Spontaneous Noise Spectroscopy of an Atomic Magnetic Resonance

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(Received 14 September 1999)

We have experimentally demonstrated a new type of noise spectroscopy, which requires neither amplitude nor frequency noise of the light source. A highly stabilized diode laser provides low-noise light for the optical magnetic resonance of Rb atoms. The laser light transmitted through the Rb vapor contains significant intensity fluctuations whose power spectrum has a distinct peak at the Larmor frequency. The fluctuations are spontaneously generated by the atoms and are attributed to the stochastic properties of the photon scattering which randomly interrupts the Larmor precession of the atomic magnetic moment.

PACS numbers: 32.80.–t, 32.90.+a, 42.62.Fi

Noise analysis of sample response has been extensively carried out in various fields of science and technology. It can generally be divided into two groups. The first is the application of randomly modulated excitation to the sample and the observation of its response, which simultaneously provides information over a wide range of frequency components. However, the information is, in principle, the same as that obtained by coherent modulated excitation at various modulation frequencies. The second is the investigation of the noise spontaneously generated by the sample itself. This noise contains information regarding the properties inherent to the sample. For example, shot noise in electric current reflects the magnitude of the carrier charge [1]. In the field of optical spectroscopy, only noise excitation spectroscopy [2–9] has been performed so far, where some noise is deliberately added to the otherwise stable light source.

In this Letter, we report on the spontaneous noise appeared in optical detection of magnetic resonance of Rb atoms. In a magnetic field, a Rb atom in the ground state $5\,^2S_{1/2}$ undergoes Larmor precession, which is described in terms of quantum mechanics as a coherent time evolution of the spin-up and spin-down sublevels. The precession modulates the photon scattering rate of the atom at the Larmor frequency and is conversely modulated by the photon scattering because it stochastically interrupts the Larmor precession by exciting the atom. Therefore, the light intensity transmitted through the Rb vapor fluctuates (spontaneous noise), and the power spectrum has a peak at the Larmor frequency with a width determined by the photon scattering rate. The width is much smaller than the Doppler width for the optical transition because the time evolution of the spin sublevels is not affected by the Doppler effect. It is worth noting here that the intensity of the spontaneous noise is proportional to $\sqrt{N}\,\sigma$, whereas the signal intensity in the coherent modulation spectroscopy is proportional to $N\sigma$, where N denotes the number of atoms interacting with the light and σ is the photon scattering cross section. This dependence allows us to determine N and σ separately when used in conjunction with the conventional modulation spectroscopy.

Let us consider N atoms interacting with the resonant laser light propagating along the z axis as depicted in Fig. 1(a). A photon flux Φ_0 is partly absorbed by the atoms, and the remaining flux Φ is transmitted through the vapor. Then,

$$\Phi_0 - \Phi = \Delta\Phi = \sum_{j=1}^{N} P_j\,, \tag{1}$$

where P_j is the photon scattering rate of the jth atom.

We consider an atom as a four-level system [Fig. 1(b)] with the total angular momentum $J = 1/2$ for both the electronic ground $|g\rangle$ and excited $|e\rangle$ states; the two eigenstates of $m_J = +1/2$ and $m_J = -1/2$ are, respectively, denoted by $|+\rangle$ and $|-\rangle$. A circularly polarized σ^+ laser light induces the transition from $|g-\rangle$ to $|e+\rangle$. When the excitation is so weak that the excited state population is negligible, the atomic system can be described in terms of a normalized magnetic moment $\vec{M}$ [Fig. 1(c)]. The z component $M_z = \rho_{g+g+} - \rho_{g-g-}$ determines the scattering rate for the σ^+ light as [10–12]

