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Faraday rotation of broadband VUV light by optically-dense Xe atoms

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ABSTRACT

The diamagnetic Faraday rotation of broadband vacuum ultraviolet light was investigated for the xenon gas of thermal nuclear-spin polarization. The smaller and blue-shifted signals were observed due to the molecular absorption at the high xenon-gas pressure. For a dilute xenon gas, the rotation signals were measured in the buffer gas up to 30 kPa. The pressure broadening of atomic line was obtained from the measurements and the calculations of signal amplitude with various pressures of helium gas. Based on the observed diamagnetic rotation, the nuclear paramagnetic Faraday rotation was estimated for spin polarized xenon gas.

1. Introduction

The xenon (Xe) atoms play a uniquely important role in precise measurements. The ground state in closed-shell structure has no electron angular momentum, and the sublevel coherence in nuclear-spin state reaches the order of 10^3s in the atmospheric pressures and in the liquid phase [1,2]. At ultra-low external magnetic fields, hyperpolarized Xe atoms were detected with a pick-up coil [3,4], SQUID [1], atomic magnetometer [2], and optical method with spin–exchange interaction [5,6]. Optical detection of the nuclear-spin state is even more sensitive if the optical transition is directly addressed by vacuum ultraviolet (VUV) light. Nonlinear generation of narrow-band VUV light has progressed in recent years [7]. Therefore, it is currently important to study optically-dense Xe atoms.

Faraday rotation (FR) is the rotation of polarization plain of linearly polarized light propagating in a medium [8]. The rotation angle depends on the splitting of energy levels (diamagnetic) [9] and the electron spin polarization (paramagnetic) [10]. At sufficiently large laser detuning, the paramagnetic rotation is suitable for nondemolition measurement of electron spin [11]. Because of no valence electrons for the Xe atoms, the diamagnetic rotation becomes noticeable by excited state splitting in the magnetic field. In addition to the electronic origin, the rotation may arise from the nuclear spin polarization, which we call nuclear paramagnetic rotation. In this paper, we report on the diamagnetic rotation by the Xe atoms at the magnetic field of 13 mT. The optical transition is $^3P_1^o(5p^56s)$ – $^1S_0(5p^6)$ at $\lambda_0 = 146.96$ nm. The spectral shape of FR signal changed differently depending on the pressure of Xe gas and the buffer gases, He and N_2. The diamagnetic rotation was detectable for Xe gas of 200 Pa and N_2 gas of 30 kPa although the signal amplitude decreased with increasing buffer gas pressure. Based on the observed diamagnetic rotation, the nuclear paramagnetic Faraday rotation is studied.

2. Experiment

As shown in Fig. 1, the VUV light source was a deuterium lamp (Hamamatsu, L7292). The filtering bandwidth of monochromator (Acton, VM-502) was 0.06 nm. The collimated light was linearly polarized by a Rochon prism (Karl Lambrecht, MFRV5) and directed to a glass cell at room temperature. The polarization, phase, and amplitude of the light were not modulated intentionally [9]. The cell thickness L was 11 mm between MgF_2 windows. A commercial Xe gas was of natural isotope ratio and a purity of 99.995%, and no more purification was performed. The purity of buffer gases, ^4He and N_2, was better than 99.999%. The pressure was measured by the Pirani and Bourdon gauges. The magnetic field was applied along z axis and modulated as $B_0 = B_m \cos(2\pi f_m t)$, where the frequency $f_m = 28.5$ Hz and the root-mean-squared amplitude $B_m/\sqrt{2} = 13$ mT. The light polarization and the amplitude were changed by the absorption line of Xe atoms. The axis of the second Rochon prism was at right angle to the first one. Because of the rotation angle of light polarization $\theta_D \propto B_0$, as expressed in Eq. (6), the light power passed through the crossed prism was modulated as in Eq. (3). The photo currents from the photomultiplier (Hamamatsu, R8487) were fed into a lock-in amplifier, and the frequency component at $2f_m$ was recorded by

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scanning the monochromator. The cell windows gave negligible polarization change compared to the Xe atoms.

3. Diamagnetic Faraday rotation by Xe gas

The FR spectra were measured at several Xe pressures p_{Xe} without buffer gases, as shown in Fig. 2(a). The rotation signal of broadband VUV light was detectable at the pressure of 10 Pa, and enlarged with increasing pressure to 200 Pa. In the pressure range from 200 to 600 Pa, the signal decreased and shifted to the blue side. There were weak signals at the red side. The rotation signal became larger again with the pressure up to 2 kPa. The p_{Xe} dependences of transmission and shift are shown in Fig. 3. Because the monochromator bandwidth was broader than the absorption linewidth, the measurement did not reflect the true spectral shape. Nonetheless, we were able to clearly observe the wavelength shift and the transmission change.

If the Faraday rotation by optically-dense Xe atoms is measured by a narrow band light like a laser, the light does not transmit at the center of the absorption line. The signals are left symmetrically on both sides of the line. The height and the splitting of the wings increase with increasing atom density. In our measurement, however, the FR spectrum was not split, but shifted. The height was not monotonously changed.

