Spin noise measurement with diamagnetic atoms

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We report the measurement of the atomic spin noise of the diamagnetic atom ytterbium (Yb). Yb has various merits for utilizing the quantum nature of the atomic spin ensemble compared with the paramagnetic atoms used in all previous experiments. From the magnitude of the noise level and dependence on the detuning, we concluded that we succeeded in the measurement of ^{171}Yb atomic spin noise in an atomic beam.

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Atomic spin noise is the quantum-mechanical noise limited by the Heisenberg uncertainty relation. In the case of uncorrelated spins perfectly polarized along the x axis, which is known as coherent spin state (CSS) [1], the variance becomes $\langle \Delta S_y^2 \rangle = \langle \Delta S_z^2 \rangle = |\langle S_x \rangle|/2$, where $\mathbf{S}$ is the summation over the individual spins and $S \equiv |\langle S_x \rangle|$ is the total spin. In the case of unpolarized atoms whose individual spin is F with the same atom number, the variance is $2(F+1)/3$ times larger than the spin noise of the CSS [2].

There are many interesting topics related to the atomic spin noise. For example, quantum nondemolition measurement of spin [3], spin squeezing [1,2,4], entanglement of two macroscopic objects [5], and quantum memory for light [6] have been demonstrated. These topics are interesting in the fields of quantum information processing. Moreover, the suppression of the uncertainty will be also important, for example, for the application to the precision measurement of atomic spin, permanent electric dipole of atom [7].

Almost all the experiments in which the atomic spin noise was successfully observed [2–5,8] are based on the paramagnetic Faraday rotation of linearly polarized light [9]. The polarization state of light after the transmission of the atomic spin $\mathbf{J}^{(\mathrm{out})}$ is connected with that of the initial state $\mathbf{J}^{(\mathrm{in})}$ as [10]

$$J_y^{(\mathrm{out})} = J_y^{(\mathrm{in})} + J_x^{(\mathrm{in})} \alpha t_1 S_z, \tag{1}$$

$$J_z^{(\mathrm{out})} = J_z^{(\mathrm{in})}, \tag{2}$$

where αt_1 is a real constant, the z axis of $\mathbf{S}$ is set parallel to the wave vector of the probe light, and we assume $\alpha t_1 S_z \ll 1$. $\mathbf{J}$ is the quantum-mechanical Stokes vector of the light, which obeys the usual commutation relation of angular momenta $[J_i, J_j] = i\varepsilon_{ijk} J_k$. For a light pulse with the duration T propagating in free space, $\mathbf{J}$ can be written as $J_x = (1/2)\int_0^T (a_+^\dagger a_- + a_-^\dagger a_+) dt$, $J_y = (1/2i)\int_0^T (a_+^\dagger a_- - a_-^\dagger a_+) dt$, and $J_z = (1/2)\int_0^T (a_+^\dagger a_+ - a_-^\dagger a_-) dt$, where $a_\pm$ is the annihilation operators of $\sigma_\pm$ circular polarization mode, respectively [11]. When the probe light is a coherent pulse which is linearly polarized along the x axis and contains $2J \gg 1$ photons on the average, the variance of the y component of the Stokes vector becomes

$$\langle \Delta J_y^{(\mathrm{out})2} \rangle = \frac{J}{2} + (J\alpha t_1)^2 \langle \Delta S_z^2 \rangle. \tag{3}$$

As Eq. (3) shows, the fluctuation of the atomic spin induces the fluctuation of the polarization of the probe light. In Fig. 1, we schematically illustrate this relation.

In this paper, we report the successful measurement of the atomic spin noise of diamagnetic atom, ytterbium (Yb) in an intense atomic beam. The electronic ground state of Yb is diamagnetic ($^1S_0$) and the magnetic moment is three order of magnitude smaller than the paramagnetic atoms. Therefore, the suppression of the systematic noises caused by the fluctuation of the stray magnetic field is experimentally easier, and the large spin polarization is relatively easily obtained since the optical pumping process can be faster than the decoherence and the Larmor precession [12]. In the case of the atomic beam of Yb, it can be confirmed whether the origin of the noise is the atomic spin or not by comparing spin-0 isotopes (^{168}Yb, ^{170}Yb, ^{172}Yb, ^{174}Yb ^{176}Yb), spin-1/2 isotope (^{171}Yb), and spin-5/2 isotope (^{173}Yb). We also report the successful measurement of spin-0 isotopes at the shot noise level, which indicates that the contribution of ^{171}Yb classical excess noise to the observed noise measurement are negligible. The experimental result is the important step for the realization of the atomic spin ensemble with the long coherence time.