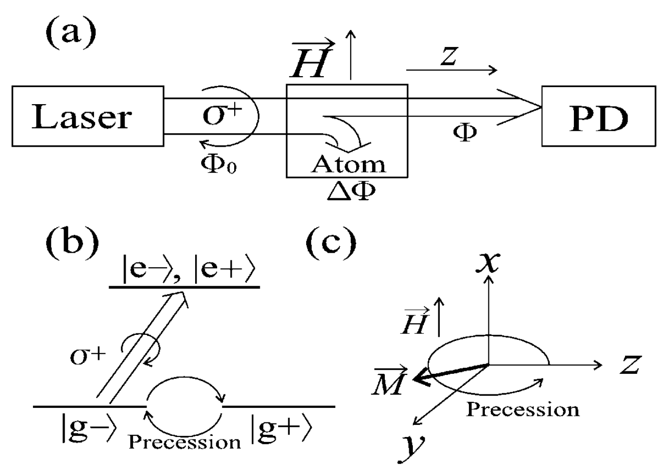

FIG. 1. (a) Optical system. (b) A four-level system, together with the laser excitation and the Larmor precession. The excited levels are represented by a single state, assuming the collisions mix them in the high pressure buffer gas. (c) The same four-level system is described in terms of a normalized magnetic moment $\vec{M}$, when the excited state populations are negligible. It precesses around the magnetic field at the Larmor frequency.

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$$P_j = \frac{\phi(\vec{r}_j)\sigma}{2}(1 - M_{zj}), \tag{2}$$

where ρ is the density matrix and $\phi(\vec{r}_j)$ is the photon flux per unit area at the jth atomic position $\vec{r}_j$.

When the magnetic field is applied perpendicularly to the z axis, the magnetic moment of the atom precesses about it at the Larmor frequency [Fig. 1(c)]. This precession modulates the photon scattering rate P_j at the Larmor frequency according to Eq. (2). Once the photon excites the atom, the Larmor precession is interrupted. Then the excited atom rapidly decays through spontaneous emission to the ground state, in which the magnetic moment may point in any direction. Therefore, the photon scattering dephases the Larmor precession and thus reduces the autocorrelation of the atomic magnetic moments at different times. We phenomenologically introduce the stochastic properties of $M_{zj}(t)$ as

$$\langle M_{zj}(t)M_{zk}(t + \tau)\rangle = \frac{\delta_{jk}}{3}\exp(-\gamma|\tau|)\cos(2\pi\nu_0\tau), \tag{3}$$

$$\langle M_{zj}(t)\rangle = 0, \tag{4}$$

where the Kronecker delta δ_{jk} represents that there is no correlation between the atoms, the factor $1/3$ indicates the random orientations of the atomic magnetic moment, ν_0 is the Larmor frequency, $\gamma \approx \langle P_j\rangle$ is the dephasing rate of the Larmor precession by the photon scattering, and $\langle\,\rangle$ is the ensemble average over both the atoms and light.

A photodetector receives the transmitted laser light and generates photocurrent $I(t) = \eta q\Phi$, where η is the quantum efficiency of the entire photodetection system and q is the electron charge. From Eqs. (1) and (2), the photocurrent is

$$I(t) \approx \eta q\left[\left(\Phi_0 - \sum_{j=1}^{N}\frac{1}{2}\phi(\vec{r}_j)\sigma\right) + \sum_{j=1}^{N}\frac{1}{2}\langle\phi\rangle\sigma M_{zj}\right], \tag{5}$$

where we replace $\phi(\vec{r}_j)\sigma M_{zj}$ by $\langle\phi\rangle\sigma M_{zj}$. The $I(t)$ consists of two independent noises: the first term in the bracket contains the light noise, and the second term contains the atomic noises. Hence the power spectrum

$$\tilde{I}(\nu) = \sqrt{\lim_{T\to\infty}\frac{1}{T}\left\langle\left|\int_{-T}^{T}dt\, I(t)\exp(i2\pi\nu t)\right|^2\right\rangle} \tag{6}$$

can be separated into two contributions. When the light noise is limited by the shot noise, it is given by

$$\tilde{I}(\nu) = \sqrt{\tilde{I}_{\mathrm{SN}}^2 + \tilde{I}_{\mathrm{atom}}(\nu)^2}, \tag{7}$$

where $\tilde{I}_{\mathrm{SN}}$ is the shot noise known as [1]

$$\tilde{I}_{\mathrm{SN}} = \sqrt{2q\langle I(t)\rangle}, \tag{8}$$

and $\tilde{I}_{\mathrm{atom}}(\nu)$ is the spontaneous atomic noise written as

$$\tilde{I}_{\mathrm{atom}}(\nu) = \sqrt{\frac{2N}{3}\left(\frac{q\eta\sigma\langle\phi\rangle}{2}\right)^2\frac{\gamma}{\gamma^2 + 4\pi^2(\nu_0 - \nu)^2}}, \tag{9}$$

from Eqs. (3)–(6). The expression is proportional to $\sqrt{N}\,\sigma$, which indicates that the spontaneous noise is based on the granularity of the atomic system, just as the shot noise of the photocurrent is caused by the granularity of the photon.

