

Development of a Magneto-Optical Trap System of Francium Atoms for the Electron Electric-Dipole-Moment Search

K Harada¹, T Aoki², K Kato¹, H Kawamura³, T Inoue³, T Aoki¹,
A Uchiyama¹, K Sakamoto¹, S Ito¹, M Itoh¹, T Hayamizu¹,
A Hatakeyama⁴, K Hatanaka⁵, T Wakasa⁶ and Y Sakemi¹

¹ Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Sendai, Japan

² Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan

³ Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai, Japan

⁴ Department of Applied Physics, Tokyo University of Agriculture and Technology, Tokyo, Japan

⁵ Research Center for Nuclear Physics, Osaka University, Osaka, Japan

⁶ Department of Physics, Kyushu University, Fukuoka, Japan

E-mail: kenichi.harada.a1@tohoku.ac.jp

Abstract. The finite value of an electron electric dipole moment (eEDM) provides the direct evidence for the violation of time reversal symmetry. Fr atoms, whose enhancement factor is 895, trapped by laser cooling and trapping techniques are one of the strongest candidates for measuring the eEDM. We are constructing a beamline for measuring the eEDM using laser-cooled Fr atoms at the Cyclotron and Radioisotope Center. We have developed laser light sources including the frequency stabilization system and a magneto-optical trap system for Fr atoms. As the Fr production requires the cyclotron operation, we also use Rb atoms whose chemical properties are similar to those of the Fr atoms. Thus, the Rb beam is utilized for optimizing the operation parameters of the entire apparatus. We have also developed the laser light sources for Rb atoms and observed the beat signal for frequency stabilization of the source using the frequency offset locking method.

1. Introduction

A permanent electric dipole moment of an electron requires both violations of time-reversal (T) and parity (P) invariance. The finite value of an electron electric dipole moment (eEDM) also suggests a charge-parity (CP) violation on the basis of the CPT theorem, and it is crucial for explaining the observed matter-antimatter asymmetry of the universe. The Standard Model (SM) predicts a value of $\sim 10^{-38}$ ecm for the eEDM [1]; however, this value is extremely small and far below the current detection limit. On the other hand, several theoretical models such as the supersymmetric model beyond the SM predict much larger eEDM values [2], which can be observed using modern technologies.

The eEDM measurements using thorium monoxide (ThO) molecules [3] are well known as the most precise measurement in polar molecules. The upper limit of the eEDM obtained from the experiments is $\leq 8.7 \times 10^{-29}$ ecm. A pulsed beam of the ThO molecules cooled in cold neon carrier gas are employed in this experiment. The interaction time between the ThO molecules



and the external electric field applied using the plates having a length of about 22 cm is almost 1 ms due to the effect of a buffer-gas cooling technique. The main advantage of the experiments using polar molecules such as ThO and YbF [4] is that the internal effective electric field $\mathcal{E}_{\text{eff}}$ can be much higher than that in atoms. The $\mathcal{E}_{\text{eff}}$ in a ThO molecule is about 84 GV/cm, and it is approximately one thousand times larger than that in a Tl atom. However, in the atomic or molecular beam experiment, the significant systematic effects are caused by the motional magnetic field $v \times E/c^2$ that is obtained from the atoms moving with velocity v through an electric field E and by the geometric phase shifts generated by the complicated field gradients. These systematic errors mimic the true eEDM signal and limit the accuracy of measuring the eEDM.

The laser cooling and trapping techniques of atoms are useful to overcome these drawbacks. The velocity of laser cooled atoms is dramatically low; and therefore, the motion-induced magnetic field is strongly suppressed. In particular, an optical lattice suppresses the detrimental effects induced by the atomic collision interaction, which reduces the systematic errors of the eEDM signal [5]. Additionally, the coherence time increases to about a few second by using the laser cooled atoms, which is much longer than that of the ThO molecular beam experiment. Moreover, since the atomic ensembles are confined in a small region, it is unsusceptible to the magnetic and electric field inhomogeneities. Thus, there are several advantages of using optically cooled and trapped atoms for measuring the eEDM.

