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Observation of Larmor spin precession of laser-cooled Rb atoms via paramagnetic Faraday rotation

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We have observed Larmor spin precession in the ground state of laser-cooled ^{85}Rb atoms through paramagnetic Faraday rotation. We have been able to obtain a precision of 18 pT in the determination of the applied magnetic field, which proves the usefulness of laser-cooled atoms as an atomic magnetometer.
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There has been much progress in laser-cooling and -trapping techniques. Among many applications, sublevel coherence of cold atoms is one of the important topics. The long hyperfine coherence time realized by the atomic fountain has been successfully applied to the Cs atomic clock [1,2]. Collisional shift and broadening of the sublevel resonance have been calculated for several kinds of atoms [3,4] and the measurement with Cs atoms has been performed [1], which has given useful information on ultracold collisions. It has also been pointed out [4–6] that the precise measurement of a Larmor precession frequency using laser-cooled atoms is a promising way to search for an atomic electric-dipole moment (EDM), the existence of which is direct evidence of the violation of time-reversal symmetry [6]. Quite recently, a Bose-Einstein condensate with spin freedom has been realized in a dipole force trap [7].

In spite of such importance, there are few experiments on the Zeeman sublevel coherence of laser-cooled atoms [8]. In the present paper we describe our experiment on the observation of Larmor spin precession in the ground state of laser-cooled ^{85}Rb atoms through paramagnetic Faraday rotation. So far we have been able to demonstrate a precision of 18 pT in the determination of the applied magnetic field, which proves the usefulness of laser-cooled atoms as an atomic magnetometer. This experiment can be considered as a first step of a spin quantum nondemolition measurement recently proposed by us [9]. It is also noted here that, as pointed out by Dubetsky and Berman [10], the recoil during spontaneous emission induces a Faraday rotation, which can be verified experimentally with cold atoms.

Figure1(a) shows the schematic view of an experimental setup of our paramagnetic Faraday rotation experiment [11]. A linearly polarized probe laser beam was tuned at the wing of the ^{85}Rb D_2 resonance and was applied to the laser-cooled ^{85}Rb atoms along the z direction. In the presence of the atomic spin polarization S_z, σ^+ and σ^- circularly polarized beam components acquire different phase shifts ϕ_+ and ϕ_-, respectively, which are given as

$$\phi_\pm = \frac{2\pi l}{\lambda} n^\pm, \tag{1}$$

where l is the sample length in the z direction, λ the wavelength of the probe laser, and $n^\pm$ the refractive index for $\sigma^\pm$ circularly polarized light. This results in the rotation of the laser polarization with the angle $\Theta = (\phi_+ - \phi_-)/2$, which becomes proportional to the spin polarization S_z in the ordinary cases where hyperfine structures in the excited state can be neglected compared to the Doppler width [12–14]. Since the spin polarization initially produced in the x direction precesses around the magnetic field H_0 along the y direction at the Larmor frequency $\omega_L = \gamma H_0$ in the x-z plane, the observed rotation of the laser polarization is modulated at the Larmor frequency, from which we can know the magnitude of the applied magnetic field H_0. Here γ is the gyromagnetic ratio.

For paramagnetic Faraday rotation experiments, laser-cooled alkali-metal atoms are advantageous compared to an atomic vapor in a cell. The optical spectra of laser-cooled atoms are free from Doppler broadening and collisional broadening with a buffer gas. Consequently, the detuning of the probe laser can be smaller, which leads to a larger signal-to-noise ratio (SNR). However, the usually adopted approximation of neglecting hyperfine structures in the excited state