In the experiment, we use a long cavity distributed Bragg reflection laser ($\lambda = 795$ nm, YL78XNW, Yokogawa, Japan). It has a 5-mW output and a spectral linewidth of 700 kHz at a free oscillation. We reduce the amplitude modulation (AM) noise and frequency modulation (FM) noise of the laser as follows. To eliminate the AM noise, we suppress the injection current noise using a low-pass filter with a time constant of 10 ms [13]. The residual AM noise at the light intensity of 50 μW is measured with a frequency spectrum analyzer (Hewlett Packard, ESA-L1500A) to be at most 15% above the shot noise level in the frequency range of 2 to 10 MHz. The FM noise of the diode laser is greatly reduced by an optical feedback from a confocal cavity (SA-300, Technical Optics) with a free spectral range of 300 MHz and a finesse of 300 [14], which makes the spectral linewidth of the laser as narrow as 500 Hz with a time constant of 10 ms.

Figure 2 shows the experimental setup. It is for a transverse optical pumping experiment [15], where a static magnetic field of 3 to 15 G is applied by a pair of Helmholtz coils. The stabilized laser light with a beam diameter of 0.5 mm, a power level of 110 μW, and σ^+ polarization passes through a sample cell and is detected by a Si-pin photodiode. The detected power level is 50 μW, and the power spectrum of the intensity fluctuation is observed by the frequency spectrum analyzer.

Rubidium atoms are sealed in a glass cell with a buffer gas of 200-Torr nitrogen, and the ^{85}Rb-D_1 line ($5\,^2S_{1/2}$-$5\,^2P_{1/2}$) is optically excited. The cell has a 5-cm long optical path and is heated up to 80 °C where the

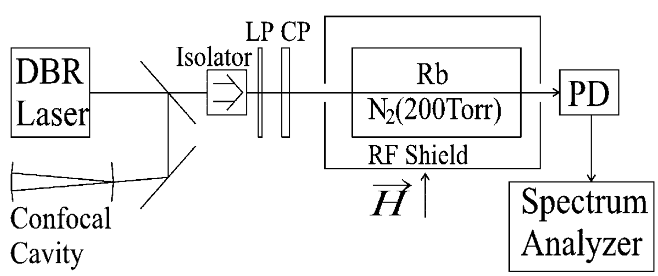

FIG. 2. Experimental setup: LP, linear polarizer; CP, circular polarizer; PD, photodetector. An rf shield prevents atoms from being excited by a radio-frequency magnetic field.

number density is estimated to be $10^{12}/\text{cm}^3$. The buffer gas expands the spectral linewidth up to 6 GHz beyond the hyperfine splitting of 3 GHz, which greatly simplifies the quantitative analysis of the experimental results for three reasons: First, the four-level system is experimentally realized. Second, we can estimate the number of atoms interacting with the laser light without considering the hyperfine optical pumping effect. Third, when the spectral line profile sharply varies with the laser frequency, the FM noise of the laser is efficiently converted to the intensity fluctuation in the transmitted light. The broad linewidth drastically reduces the conversion.

Figure 3 shows the observed noise spectra as a function of the frequency for various magnitudes of the magnetic field. The vertical axis is the observed photocurrent noise normalized to the shot noise level $\tilde{I}_{\text{SN}}$. In the present case, the photocurrent of $\langle I \rangle = 20\ \mu\text{A}$ corresponds to $\tilde{I}_{\text{SN}} = 2.53\ \text{pA}/\sqrt{\text{Hz}}$. In Fig. 3, a distinct peak appears above the shot noise level at the Larmor frequency. Here the gyromagnetic ratio of the ground state is 0.467 MHz/G.