In Fig. 2, we depict the experimental setup.

As the model of the system, we consider the case that the atoms are a CSS polarized along the x axis and traveling along the y axis with the velocity v. They are continuously probed by a coherent light propagating along the z axis with

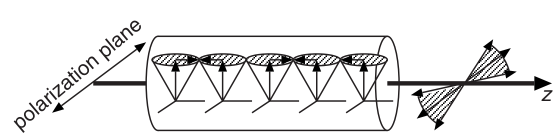

FIG. 1. Schematic illustration of atomic spin noise measurement via the paramagnetic Faraday rotation. The fluctuation of the atomic spin induces the fluctuation of the polarization of the probe light.

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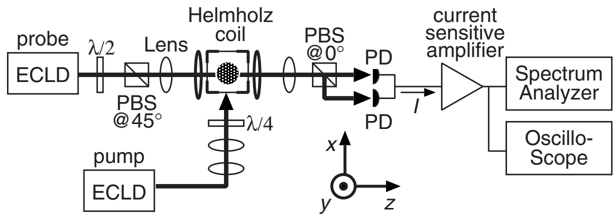

FIG. 2. Experimental setup. The atomic beam was generated from an atomic oven heated about T_a=600 °C and collimated by an aperture of the diameter L=5 mm. The probe beam was focused with the beam waist w=0.14 mm. The optical pumping beam was magnified so as to cover the diameter of the atomic beam. A pair of Helmholtz coils was set around the atomic beam. The differential current of the two photodiodes was amplified by a low-noise amplifier. The amplifier was connected to an oscilloscope and a spectrum analyzer. ECLD: External cavity laser diode, PD: Photodiode; PBS: Polarization beam splitter. The angle of the PBS from the x axis is also written.

the beam waist w. Since the atoms transit the probe region, we phenomenologically introduce the autocorrelation function as

$$\langle S_z(t)S_z(t+\tau)\rangle = \langle \Delta S_z^2\rangle \exp(-|\tau|/T), \tag{4}$$

where T is the mean transit time of an atom through the probe region. The differential current of the two photodiodes I can be written as

$$I(t) = 2\eta e[j_y(t) + \alpha t_1 j S_z(t)], \tag{5}$$

where $j_y \equiv (a_+^\dagger a_- - a_-^\dagger a_+)/2i$ and $2j \equiv \langle a_+^\dagger a_+ + a_-^\dagger a_-\rangle$ is the photon flux per unit time, η is quantum efficiency of the photodiodes, and e is the charge of an electron. The power spectrum of I can be separated into two terms as

$$\bar{I}(\nu)^2 = \int_{-\infty}^{\infty} \langle I(0)I(\tau)\rangle \exp(-i2\pi\nu\tau)d\tau = \bar{I}_{\mathrm{SN}}^2 + \bar{I}_{\mathrm{spin}}^2(\nu), \tag{6}$$

where $\bar{I}_{\mathrm{SN}}^2 = 2e\langle I_+\rangle$ is the shot noise of the probe light and $\bar{I}_{\mathrm{spin}}^2(\nu)$ is the noise caused by the atomic spin,

$$\bar{I}_{\mathrm{spin}}^2(\nu) = (\alpha t_1 \langle I_+\rangle)^2 \frac{2\langle \Delta S_z^2\rangle/T}{(2\pi\nu)^2 + (1/T)^2}. \tag{7}$$

The quantity of $\langle I_+\rangle = 2\eta e j$ can be evaluated experimentally by summing the each photocurrent of the two photodiodes.