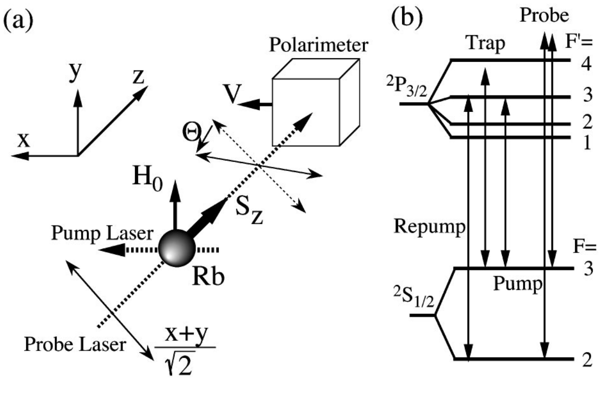

FIG. 1. (a) Experimental setup. Spin-polarized cold ^{85}Rb atoms were prepared by a standard MOT, polarization gradient cooling, and optical pumping. The paramagnetic Faraday rotation of probe laser polarization was detected by a polarimeter that consisted of a polarization beam splitter and two photodetectors. (b) Energy-level diagram of ^{85}Rb. The transitions for trappping, repumping, pumping, and probing are also indicated.

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*Author to whom correspondence should be addressed. Electronic address: yitk@scphys.kyoto-u.ac.jp is basically invalid in that situation. Figure 1(b) shows the energy-level diagram of the D_2 line of the ^{85}Rb atom. Therefore, it is not clear whether or not the observed rotation of the laser polarization exactly corresponds to the behavior of the spin polarization in the populated hyperfine state of the ground state. However, it can be shown straightforwardly that the sufficiently large detuning compared to the excited-state hyperfine splittings ensures the modulation of Θ only at the Larmor frequency. In this case, the detuning Δ_F for the transition from the ground hyperfine state with F does not depend much on the hyperfine splittings in the excited state and the expression of the Faraday rotation angle Θ_F for the ground state with F can be obtained as

$$\Theta_F = \frac{Nl\lambda^2}{8T_1\Delta_F}\sin(\omega_L t)\exp(-\Gamma t) \tag{2}$$

for the ground state hyperfine level $F=3$ and

$$\Theta_F = -\frac{Nl\lambda^2}{12T_1\Delta_F}\sin(\omega_L t)\exp(-\Gamma t) \tag{3}$$

for $F=2$, where N is an atomic density, T_1 a radiative lifetime, and Γ a phenomenologically introduced damping rate. Here we have assumed that the perfect spin polarization is produced in the x direction at $t=0$ in the ground hyperfine state with F. All the experimental data reported in this paper were taken with a detuning of about 3 GHz, which is sufficiently larger than excited-state hyperfine splittings, and so were analyzed based on the expressions (2) and (3).

We trapped and cooled ^{85}Rb atoms in a glass vapor cell by using the magneto-optical trap (MOT) method [15]. The background vapor pressure was about 1×10^{-8} Torr and was dominated by the partial pressure of Rb. A quadrupole magnetic field for the MOT was produced by a set of anti-Helmholtz coils and its gradient at the trap position was 10 G/cm for the axial direction (y). A ring Ti:sapphire laser was frequency locked to a Rb saturated absorption line and was used for trap beams after the frequency and intensity were adjusted with an acousto-optic modulator (AOM). The intensity of each beam was about 18 mW/cm^2 and the frequency was detuned by about 10 MHz below the resonance of the $F=3\leftrightarrow F'=4$ transition of the D_2 line $(^2S_{1/2}\leftrightarrow {}^2P_{3/2}$, 780 nm), as is shown in Fig. 1(b). To avoid optical pumping to the lower hyperfine level of the ground state $(F=2)$, an additional beam $(10-100$ mW/cm$^2)$ from a diode laser that was resonant to the $F=2\leftrightarrow F'=3$ transition was applied. The diameter of the trapped atom cloud was typically 1.5 mm, which was determined from an image with a charge-coupled device array. The atom density was typically 5×10^{10} cm^{-3} and the typical number of the trapped atoms 9×10^7.

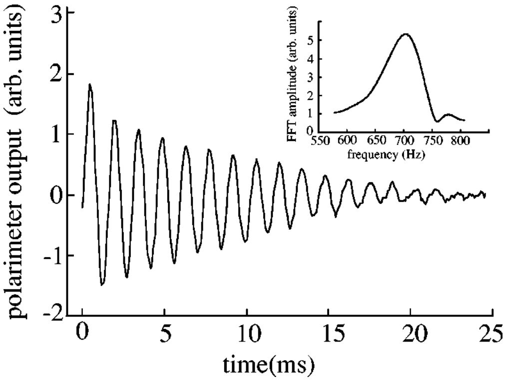

FIG. 2. Typical Faraday rotation signal from the atoms in the ground state $F=3$. An oscillation of frequency of about 1 kHz is observed, which corresponds to the applied magnetic field of about 2 mG. The inset shows the FFT spectrum of this signal.