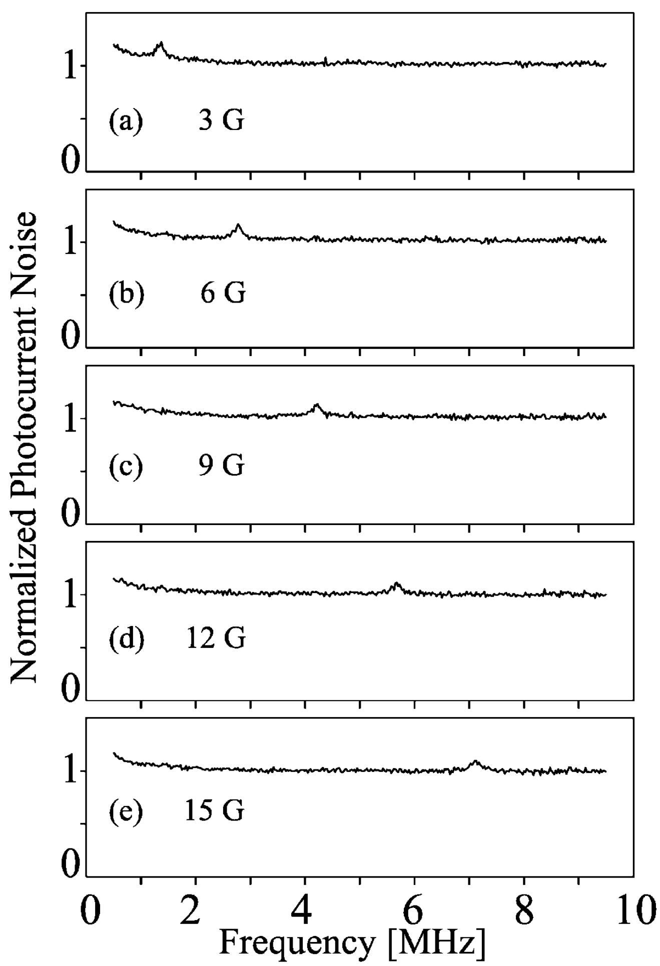

FIG. 3. The observed intensity noise spectra for various magnitudes of the magnetic field. The resolution bandwidth of the spectrum analyzer is 30 kHz.

To distinguish the spontaneous noise from the noise induced by the laser noise, we have performed a double-beam experiment. The stabilized laser light is divided into two beams, α and β, and each beam copropagates through the Rb cell with a spatial distance of 1 cm and the same optical path length, as depicted in Fig. 4. The transmitted laser beams are separately detected by two identical detection systems. The sum of the signals $(\alpha + \beta)$ contains both the spontaneous noise and the noise induced by the laser noise, and the difference $(\alpha - \beta)$ is due to only the spontaneous noise. Figure 5(a) shows the observed noise spectra under the same conditions as those for the single-beam experiment, except for the magnetic field strength of 7.5 G. The mean values of the photocurrent are $\langle I_\alpha \rangle = \langle I_\beta \rangle = 20\ \mu\text{A}$ for the laser beams α and β. The $\alpha + \beta$ signal is larger than the $\alpha - \beta$ signal by 10% because of the residual AM noise of the laser light. Both spectra show peaks of similar magnitudes at the Larmor frequency. This fact suggests that the magnetic resonance signals detected by the laser beams α and β are statistically independent; hence we can conclude that they are not generated by the same noise source.

To verify the preceding interpretation, we have further performed a double-beam experiment using a noisy laser. Here the FM noise of the laser increases by removing the optical feedback. To enhance the conversion of the FM noise to the intensity fluctuation, another Rb cell without any buffer gas is used. The laser is tuned to the ^{85}Rb-D_1 transition from the $F = 3$ level in the ground state to the $F' = 2$ in the excited state. The laser beam diameter is 5 mm, the incident laser intensity is 80 μW, the transmitted light intensity is 50 μW, and the photocurrents are $\langle I_\alpha \rangle = \langle I_\beta \rangle = 20\ \mu\text{A}$.

