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Development Of ^{131}Xe Co-magnetometry For Xe Atomic EDM Search

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Co-magnetometry enables the elimination of systematic errors arising from the long-term drift in the magnetic field, and is essential for a precision measurement of spin precession frequency in experiments searching for electric dipole moment (EDM). ^{131}Xe nuclear spin maser shows great promise as a co-magnetometer in a Xe EDM experiment, because the systematic error originating from the Xe-Rb interaction, which virtually limits the sensitivity in a case of a ^{3}He co-magnetometer, will be cancelled out. The performance of a cell which contains both ^{129}Xe and ^{131}Xe was investigated. In the best cell among those fabricated this time, the signal-to-noise ratio in a free induction decay experiment turned out to be large enough for the operation as co-existing ^{129}Xe-^{131}Xe masers.

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1. Introduction

The search for electric dipole moment (EDM) is one of promising pathways to knowledge of new physics beyond the Standard Model (SM) of particle physics: The contribution from the *CP*-violating CKM phase in the SM to the EDM is many orders of magnitude smaller than those predicted from extra *CP*-violation contained in physics beyond the SM [1, 2, 3]. This extra *CP*-violation would shed light on the matter-antimatter asymmetry in our Universe [4]. The current experimental upper limit on the EDM of a diamagnetic atom ^{129}Xe, an objective of the present work, is $4.1\times10^{-27}e$cm [5]. Improvement of the upper limit on the ^{129}Xe would provide valuable information on what physics exists beyond the SM [6]. The EDM of Xe is measured by taking the Larmor frequency difference between those for parallelly and anti-parallelly applied electric fields to the magnetic field. Since an EDM of $10^{-28}e$cm in a 10 kV/cm electric field would cause a frequency shift of only 1 nHz, the ultimate precision is required for the measurement.

In order to improve the statistical sensitivity, we employ a nuclear spin maser with an external feedback scheme [7, 8]. The spin maser elongates the spin coherence time to unlimitedly long duration of time, and enables us the observation of a long-lasting spin precession which provides the statistical sensitivity that improves much faster with time, as compared to the usual measurements composed of repeated short-term spin observations. In the previous study [9], frequency precision of ^{129}Xe maser in one-shot measurement reached below 10 nHz within 3×10^4 s.

The elimination of systematic errors is also indispensable. A co-magnetometer is introduced to suppress the frequency drift arising from long-term drift in the magnetic field which is one of the most significant error sources. By taking the difference between the precession frequencies of the atom of interest and the reference atom, the frequency drift due to the magnetic field drift is eliminated. For this purpose, a ^{3}He spin maser is often introduced [5, 10, 11]. Since the size of the EDM of ^{3}He is expected to be very small and the long spin coherent time must be attainable, ^{3}He is considered quite appropriate as a reference atom. However, it turned out that in our case another systematic error originating from the interaction between Xe or He and polarized Rb atom can not be cancelled out, because the coupling constant for the interaction between the polarized Rb and Xe is about 10^2 times larger than that between the polarized Rb and ^{3}He [12, 13]. (Note that the Rb atom is essential both for the spin-exchange optical pumping of the noble gases and for the observation of spin precession signal.) Virtually, the drift in the frequency due to the interaction between the polarized Rb and the maser species limits the ultimate sensitivity of the measurement. In order to avoid this difficulty, we newly employ ^{131}Xe as a co-magnetometer in our spin maser. The coupling strength is almost equal for the ^{129}Xe-Rb case and for the ^{131}Xe-Rb case [14].

In the present study, a cell in which ^{129}Xe and ^{131}Xe coexist is developed for the maser operation. The study on the optimization of cell cleaning procedure and parameters in the cell fabrication is reported in Section 2. The result from free induction decay measurements is presented in Section 3.