Now, we explain the details of the setup. The atomic oven was heated about T_a=600 °C. At this temperature, the average velocity is estimated as $v=\sqrt{9\pi k_B T_a/8M_a}$=0.39 km/s, where k_B is Boltzmann's constant and M_a is the mass of an atomic Yb [13]. The atomic beam was collimated by an aperture of the diameter L=5 mm. As the source of the probe light and the optical pumping light, we constructed two external cavity laser diodes (ECLD). They were tunable around the $^1S_0 \to {}^1P_1$ transition of Yb, whose wavelength is 399.8 nm. The probe beam was focused with the beam waist w=0.14 mm by a lens of focal length 150 mm, whose power at the atoms was 34 μW. Therefore, the mean transit time was estimated as $T \sim \sqrt{2}w/v$=0.51 μs. At this intensity, the Rabi frequency was estimated as $\Omega = 2\pi \times 19$ MHz. In Fig. 3, we show the absorption spectrum of the probe light, where ω is the angular frequency, and ω_{174} is the resonant angular frequency of ^{174}Yb.

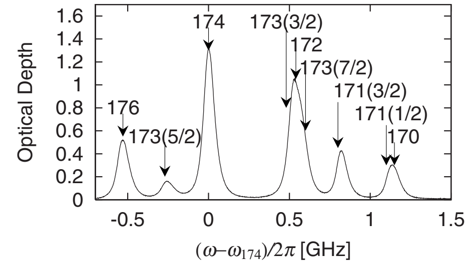

FIG. 3. Absorption spectrum of the atomic beam. The numbers and those in the parentheses represent the mass number and the hyperfine quantum number, respectively. From this figure, the linewidth caused by the transverse Doppler broadening was measured as Γ^*=54 MHz, and the number density of ^{171}Yb was estimated as $n = 1.6 \times 10^{15}$ m^{-3}.

The atomic beam was so well collimated that the linewidth caused by the transverse Doppler broadening $\Gamma^* = 2\pi \times 54$ MHz was about twice the natural linewidth $\Gamma = 2\pi \times 29$ MHz. This Γ^* was obtained from the fitting with the isotope shifts, the hyperfine splittings, and the relative transition probabilities for π polarized light among the hyperfine sublevels [14].

The spin noise measurement was performed by using a fermionic isotope ^{171}Yb. From the peak height of ^{171}Yb(F'=3/2) line in Fig. 3, the number density of the atoms of ^{171}Yb was estimated as $n = 1.6 \times 10^{15}$ m^{-3}. Therefore, total spin and the atomic spin noise of ^{171}Yb in the probe region was estimated as $S = n\pi w^2 L/2 = 2.4 \times 10^5$ and $\langle \Delta S_z^2\rangle = S/2 = 1.2 \times 10^5$, respectively. The optical pumping beam was magnified so as to cover the diameter of the atomic beam, and the power was 0.5 mW and the frequency was tuned to the $^1S_0 \to {}^1P_1(F'=1/2)$ transition of ^{171}Yb. At this condition, the polarization is estimated as $p \sim 1$. A pair of Helmholtz coils was set around the atomic beam so as to cancel the stray magnetic field parallel to the probe light below 1×10^{-4} T. The differential current of the two photodiodes (Hamamatsu S5973-02) was amplified by a low-noise amplifier (Amptek A250) with the sensitivity 5×10^4 V/A. To measure $\langle I_+\rangle$ and $\bar{I}^2(\nu)$, the amplifier was connected to an oscilloscope and a spectrum analyzer (Anritsu MS2602A).

In Fig. 4(a), we show the noise spectrum with unpolarized ^{171}Yb atoms. The spin of ^{171}Yb is F=1/2, so the spin noise of the unpolarized state is the same as that of the CSS, and the spectrum is similarly expressed by Eq. (7). The probe frequency was tuned at $\omega - \omega^{(3/2)} = 2\pi \times 0.16$ GHz, where $\omega^{(F')}$ is the resonant frequency of the $^1S_0 \to {}^1P_1(F')$ transition of ^{171}Yb. This frequency corresponds to the middle of the hyperfine levels (F'=3/2 and F'=1/2), where the atomic spin noise most clearly appears at the middle of the hyperfine levels as is shown in Fig. 5(a) and is calculated straightforwardly in [14]. The observed noise spectrum is compared with the theoretical value calculated in Eq. (7). At