Figure 5(b) shows the spectra of the double-beam experiment with the noisy laser. The large level noise in the $\alpha + \beta$ signal consists of a broad excess noise far above the shot noise level and a deformed peak at the Larmor frequency. The excess noise is generated by the conversion of the laser FM noise to the intensity fluctuation in the transmitted light through the frequency-sensitive spectrum of the atomic optical resonance [7]. The deformed peak at the Larmor frequency is produced by another mechanism. The noisy laser randomly optically pumps the atomic magnetic moment [3], which becomes efficient when the

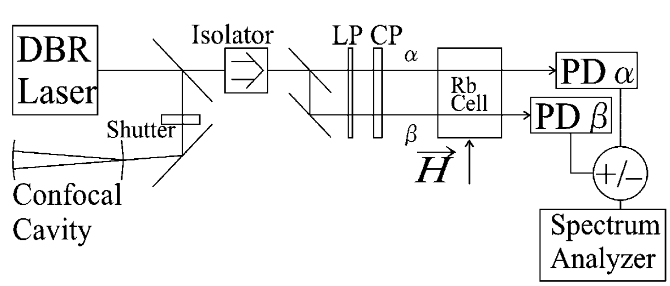

FIG. 4. Experimental setup for the double-beam experiment.

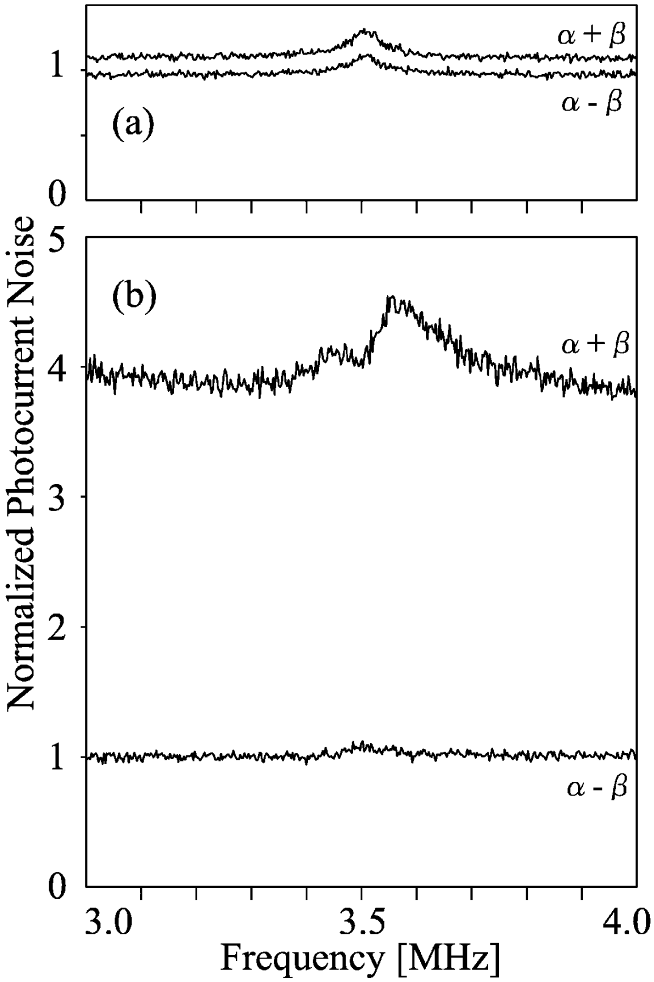

FIG. 5. Spectra observed with the double-beam experiment. Atoms are excited by the stabilized diode laser (a) and the free-running diode laser (b). The spectral resolution bandwidth of the spectrum analyzer is 10 kHz.

frequency component of the random excitation coincides with the Larmor frequency. This process is identical with the generation of the macroscopic magnetic moment when the incident light turns on and off at the Larmor frequency. Since these noises are generated by the same laser noise, in spite of the different mechanisms they interfere and thereby distort the peak at the Larmor frequency in the $\alpha + \beta$ spectrum as seen in Fig. 5(b).