2. Study on the optimum parameters for the ^{129}Xe and ^{131}Xe cell

The magnitude of the magnetization, or the product of the polarization and the number density of atoms, is an important factor for the stable operation of the maser. The attainable polarization is typically smaller for ^{131}Xe than for ^{129}Xe due to a smaller spin-exchange rate between ^{131}Xe and Rb compared to that between ^{129}Xe and Rb. In addition, unlike ^{129}Xe, the spin 3/2 nucleus ^{131}Xe has a quadrupole moment, thus allowing the quadrupole relaxation due to the wall and atom-atom interactions to enter. In the case where ^{131}Xe is in a mixture of gases, the behavior of the polarization is expected to be different from the case where only ^{131}Xe is filled in the cell. Thus the polarization and relaxation of Xe spins should be investigated. For this purpose, dependences of the cell performances on parameters such as the cleaning procedure, the partial pressures and the temperature of the cell environment were studied by means of the adiabatic-fast-passage nuclear-magnetic-resonance (AFP-NMR) method.

First, the performance of cells which were fabricated with different cleaning procedures and gas partial pressures was studied. The cell was made of Pyrex glass. The outer diameter was 20mm with the wall thickness 1mm. In order to control the temperature, the cell was installed in a box with AR-coated windows for the laser access and a port for the hot air flow. A circularly polarized laser light for the spin-exchange optical pumping was introduced along the axis of the static field. The pumping light was provided from a cascade of an external-cavity laser diode and a tapered amplifier [15]. The wavelength of the laser light was ∼795 nm and the power was ∼1 W. The polarization of Xe was generated by the spin-exchange with optically pumped Rb atoms. An rf field whose frequency was $\nu_{RF} = 34.2$ kHz was applied by using a pair of coils surrounding the box. The static magnetic field B_0 was applied using a solenoid coil. The current in the coils for B_0 was swept to cross the resonance corresponding to ν_{RF} while keeping the AFP condition. The AFP-NMR signal was obtained by using a pick-up coil surrounding the cell and a detection circuit. The polarization was obtained from the observed peak height of the signal which was normalized to the AFP signal for the pure water. Typical signal obtained for ^{131}Xe is shown in Fig. 1 (a). The spin relaxation time T_1^* was determined by fitting the experimental peak heights plotted with a function of time. Typical plot for ^{131}Xe is shown in Fig. 1 (b).

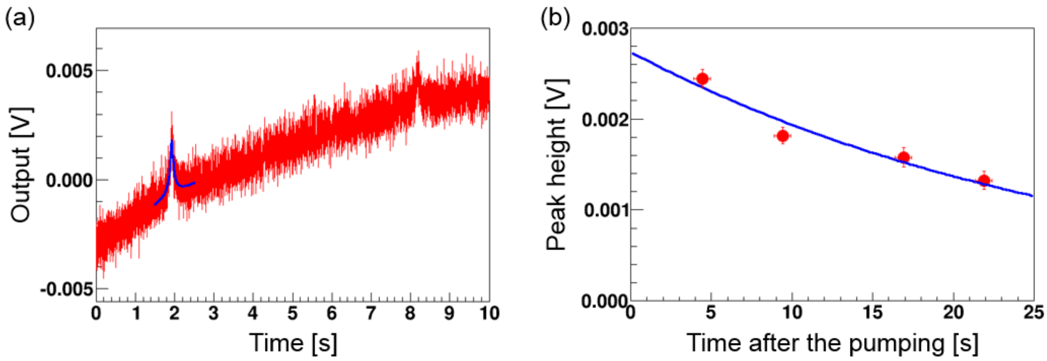

Figure 1: The obtained AFP-NMR signal for ^{131}Xe (a) and peak height plotted as a function of time after the pumping light is turned off (b). The red points are obtained data and the blue lines are fit function. The temperature was maintained at ∼83°C.

