II. 5. Development of the Magnetometer toward the Search for the Electron EDM

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A permanent electric dipole moment (EDM) of a particle, an atom or a molecule directly violates the time reversal symmetry, and hence the CP symmetry because of the CPT theorem. Since the EDM is sensitive to the CP violation in the theories beyond the standard model (SM) of elementary particles[1)], the EDM is a good candidate to probe the physics beyond the SM. We plan to search for the electron EDM using laser cooled francium (Fr) atoms. By using the laser cooled atom, the long coherence time can be realized and some systematic effects, such as a motional magnetic field and a field inhomogeneity, which limit the EDM sensitivity in the previous experiments, can be suppressed[2)]. The laser cooling technique is relatively easily applicable to the Fr atom, since the Fr atom is an alkali atom. Furthermore, the Fr atom has the largest enhancement factor of electron EDM due to the relativistic effect in the alkali atoms. In view of these advantages, we have chosen the Fr atom as the substance where the electron EDM is searched for.

Experimentally, the atomic EDM is deduced from a tiny change in spin precession frequency induced from a reversal of an electric field E applied to the atom along a magnetic field. The electric field couples with the EDM, while the magnetic field defines the quantization axis. A small fluctuation of the magnetic field, however, can easily produce the false EDM effect. In our assumed experimental condition that is E = 100 kV/cm application and the EDM sensitivity of 10^{-29} $e$cm, the frequency change due to the EDM is less than 1 μHz. This tiny frequency change corresponds to the magnetic field fluctuation of about 10 fT. Thus we need to monitor the magnetic field with the sensitivity of 10 fT order. In order to realize this sensitivity we are now developing a rubidium (Rb) atomic magnetometer based on a nonlinear magneto-optical rotation (NMOR) effect[3)].

The principle of the NMOR effect is as follows. The linear polarized light, whose wavelength is tuned to the Rb atomic transition, irradiates the Rb atom along an applied magnetic field. A spin alignment state of the Rb atom is produced by the optical pumping. Then, the produced alignment state precesses around the magnetic field and is probed by the incident light. This probe results in the rotation of the polarization plane of the incident light, which has the dispersive shape as a function of the magnetic field. Thus the magnetic field can be monitored by measuring the rotation angle of the polarization plane. However, the NMOR spectrum is observed only around $B = 0$ T, since the optically pumped alignment relaxes before the full alignment in the high field. In the EDM measurement, the finite field is required to define the quantization axis. We employed the amplitude modulated (AM) NMOR method[4)] to monitor the finite field. When the amplitude of the linear polarized light is modulated at a frequency ν_{mod}, the optical pumping rate is also modulated at ν_{mod} (Fig. 1). If the modulation frequency ν_{mod} matches the spin precession frequency $2 \times \nu_{Rb}$ of the Rb atom, the optical pumping efficiency reaches its maximum and hence the spin alignment is produced in the finite field.

The experimental setup for the measurement of the AM NMOR spectrum is shown in Fig. 2. A 4-layer magnetic shield is introduced to suppress the effect of the environmental field. A glass cell, which contains the Rb vapor, is installed inside the shield. The magnetic field is produced by a 3-axis coil, which is also installed inside the shield. The linear polarized light is supplied from a distributed feedback (DFB) laser. The amplitude modulation of the laser light is realized using an acousto-optic modulator (AOM). The laser light transmitted the cell is divided using a polarized beam splitter to measure the rotation angle of the polarization plane. The intensities of the divided lights are detected by photo detectors and these outputs are sensed in a lock-in amplifier to perform a phase sensitive detection.

Figure 3 shows the typical AM NOMR spectrum observed. By using the AM NMOR method, we observed the NMOR spectrum around $B \approx 540$ nT. The line width of the spectrum was about 30 nT. The narrow line width is one of key issues for the highly sensitive magnetometry. Since the line width is limited by the spin decoherence due to the collision between the Rb atom and an inner surface of the glass cell and the residual field of the magnetic shield, we are now preparing a production system of the cell whose inner surface is coated with antirelaxation material, such as a paraffin, and a demagnetization of the shield.

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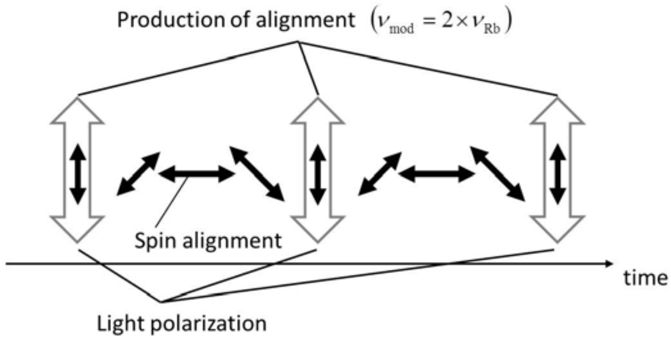

Figure 1. Production of the spin alignment by using the amplitude modulated.

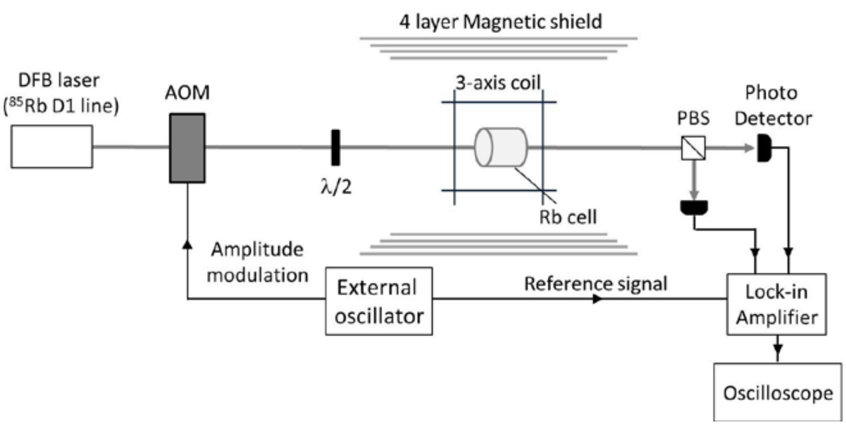

Figure 2. Experimental setup for the measurement of the AM NMOR effect.

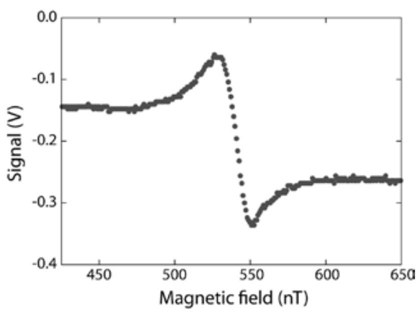

Figure 3. Observed AM NMOR spectrum.