Fr being the heaviest alkali atom has a large enhancement factor of about 900 [6, 7]. The EDM experiment using the laser cooled Fr atoms can achieve sensitivities even with their upper bounds, which is better than that of the ThO molecular beam experiment. However, the Fr atom poses an experimental challenge as there is no stable isotope that has a half-life longer than 22 min and is radioactive. As the Fr production requires the cyclotron operation, we also use stable Rb atoms having chemical properties similar to that of the Fr atom. The Rb beam is utilized for optimizing the operation parameters of the entire apparatus. We are constructing a beamline for measuring the eEDM using laser-cooled Fr atoms at the Cyclotron and Radioisotope Center (CYRIC), as reported in [8, 9, 10, 11].

The frequency reference and stabilization of laser light sources using several methods are required for trapping of atoms. A reference cell containing stable atoms is generally used for frequency reference and stabilization when atoms are laser-cooled and trapped. However, the Fr atom has no stable isotopes, and the methods of stabilizing the laser frequency using Fr atoms are not available. Therefore, the frequency stabilization using I₂ [12], a Fabry-Pérot cavity with a frequency-stabilized He-Ne laser light [13], and a frequency offset locking (FOL) technique are employed.

In this paper, we report the current development status of the experimental setup for trapping Fr and Rb atoms at CYRIC. We have two rooms for the experiment at CYRIC. One is a laser experimental room (lab A) where the development of laser light sources and its frequency stabilization for Fr and Rb magneto-optical traps (MOTs) are performed. The other is an EDM measurement room (lab B), which is in the radiation controlled area. In this room, we have constructed a MOT system with the neutralizer for the Fr and Rb ions as they are transported through the beamline as ions from the production area. Optical fibers having a length of 150 m are placed between lab A and lab B, which transport the laser light.

2. Experimental setup

2.1. Laser light sources

The experimental setup is schematically illustrated in Fig. 1. As a trapping light source for ^{210}Fr , we use a single frequency Ti:sapphire (Ti:S) laser source, tuned to the $7S_{1/2} (F = 13/2) \rightarrow 7P_{3/2} (F' = 15/2)$ D2 transition of Fr atoms at 718.216 nm. F and F' represent the total angular momentum of the ground and excited states, respectively. The maximum output power of the

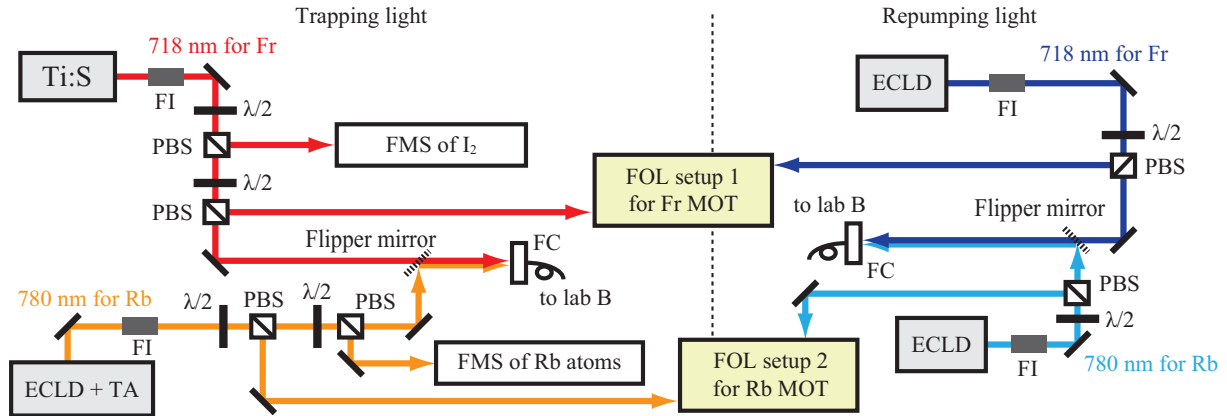


Figure 1. Experimental setup of trapping and repumping lights for the Fr and Rb atoms in lab A. The laser lights having a wavelength of 718 nm and 780 nm are exchanged using flipper mirrors and are transported to lab B using optical fibers. $\lambda/2$, half-wave plate.

Ti:S laser is 3.5 W when the output power of the pump laser light at a wavelength of 532 nm is 18 W. After the laser light passes through a Faraday isolator (FI), a part of it is used for frequency stabilization and reference using I_2 and the FOL setup divided using polarizing beam splitters (PBSs), respectively. Fr atomic vapor cells are not available as frequency references because no stable Fr isotopes exist. Therefore, I_2 is employed for the frequency stabilization and reference of trapping light. Frequency modulation spectroscopy (FMS) is a technique for precisely observing the spectrum of atoms and molecules without the Doppler effect due to their velocity. The details of the setup are reported in [11]. On the other hand, the FOL technique is used for frequency stabilization of repumping light. The error signal for stabilization is obtained by using the beat signal between the 10th-order sideband component and the repumping frequency. The details of the FOL setup 1 will be also reported in a forthcoming paper. The remaining light is transported by using a polarization-maintaining fiber (PMF) using a fiber coupler (FC) for the Fr MOT to lab B.