Several findings emerged from the above measurements: The best-performing cell among those produced this time, namely the one with high magnetizations and the long relaxation times for both ^{129}Xe and ^{131}Xe, was obtained by cleaning the cell inner wall sequentially with neutral detergent, ethanol, water and nitric acid, and by filling it with gases of 1 Torr of ^{129}Xe, 25 Torr of ^{131}Xe, 10 Torr of N_2 and 200 Torr of ^{3}He. The relaxation time for ^{129}Xe was found to be strongly influenced by the cleaning procedure, while for ^{131}Xe the influence was barely seen. The relaxation time for ^{129}Xe in the cell which was cleaned with neutral detergent, ethanol, water and then nitric acid was obviously longer than in those cleaned only with neutral detergent, ethanol and water. This might suggest that the relaxation was dominated by the collisions between ^{129}Xe and wall of the cell. The observed independence of the ^{131}Xe relaxation time on the cleaning procedure would imply that the dominant contribution to the ^{131}Xe relaxation may not come from the wall collision. The ^{131}Xe polarization turned out to decrease with increasing ^{129}Xe partial pressure. Since the spin-exchange cross section between ^{129}Xe and Rb is larger than that between ^{131}Xe and Rb [16], the polarization of Rb would be consumed more by ^{129}Xe than by ^{131}Xe. In addition, the collision between ^{129}Xe and ^{131}Xe would destroy the ^{131}Xe polarization [17]. Then, although the addition of certain amount of N_2 gas is known to be necessary as a buffer gas for the spin-exchange optical pumping, the present experiments indicated that excessive amounts of N_2 ($P(N_2)$ = 250 Torr) lead to a decrease of the ^{131}Xe polarization. This was considered to be due to the collision between ^{131}Xe and N_2, and in fact directed us to go to a lower N_2 pressure, so long as its function as a buffer gas was secured. Finally, ^{3}He was introduced instead of N_2 for the pressure broadening of the Rb absorption line, because the collisional cross section between He and ^{131}Xe is smaller than that between N_2 and ^{131}Xe [18].

Next, the cell-temperature dependence of the polarization was studied. The temperature was controlled by changing the power for the hot air flow. The results are shown in Fig. 2. The polarization reached ∼90% around 120°C for ^{129}Xe and ∼10% around 130°C for ^{131}Xe. However, the relaxation time turned out to be too short for the maser experiment, due to the Xe-Rb interaction. We thus concluded that the temperature should be lowered. Finally, it was found that we still had ∼1% of the polarization of ^{131}Xe even at around 83°C. The longitudinal spin relaxation time was ∼42 s for ^{129}Xe and ∼30 s for ^{131}Xe, both sufficiently long for the maser operation.

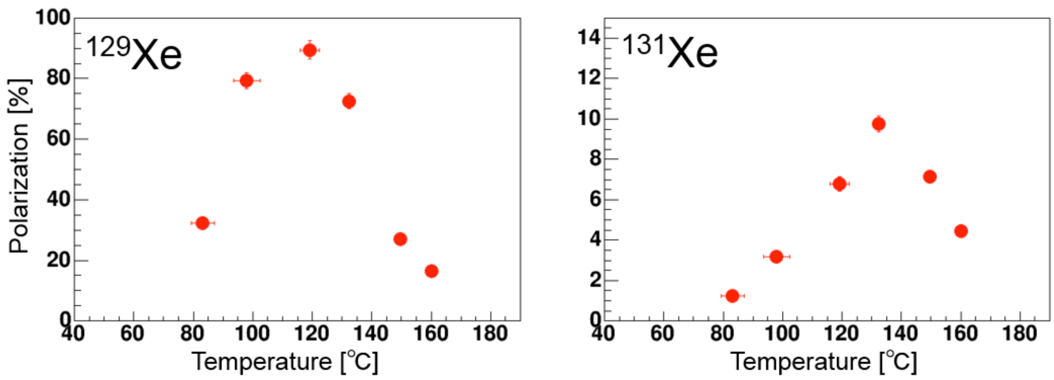

Figure 2: Temperature dependence of the polarization of ^{129}Xe (left panel) and ^{131}Xe (right panel).