After a MOT loading time of about 1 s, we turned off the magnetic-field gradient for the MOT and simultaneously reduced the trap beam intensity and increased the detuning. As a result, the atoms were further cooled to about 10 μK by the polarization gradient cooling mechanism [16]. Stray magnetic fields were considerably reduced and compensated for by a magnetic shield around the chamber and three orthogonal sets of Helmholtz coils about 25 cm in diameter. This was effective for obtaining low temperature and was also crucial for clear Faraday rotation signals. The temperature was measured by a standard time-of-flight method where the resonance fluorescence induced by a weak probe laser placed about 7 cm below the MOT region was monitored. After the polarization gradient cooling, the atoms were optically pumped by a circularly polarized light pulse 500 μs wide which was resonant to the $F=3\leftrightarrow F'=3$ transition, together with the repumping light tuned to the $F=2\leftrightarrow F'=3$ transition.

The power of the probe diode laser was well attenuated by a neutral density filter to several μW and the detuning was normally about 3 GHz, which is sufficiently larger than the natural linewidth and the excited hyperfine splittings. The cross section of the probe laser beam of about 1 mm^2 was almost the same as that of the trapped atom cloud, which gave the largest SNR. As is shown in Fig. 1(a), the polarization rotation of the probe laser was detected by a polarimeter [17] that consisted of a polarization-dependent beam splitter (PBS) and two photodetectors. The PBS divided x and y linearly polarized components and their powers were separately detected by two photodetectors. The difference of the two photodetector outputs was the final polarimeter output V, which is given as

$$V = 2V_0\sin(\Theta)\cos(\Theta) \simeq 2V_0\Theta, \tag{4}$$

when the incident probe laser polarization is aligned along the $(\mathbf{x}+\mathbf{y})/\sqrt{2}$ direction so that the output became zero in the case of no spin polarization. Here V_0 corresponds to the sum of the two photodetector outputs. The polarimeter output was amplified after a low-pass filter of 10-kHz cutoff frequency. Typically 20 signals were averaged. It is noted that mechanical stabilities of probe diode laser and polarimeter were crucial for observing the unfluctuated signal.

Figure 2 shows a typical Faraday rotation signal. One can recognize the sinusoidally modulated signal with a good SNR. Here we have defined $t=0$ as the end of the optical pumping. The oscillation frequency of about 1 kHz corresponds to the Larmor frequency in the $F=3$ state under the applied magnetic field of about 2 mG. By turning off the repump laser during the last several hundred microseconds of the optical pumping period, the atoms were also populated in the $F=2$ state. The Faraday rotation signals of the $F=2$ state were π out of phase with those of the $F=3$ state, which is consistent with Eqs. (2) and (3). The signals showed sign reversal across the resonance, as was expected from the detuning dependence of the expressions (2) and (3).

Several mechanisms were considered for the decay of the Faraday rotation signal. Ballistic motion of the atoms in an inhomogeneous magnetic field gives dephasing of the spin polarization. In our experiment, the MOT coils were driven by a high-power operational amplifier and a diode in series with the coils ensured minimal current flow in the off state. The irradiation of the nearly resonant light also destroys the spin polarization. In fact, the decay time was found to be sensitive to even a weak leakage light beam from AOM, so we used mechanical shutters to completely shut off the leakages of the pumping and trapping light beams. In addition, as was mentioned earlier, the probe beam power was well attenuated and the large detuning of typically 3 GHz was taken so that the probe beam irradiation did not affect the decay time. After these improvements, we obtained longest decay time of 11 ms, as shown in Fig. 2.