We use the repumping laser light with a wavelength of 718 nm generated using the custom-made external-cavity laser diode (ECLD, TOPTICA Photonics) for $7S_{1/2}$ ($F = 11/2$) $\rightarrow$ $7P_{3/2}$ ($F' = 13/2$) D2 transition of Fr atoms. The output power of the repumping light is 36 mW. The light from the ECLD passes through an isolator, and is divided into two for the FOL setup and Fr MOT using the PBS.

On the other hand, a trapping laser light generated using the ECLD, tuned to the $5S_{1/2}$ ($F = 2$) $\rightarrow$ $5P_{3/2}$ ($F' = 3$) transition of ^{87}Rb atoms, is employed for the Rb MOT. The output power is amplified up to 1 W by using a tapered amplifier (TA). The light then is divided for FOL setup 2, and the FMS using a Rb vapor cell by PBSs for the frequency reference and stabilization. After the light passes through the PBS, it is transported to lab B for trapping Rb atoms by using the PMF. The laser lights can be exchanged between 718 nm and 780 nm wavelengths by a flipper mirror.

Further, the repumping light for the Rb MOT is generated using the ECLD. The wavelength of the light is tuned to the $5S_{1/2}$ ($F = 1$) $\rightarrow$ $5P_{3/2}$ ($F' = 2$) transition and its output power is 38 mW. The laser light from the ECLD is split by the PBS after it passes through the FI, and the transmitted one is input into the PMF. The other is employed for the FOL setup 2. As already mentioned, we have already developed the FOL setup 1 for Fr atoms. The purpose of developing of the FOL setup 2 is to confirm the operation of the setup and benefit the FOL technique using the Rb MOT.

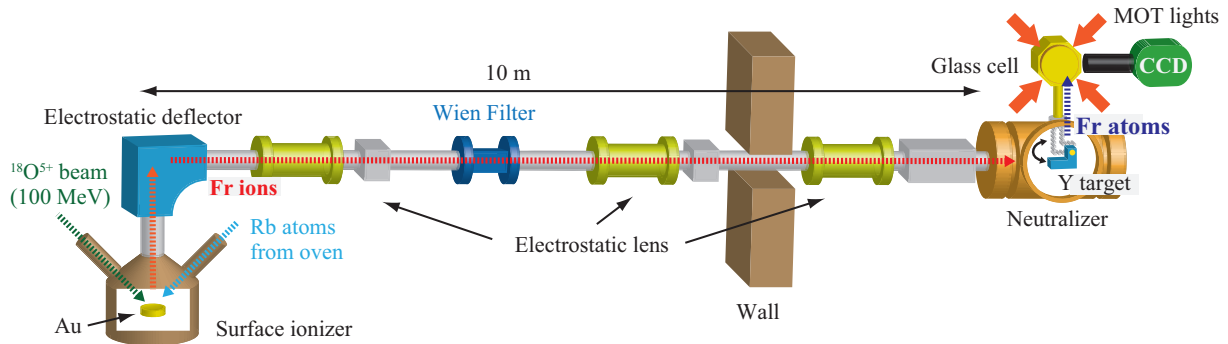


Figure 2. Schematic diagram of the beam line for the magneto-optical trapping of Fr atoms in lab B. The MOT lights are transported from lab A.

2.2. Fr and Rb MOTs

In lab B, we have developed the MOT system with a neutralizer for trapping the Fr and Rb atoms, as shown in Fig. 2. A primary beam of ^{18}O with having an energy of 100 MeV obtained from the AVF cyclotron is injected to the surface ionizer. Fr is produced by the nuclear fusion reaction, $^{18}\text{O} + ^{197}\text{Au} \rightarrow ^{210}\text{Fr} + 5\text{n}$. Fr is then extracted from the Au surface as an ion upward, and is transported about 10 m by the electric fields generated by an electrostatics lens and deflector to avoid the radiation from a nuclear fusion reaction. The maximum yield of the Fr beam is estimated to be about 10^6 ions/s. On the other hand, the Rb atoms from an oven are also hit on the Au surface for ionization. Rb beam is used for adjusting the parameters including the surface ionizer, beamline apparatus, and MOT system without an accelerator.