3. Free induction decay measurement

The signal-to-noise ratios and transverse relaxation times for ^{129}Xe and ^{131}Xe were obtained from the measurement of free induction decay (FID). The setup used is shown in Fig 3. The cell was installed in a box in order to maintain the temperature. The temperature of the cell environment was stabilized at ∼83°C by a PID-controlled heater. A set of Helmholtz coils surrounded the box for the rf pulse application. The static field and the symmetry axis of the coils were orthogonal to each other. The box and coils for the feedback field were installed in a three-layer magnetic shield. Pairs of coil for the static field B_0 [19] were installed next to the innermost layer of the shield. In this experiment, the static field was 9.4 mG which corresponded to the precession frequency of ∼11 Hz for ^{129}Xe and ∼3 Hz for ^{131}Xe. A ∼1 W of circularly polarized laser light was introduced to the cell along the B_0 axis for the optical pumping. The pumping light was provided from a distributed feedback (DFB) laser combined with a tapered amplifier (TOPTICA, TA-DFB). The probe light was provided from another DFB laser (TOPTICA, DL-DFB). The laser light for the observation was introduced to the cell in the direction perpendicular to the B_0 axis and its transmission was monitored by a photo-diode. The power of the probe light was a few mW. Signal of the spin precession appeared as a change in the power of the transmitted probe laser light. Two stage lock-in amplification scheme was employed in order to improve signal-to-noise ratio. The output after the amplification was a beat signal between the precession signal of Xe and the reference signal whose frequency was set close to the Xe precession frequency. The frequency of the beat signal was ~1 Hz. The outputs were sent to analog-to-digital converters for data taking.

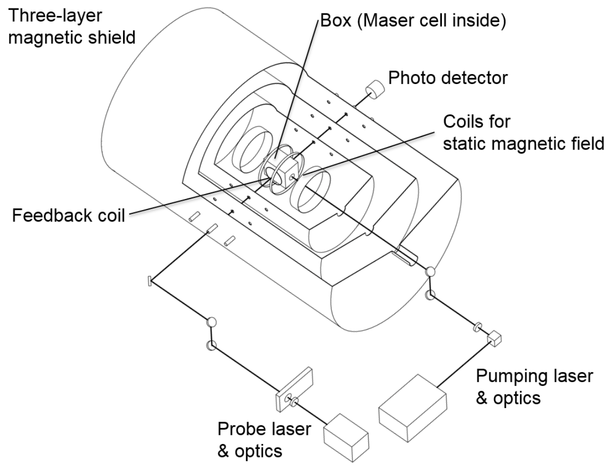

Figure 3: Setup for the FID experiment.

Figure 4 shows the observed signals from the second-stage lock-in amplifiers and amplitudes calculated from the observed data. The FID signals for ^{129}Xe and ^{131}Xe were successfully obtained. The S/N ratios were obtained to be 226 for ^{129}Xe and 76 for ^{131}Xe. The transverse relaxation times were determined to be ~21 s for ^{129}Xe and ~18 s for ^{131}Xe. The amplitude of the maser in the steady state can be written as

$$V \propto P \times \sqrt{\frac{T_2}{T_1^*}} \tag{3.1}$$

where P is the polarization, T_1^* and T_2 are the effective longitudinal and transverse relaxation times of the spin. In current situation, the magnetic field gradient at the cell position would not shorten the spin coherence time, and thus T_2 is expected to be nearly equal to T_1^*. Therefore the S/N ratio of the maser would be about a half of the FID signal. It was suggested that the co-existing ^{129}Xe and ^{131}Xe maser can be operated. The improvement in the S/N ratio will be achieved by further optimization of experimental conditions, such as the cell temperature, the power and the path of the pumping and probe laser light. Further optimization of parameters for the cell production also should improve the S/N ratio and the relaxation time.

4. Summary and future outlook

We propose the introduction of a ^{131}Xe spin maser with an external feedback scheme as a co-magnetometer for the measurement of atomic EDM of Xe. The pair of ^{129}Xe and ^{131}Xe is advantageous compared to others such as the ^{129}Xe-^{3}He pair, because in the former the systematic errors from the magnetic field drift and from the polarized Rb interaction can both be eliminated by the phase comparison, thanks to the almost identical strength of Xe-polarized Rb interaction for these two Xe isotopes. The performance of the ^{129}Xe-^{131}Xe co-existing cell was investigated through AFP-NMR measurements. The polarizations and the relaxation times presently obtained