In contrast, the noise spectrum of $\alpha - \beta$ in Fig. 5(b) is at the shot noise level except for the small peak at the Larmor frequency. This indicates that the noises of α and β are so strongly correlated with each other that they cancel out in $\alpha - \beta$. The correlation is generated by the fact that the laser beams α and β are prepared by dividing the same laser light. The uncorrelated components in α and β come from the shot noise and the spontaneous noise (a small peak at the Larmor frequency in $\alpha - \beta$).

Finally we theoretically estimate the normalized intensity of the spontaneous noise. Using Eqs. (8) and (9), we derive

$$\frac{\tilde{I}_{\mathrm{atom}}(\nu)}{\tilde{I}_{\mathrm{SN}}} = \sqrt{\frac{1}{3qN}\frac{\langle \Delta I\rangle^2}{\langle I\rangle}\frac{\gamma}{\gamma^2 + 4\pi^2(\nu_0 - \nu)^2}}, \quad (10)$$

where $\langle \Delta I\rangle = \eta q\langle \Delta\Phi\rangle = Nq\eta\sigma\langle\phi\rangle/2$. Substituting the experimental conditions of the single-beam experiment, $\langle I\rangle = 0.83\langle\Delta I\rangle = 20\ \mu\mathrm{A}$, $N = 10^{10}$, $\eta = 0.625$, and $\gamma = \langle P_j\rangle = 2.4 \times 10^4/\mathrm{s}$, we obtain $\tilde{I}_{\mathrm{atom}}(\nu_0)/\tilde{I}_{\mathrm{SN}} = 0.5$. This theoretical estimate agrees with the increase of the observed noise $\sqrt{1 + [\tilde{I}_{\mathrm{atom}}(\nu_0)/\tilde{I}_{\mathrm{SN}}]^2}$ which is 10% above the shot noise level. This agreement supports our understanding that the spontaneous noise is generated by a finiteness of the number of atoms interacting with the light.

We observed the spontaneous noise and attributed the origin of the noise signal to the stochastic properties of the photon scattering which interrupts Larmor precession. In the present work, the spontaneous noise appears on the broad background of the shot noise. If we apply a squeezed-light source [6,13] to observe the spontaneous noise, we expect that the background level will be greatly reduced, thereby enabling us to observe even more subtle effects.

We thank Dr. Hiroyuki Sasada and Dr. Kenichiro Aoki for a critical reading of the manuscript.

[1] S. O. Rice, Bell Syst. Tech. J. **23**, 282 (1944).
[2] K. P. Dinse, M. P. Winters, and J. Hall, J. Opt. Soc. Am. B **5**, 1825 (1988).
[3] T. Yabuzaki, T. Mitsui, and U. Tanaka, Phys. Rev. Lett. **67**, 2453 (1991).
[4] T. Mitsui, T. Kinugawa, and K. Sakurai, Jpn. J. Appl. Phys. **38**, 923 (1999).
[5] M. Misono, H. Fujimoto, T. Kohmoto, Y. Fukuda, and M. Kunitomo, Phys. Lett. A **240**, 29 (1998).
[6] S. Kasapi, S. Lathi, and Y. Yamamoto, Opt. Lett. **22**, 478 (1997).
[7] D. H. McIntyre, C. E. Fairchild, J. Cooper, and R. Walser, Opt. Lett. **18**, 1816 (1993).
[8] R. Walser, J. Cooper, and P. Zoller, Phys. Rev. A **50**, 4303 (1994).
[9] H. Ritsch, P. Zoller, and J. Cooper, Phys. Rev. A **41**, 2653 (1990).
[10] H. G. Dehmelt, Phys. Rev. **105**, 1487 (1957).
[11] H. G. Dehmelt, Phys. Rev. **105**, 1924 (1957).
[12] W. Happer, Rev. Mod. Phys. **44**, 169 (1972).
[13] Y. Yamamoto, S. Machida, and O. Nilsson, Phys. Rev. A **34**, 4025 (1986).
[14] B. Dahmani, L. Hollberg, and R. Drullinger, Opt. Lett. **12**, 876 (1987).
[15] A. Kastler, C.R. Acad. Sci. (Paris) **252**, 2396 (1961).