattachment. Also, in the course of the field measurement, it turned out that our positioning system for the flux-gate magnetometer probe exhibited non-negligible uncertainties for  $\rho > 20$  mm. The error caused by these uncertainties in the probe position was estimated

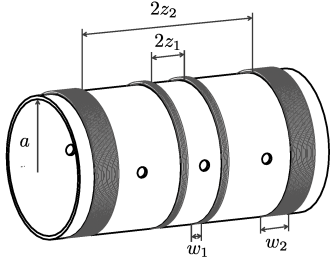


Figure 1: A sketch of the coil set. The set consists of two pairs of symmetrical spaced concentric solenoids. Coil parameters ( $z_1$ ,  $w_1$ ,  $z_2$ ,  $w_2$ ,  $a$ ) were tuned in order to eliminate the 2nd and 4th order terms in the magnetic field. The coil bobbin has holes to allow the probe laser light to pass through it.

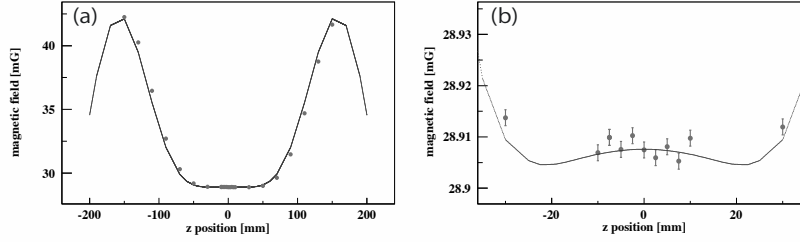


Figure 2: (a) Measured (plot) and calculated (solid line) field distributions  $B_z(z)$  along the  $z$ -axis. The measurement was made using a flux-gate magnetometer. The calculation was done with a simulation code Opera-3D. (b) The same presentation, but with expanded scales in the  $z$ - and  $B_z$ -axes.

by simulation. The results are shown Figs. 2 and 3. The plotted points represent the field produced by the coils, which are obtained by subtracting the residual field (measured without the current in the coils) from the measured field (with the current in the coils). The curves drawn in Figs. 2 and 3 represent the calculations using the Opera-3D code, in which the parameters  $z_1$  and  $z_2$  are adjusted (by changing the same amount) to adapt to the small centering error in the measurement. Only the machining accuracy in the coil bobbin is considered in the uncertainty of simulation result. In fact, the adjustment of  $z_1$  and  $z_2$  values within the machining accuracy was sufficient. As seen in Figs. 2 and 3, the simulation results well reproduce the measured distribution of the coil field over a wide range of positions. Based on this result, we evaluate the field gradient using the simulated field distribution. As a result, the field gradients in the positions within 10 mm from the center along the  $z$ - and  $\rho$ -axes were evaluated as  $1.0 \mu\text{G}/\text{cm}$  and  $0.4 \mu\text{G}/\text{cm}$  on average, and  $2.4 \mu\text{G}/\text{cm}$  and  $1.9 \mu\text{G}/\text{cm}$  at maximum, respectively. In particular, the field distribution along the  $\rho$ -axis is found to be quiet homogeneous over a wide range of positions. The field gradient in the special region within 35 mm from the center along the  $\rho$ -axis is evaluated to be  $3.2 \mu\text{G}/\text{cm}$  on average and  $19.9 \mu\text{G}/\text{cm}$  at maximum.

#### 4. Performance test of the new setup

The new magnetic-field system was tested through  $T_2$  measurement by means of Free Induction Decay (FID). In the FID measurement, a gas cell enclosing 470 Torr of  $^3\text{He}$ , 1 Torr of  $^{129}\text{Xe}$ , and 100 Torr of  $\text{N}_2$ , was placed at the

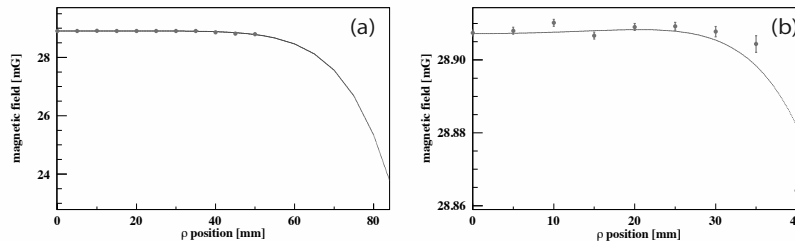


Figure 3: (a) Measured (plot) and calculated (solid line) field distributions  $B_z(\rho)$  along a radial direction (the  $\rho$ -axis). (b) The same presentation, but with expanded scales in the  $\rho$ - and  $B_z$ -axes.