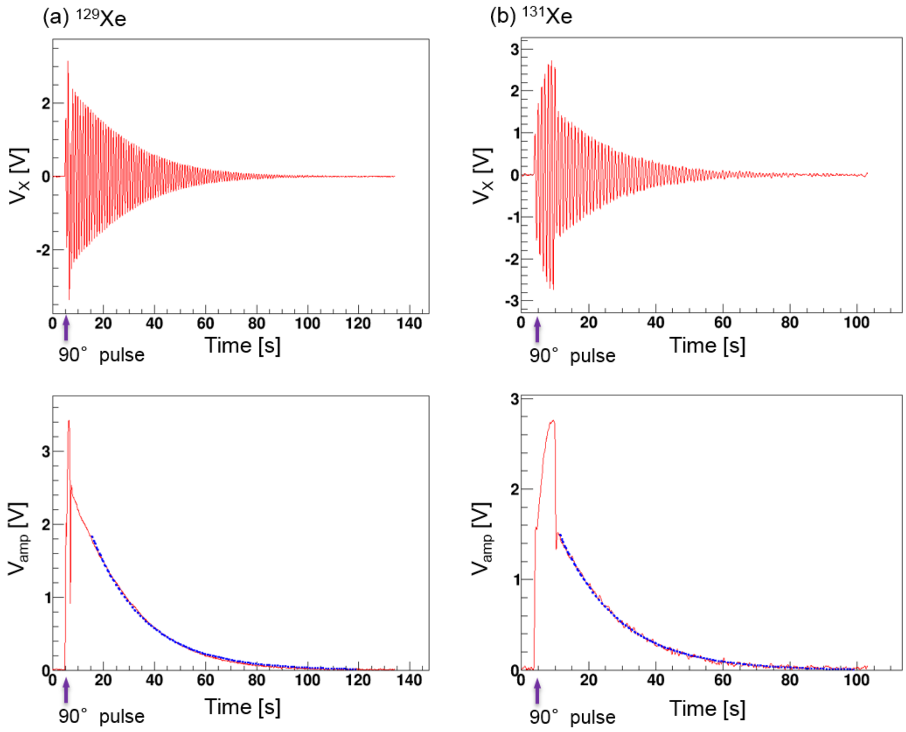

Figure 4: Observed FID signal (upper low) and amplitude (lower low) for ^{129}Xe and ^{131}Xe. The red points are obtained data and the blue dotted lines are fit function.

for ^{129}Xe and ^{131}Xe turned out to be sufficient for the maser operation. The FID signals for ^{129}Xe and ^{131}Xe were obtained in a ^{129}Xe-^{131}Xe co-existing cell. The detailed operation of the co-existing ^{129}Xe and ^{131}Xe masers and their performance will be presented in a forthcoming report.

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References

[1] N. G. Deshpande *et al.*, Phys. Lett. B **108**, 42 (1982).

[2] M. E. Pospelov, Phys. Lett. B 328, 441 (1994).

[3] A. I. Sanda, Phys. Rev. D 32, 2992 (1985).

[4] A. D. Sakharov, J. Exp. Theor. Phys. **5** 24 (1967).

[5] M. A. Rosenberry *et al.*, Phys. Rev. Lett. **86**, 22 (2001).

[6] T. Chupp and M. Ramsey-Musolf, Phys. Rev. C **91**, 035502 (2014).

[7] A. Yoshimi *et al.*, Phys. Lett. A **304**, 13 (2002).

[8] A. Yoshimi *et al.*, Phys. Lett. A **376**, 13 (2012).

[9] T. Inoue *et al.*, Eur. Phys. J. D **70**, 129 (2016).

[10] Y. Ichikawa *et al.*, EPJ Web of Conf. **66**, 05007 (2014).

[11] T. Sato *et al.*, JPS Conf. Proc. **6**, 020031 (2015).

[12] Z. L. Ma *et al.*, Phys. Rev. Lett. **106**, 193005 (2011).

[13] M. V. Romalis *et al.*, Phys. Rev. A **58**, 3004 (1998).

[14] M. Bulatowicz *et al.*, Phys. Rev. Lett. **111**, 102001 (2013).

[15] C. Funayama *et al.*, Hyperfine Interact. **236** 59 (2015).

[16] C. H. Volk, *et al.*, Phys. Rev. Lett. **44**, 3 (1984).

[17] D. Brinkmann, *et al.*, Helv. Phys. Acta. **29** 246 (1956).

[18] C. H. Volk, *et al.*, Phys. Rev. Lett. **44**, 136 (1980).

[19] Y. Sakamoto *et al.*, Hyperfine Interact. **230** 141 (2015).