This decay time was found to be almost the same as the interaction time that the atoms spend escaping from the probe beam region by free fall. This interaction time τ_I is given by

$$\tau_I = \sqrt{2L/g}, \tag{5}$$

where g is the gravitational acceleration constant and L the diameter of the probe beam. In fact, the absorption measurement of a weak resonant probe laser beam in exactly the same configuration showed almost the same decay time. From the square-root dependence of L for the interaction time τ_I, a longer decay time is expected by increasing the probe beam diameter L. It is noted, however, that only the partial cross section of the beam that interacts with the atom cloud can contribute to the signal. The expected signal amplitude scales as $1/L^2$ for a round beam as long as the size of the atom cloud does not change and remains small compared to the beam size. The noise in our experiment was mainly determined by the probe laser power and not by the beam diameter L. Thus a longer decay time obtained with large L did not pay from the viewpoint of the SNR. All the measurements in this paper were therefore performed under the optimal condition of $L\sim 1$ mm, which was almost equal to the size of the atom cloud.

In addition, when the time for polarization gradient cooling was short, we observed a chirped Faraday rotation signal probably due to the residual magnetization of the surrounding magnetic shield. The Fourier-transformed spectrum showed extra broadening by about 100 Hz. About 20 ms of polarization gradient cooling was enough to eliminate the chirping behavior in the signals.

To deduce the magnitude of the applied magnetic field H_0, we have performed a Fourier transformation of the signals. In this process we applied some useful techniques widely used in Fourier transform nuclear magnetic resonance spectroscopy [18]. To obtain the digital frequency resolution of 0.2 Hz, we artificially added null points for 5 s after the signal, which was 40 ms wide, which is known as a zero filling [18]. The width of the fast Fourier transform (FFT) spectra was about 70 Hz, which is consistent with the observed decay time. The obtained FFT signals were not symmetrical due to a feeble parasitic noise at $t\sim 9$ ms, as is shown in the inset of Fig. 2. The symmetrical spectra were obtained by using only the data after $t=9$ ms and the method of a matched filter [18] was helpful for increasing the SNR. By using these spectra, we estimated the precision in the determination of the change of the magnetic field, which is important in the search for the EDM. Since the FFT spectra obtained by the truncated data were broader than that obtained by the full data, the latter showed better precision. Figure 3 shows the histogram of the 30 peak frequencies of the FFT spectra obtained by using the full data. It is noted that the frequency that gives the maximum value in the FFT spectrum was chosen as the peak frequency. The best-fit Gaussian function is also shown. From this histogram we obtain a precision of 18 pT in the determination of the applied magnetic field. Although this is still about three orders of magnitude larger than the shot-noise limit, the obtained precision of a region of 100 mHz [19] demonstrates the usefulness of laser-cooled atoms in magnetometry.

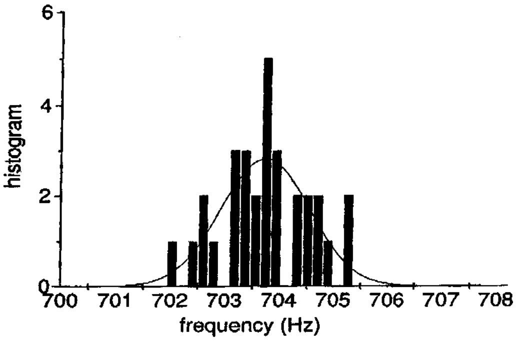

FIG. 3. Histogram of the peak frequencies of 30 Fourier transformation spectra of Faraday rotation signals. Note that the magnetic field applied in these measurements was slightly higher than that in the measurement of Fig. 2. A fit with a Gaussian function is also shown.

We have several plans to improve the precision. The dipole force trapping technique [20] will be effective for obtaining a longer observation time than the present value of about 10 ms limited by free fall by gravity. The dipole force trap with a blue-detuned laser beam is particularly suitable for this purpose since the atoms spend most of the time in a free space in the trap, which is in contrast to the trap with a red-detuned laser beam. The atomic fountain technique will be also useful. To reduce the transverse spread of the atom cloud during the fountain, the guidance by a blue-detuned dipole force with a Laguerre-Gauss mode beam will be effective.

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