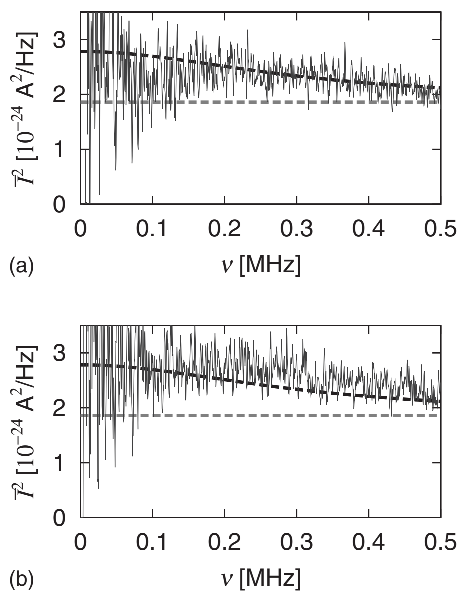

FIG. 4. Noise spectra of ^{171}Yb obtained for the probe frequency was tuned at $\omega-\omega^{(3/2)}=2\pi\times0.16$ GHz. The bandwidth of the spectrum analyzer was 10 kHz. Note that the measured noises shown in these figures were divided by this bandwidth. (a) Noise spectrum with unpolarized ^{171}Yb atoms (black solid line). This spectrum agrees well with the fitting curve based on Eq. (6) (black dotted line). The shot noise level $2e\langle I_+\rangle$ (gray dotted line) is also shown. (b) Noise spectrum with polarized ^{171}Yb atoms (black solid line). The shot noise level (gray dotted line) and the fitting curve for the unpolarized atoms (black dotted line) are also shown.

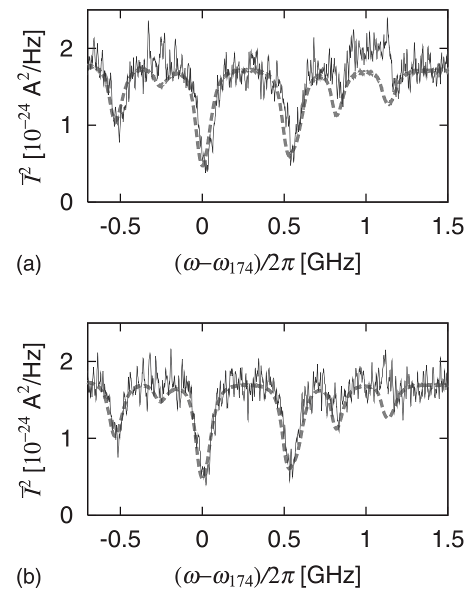

FIG. 5. (a) Dependence of the noise on the probe laser detuning (solid black line). The gray dotted line is the shot noise level $2e\langle I_+\rangle$, where the attenuation of the probe transmission due to the absorption is incorporated. The noise level around the resonance of the spin-0 isotopes (^{174}Yb, ^{176}Yb) are the same as the shot noise level. The excess noises between the resonance of ^{171}Yb($F'=1/2$) and ^{171}Yb($F'=3/2$), and close to the resonance of ^{173}Yb($F'=5/2$) were clearly observed. (b) Noise when the polarimeter has the sensitivity to $j_z=(a_+^\dagger a_+ - a_-^\dagger a_-)/2$ (gray solid line). The gray dotted line is the shot noise level $2e\langle I_+\rangle$.

the low frequency region below 0.15 MHz, however, some classical noise is dominant and we do not consider the noises at this region. As Eq. (7) indicates, the atomic spin noise decreases at high frequency region above $1/T\sim2\pi\times0.31$ MHz. The noise level without atoms was well suppressed to the shot noise level $2e\langle I_+\rangle$, which we have confirmed experimentally.