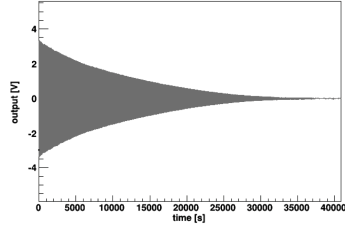


Figure 4: FID signal of  $^3\text{He}$  was obtained in new setup.  $T_2$  was determined to be 11,000 s.

center of the shield, and was irradiated with a pumping laser light to produce the Rb polarization. In order to detect the  $^3\text{He}$  precession, the cell was illuminated also with a probe laser light, which passed through the cell and was detected by a photo detector. The signal from the photo detector was lock-in-amplified with a reference signal set close to the known  $^3\text{He}$  precession frequency. Thus, we obtained the  $^3\text{He}$  precession signal as a beat at around 0.1 Hz, as shown Fig. 4. From a least  $\chi^2$  fitting the  $T_2$  was obtained as 11,000 s which is larger than the target  $T_2$ .

The obtained value of  $T_2$  is related via Eq. 1 to the root-mean-square (rms) field gradient  $|\nabla B_z|^2$  over the cell region. Inserting  $T_2 = 11,000$  s as obtained above, the rms field gradient within cell region was evaluated to be  $4.7 \mu\text{G}/\text{cm}$ . This is in face agreement with the estimated field gradient of about  $5 \mu\text{G}/\text{cm}$  at maximum based on the measured residual field of  $3.5 \pm 0.5 \mu\text{G}/\text{cm}$  and the calculated coil field of  $1.0 \mu\text{G}/\text{cm}$ . Thus we conclude that the present coil-shield setup provides a field homogeneity of about  $5 \mu\text{G}/\text{cm}$ . ( The rms value of the field gradient evaluated by the simulation results and the measurement results of the residual magnetic field in the shield was  $3.8 \pm 0.2 \mu\text{G}/\text{cm}$ . ) We also note that the the field variation on along the radial direction is moderate over a wide region. Within 35 mm from the center, the relative gradient against the static field  $\sim 30$  mG was  $10^{-3} / \text{cm}$ .

## 5. Summery

The small  $\frac{T_2}{T_1}$  ratio suppresses the amplitude of nuclear spin maser. In particular, improvement in the maser amplitude of  $^3\text{He}$  which exhibits a long  $T_1^*$  relies largely on long  $T_2$ . Thus in the present work we designed and constructed a new magnetic-field system in order to improve the  $T_2$  of  $^3\text{He}$  up to 10,000 s. The setup consists of a triple layer magnetic shield and coils for a static field. The residual field gradient in the shield was measured to be  $3.5 \pm 0.5 \mu\text{G}/\text{cm}$ . Also new coils were designed, because the cause of inhomogeneous field was considered to originate mainly from gradients of a static field produced by the coils. By tuning five parameters for the coil configuration, the 2nd and 4th order terms of the magnetic field was eliminated. The resulting magnetic field was measured using a flux-gate magnetometer. The measured field was well reproduced by a Opera-3D calculation after a fine tuning of the coil position within the machining accuracy. Thus established Opera-3D calculation gives a simulated average magnitude of coil field gradients of  $1.0 \mu\text{G}/\text{cm}$  along the  $z$ -axis and  $0.4 \mu\text{G}/\text{cm}$  along the  $\rho$ -axis. Finally, we performed a measurement of  $T_2$  for  $^3\text{He}$  in the new setup. The obtained value,  $T_2 = 11,000$  s, turned out to even exceed the target value of 10,000 s. Based on these calculations and measurements, we conclude that the new setup provides a field homogeneity of around  $5 \mu\text{G}/\text{cm}$  in the cell region and  $30 \mu\text{G}/\text{cm}$  in  $\rho$  region within 35 mm form the center.

## acknowledgments

This work was partly supported by the JSPS KAKENHI (No.21104004 and No.21244029). One of the authors (T.Sato) would like to thank the JSPS Research Fellowships for Young Scientists for the support.

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