To study the strange behavior, the absorption $\alpha L = \ln(I_0/I)$ was measured without applied magnetic field, where I and I_0 were the light powers after the glass cell with and without the Xe gas, respectively. By increasing pressure, the absorption line was asymmetrically broadened with a tail at the red side, as shown in Fig. 2 (b). Since the pressure shift and broadening of atomic line was negligible, the tails were due to the absorption by van der Waals molecules, Xe_2 [12,13]. Therefore, the observed spectrum consisted of the large atomic line and the weaker band of molecular transitions. By averaging in the bandwidth of monochromator, the mean absorption αL was on the order of unity even for dense Xe gas at 1 kPa. Because of the light absorption by Xe_2 molecules, the FR signal was observed weak on the red side, resulting in blue shift. As shown in Fig. 4, the mean FR angle is calculated by Eq. (3) described below and measurements in Fig. 2(a) and (b). The rotation angle was approximately 20° at the blue side. However, the asymmetric shape was still observed because of insufficient signal-to-noise ratio arising from strong absorption at the red side.

For the transition ${}^1P_1^o(5p^56s') - {}^1S_0(5p^6)$ at 129.56 nm, the p_{Xe} dependence of FR signal was similar to those shown in Fig. 2(a). Since the hyperfine splitting of ${}^1P_1^o$ state is larger than that of ${}^3P_1^o$ state [14,15], the transition to ${}^1P_1^o$ state is suitable for detecting the nuclear paramagnetic rotation as discussed below. To overcome large transmission loss in the optics at the short wavelength, we need to improve lamp power and detection efficiency using phase modulation of light [9].

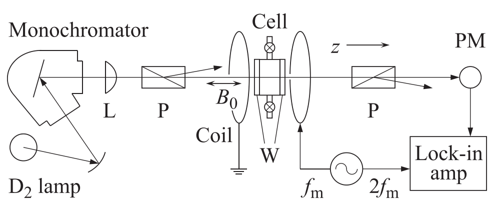

Fig. 1. Experimental setup. A monochromator was used for spectral filtering of the emission from deuterium (D_2) lamp. Transmission of VUV light through the crossed polarizers was due to Faraday rotation by Xe gas. The thickness of glass cell was 11 mm between MgF_2 windows (W). The optical path from the lamp to the photomultiplier (PM) was evacuated. Optical alignment of CaF_2 lens (L) and MgF_2 Rochon prism (P) was adjustable in vacuum. The magnetic field was modulated as $B_0 = B_m \cos(2\pi f_m t)$ along the z axis.

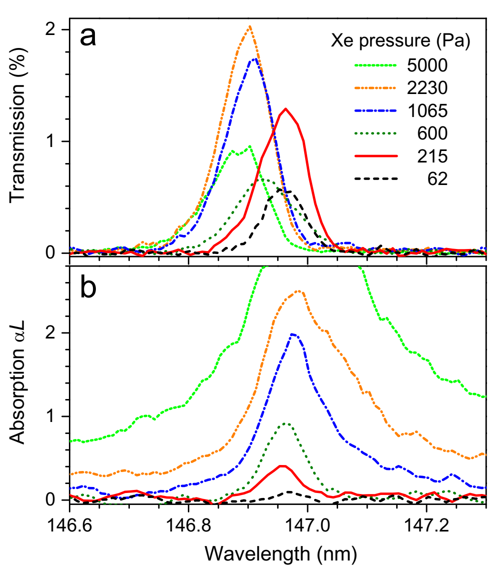

Fig. 2. (a) Xe-pressure dependence of FR spectrum, with no other gases in the glass cell. The 100%-transmission corresponds to the FR angle $\theta_D \sim \pi/2$ and small absorption $\alpha \sim 0$, as shown in Eq. (3). (b) The absorption spectra at the respective Xe pressures at $B_0 = 0$. The wavelength of monochromator was scanned with the resolution of 0.06 nm, the speed of 0.01 nm/s, and the averaging time of 1 s. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

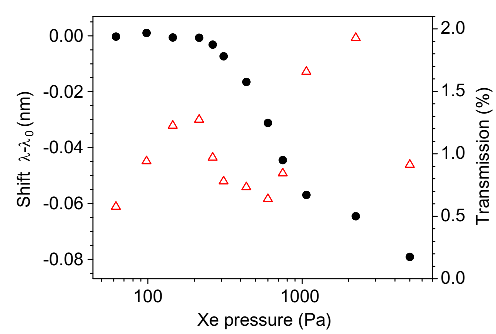

Fig. 3. The wavelength shift (●) and the transmission (△) at the peak of each FR spectrum. The shift is relative to the transition wavelength of dilute atomic gas, $\lambda_0 = 146.96$ nm. There were no other gases in the glass cell.

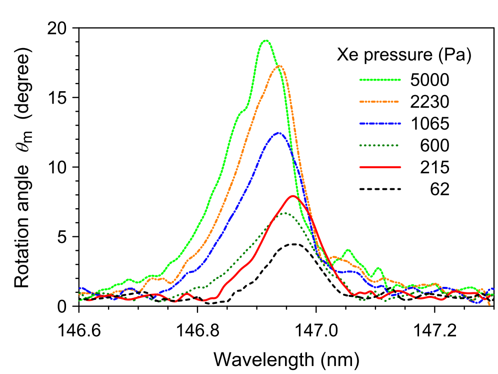

Fig. 4. Faraday rotation angles calculated from Eq. (3) and measurements shown in Fig. 2(a) and (b). The angle θ_m is the root-mean-squared amplitude of rotation angle θ_D modulated by the magnetic field B_0, as shown in Eq. (6).