For quantitative comparison of the spectrum above 0.15 MHz, we need to know the value of αt_1 in Eq. (7) to theoretically evaluate $\bar{I}^2(\nu)$. In the case of ^{171}Yb, αt_1 is written as [14]

$$\alpha t_1 = \frac{\sigma_0 \Gamma^*}{3\pi w^2}\,\mathrm{Re}(g^{(3/2)} - g^{(1/2)}), \tag{8}$$

where $\sigma_0=7.598\times10^{-14}$ m^2 is the photon-absorption cross section of an atom, and $g^{(F')}$ is a complex line shape function around $\omega^{(F')}$,

$$g^{(F')} = \frac{(\omega^{(F')}-\omega) + i\Gamma^*/2}{(\omega^{(F')}-\omega)^2 + (\Gamma^*/2)^2}. \tag{9}$$

At the detuning of $\omega-\omega^{(3/2)}=2\pi\times0.16$ GHz, αt_1 was estimated as $\alpha t_1=-2.7\times10^{-7}$. When we fit the spectrum with unpolarized atoms based on Eq. (6) above 0.15 MHz, we obtain $T=0.51$ μs and $\langle\Delta S_z^2\rangle=3.6\times10^5$, with the measured value $\langle I_+\rangle=5.8$ μA. The time constant T and the atomic spin noise $\langle\Delta S_z^2\rangle$ agree with the estimation which we have discussed above. The rather good fitting (black dotted line) for the experimental result supports the phenomenological introduction of Eq. (4).

We show the noise spectrum for the polarized state in Fig. 4(b). Although the noise level for the polarized state is quite similar to that for the unpolarized atoms, the small difference is recognized between Figs. 4(a) and 4(b). The observed difference was not fully understood yet. It might be related to fluctuation of the spin polarization introduced by the photon scattering by the probe light. The photon scattering rate can be written as [14]

$$r = \frac{\Omega^2}{6}\,\mathrm{Im}(2g^{(3/2)} + g^{(1/2)}), \tag{10}$$

and was estimated as $r=1.2\times10^6$ s^{-1} at the detuning of $\omega-\omega^{(3/2)}=2\pi\times0.16$ GHz. Since the interaction time was $T=0.51$ μs, the number of the photon scattering was estimated as $rT=0.62$, which is not large enough to completely depolarize the spins and at the same time not small enough to satisfy the condition for the conservation of the spin state, $rT\ll1$. Another possibility for the slight difference may be the intensity difference of the atomic beam for the unpolarized atoms and that for the polarized atoms.

Secondly, we examined the dependence of the observed excess noise on the detuning of the probe laser. In the following measurements, we switched off the optical pumping beam, and set the frequency of the spectrum analyzer at ν

=0.5 MHz with the bandwidth at 10 kHz. In Fig. 5(a), we show the result.

The noise around the resonance of the spin-0 isotopes (^{174}Yb, ^{176}Yb) were the same as the shot noise level, which indicates that classical excess noise caused by the atoms are negligible. Such a calibration was possible because Yb includes spin-0 isotopes. And there were excess noises between the resonances of ^{171}Yb($F'=1/2$) and ^{171}Yb($F'=3/2$), and close to the resonance of ^{173}Yb($F'=5/2$). This observation also supports that the excess noise is caused by the atomic spin.

Finally, we performed the noise measurement by inserting a $\lambda/4$ plate in front of the polarization beam splitter in the polarimeter to confirm the observed excess noise was due to the fluctuation of the linear polarization. In this case, the output of the polarimeter corresponds to $j_z=(a_+^\dagger a_+ - a_-^\dagger a_-)/2$, and from Eq. (2), the noise level for this configuration becomes $\bar{I}^2(\nu)=\bar{I}_{SN}^2$, which means that the atomic spin noise vanishes. In Fig. 5(b), we show the experimental result. The noise was almost at the shot noise level at all detunings except at the resonance of ^{171}Yb($F'=1/2$). We think the excess noise in this case is caused by the optical pumping with the probe light. However, we stress that the large noise between the hyperfine splitting of ^{171}Yb vanished as we expected.

In this paper, we report the observation of the atomic spin noise with Yb. From the magnitude of the noise level and dependence on the probe laser detuning, we concluded that we have succeeded in the measurement of the atomic spin noise. By use of laser cooling and trapping of Yb [14], the coherence time will be much longer.

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