The Fr and Rb ions coming from the upstream of the beamline are hit and accumulated on the surface of the Y metal. After several tens of seconds, the Y surface was turned in the direction of the glass cell and was heated up to about 700 °C for a few seconds. The neutralized Fr atoms were released into the glass cell and trapped by the MOT. Then, the Y surface was returned to its initial position and ions were accumulated on the surface again. This process was repeated again and again. The inside wall of the glass cell was coated by octadecyltrichlorosilane (OTS) to prevent the adsorption of atoms on the surface of the glass. This effect is useful for increasing the number of trappable atoms.

The vacuum pressure of the MOT system was 1.0×10^{-7} Pa. We have already achieved the trapping of the neutralized Rb atoms in the glass cell using the Rb ion beam. The maximum number of the trapped atoms detected using a charge coupled device (CCD) camera is estimated to be approximately 10^6 when the flux of the Rb beam on the Y surface was 1 nA. In the case of Fr atoms, the probability of getting large number of Fr atoms for being trapped in MOT is less. Thus, the lens system composed by four spherical lenses was installed at a distance of 56 mm from the atom trapped at the center of the glass cell. This system is used to efficiently collect the fluorescence from atoms and to compensate for a spherical aberration [14]. As the saturation parameter of a Fr atom is 1.87, the fluorescence intensity from an atom in the MOT is calculated to be 8.3 fW, which can be detected using an avalanche photo diode. We will perform the experiment for trapping Fr atoms by using this system.

2.3. FOL for the Rb MOT

The FOL technique can lock the frequency difference between the trapping and repumping lights to a constant value [15]. The technique is used for frequency stabilization and also as a means of scanning both the lasers simultaneously, while maintaining a constant frequency difference when the servo loop for feedback is closed. We have been already achieved the FOL of the

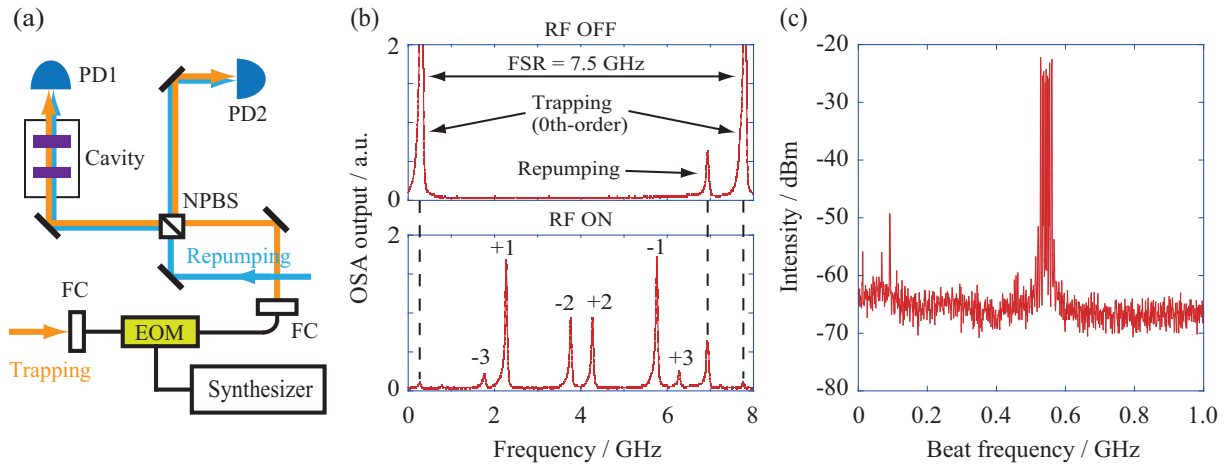


Figure 3. (a) The detailed illustration for the FOL setup 2. (b) Optical spectra measured by PD1 for (above) the trapping light without EOM modulation and repumping light, and (below) the trapping light modulated by 2.0 GHz RF with 19.0 dBm and the repumping light. (c) The beat signal between the 3rd-order sideband component and the repumping frequency.

laser source using an electro-optic modulator (EOM) for the Fr MOT. As the beat frequency between the trapping and repumping lights is about 46 GHz, it is difficult to detect a frequency of 46 GHz directly by using a photodetector and to generate the frequency components with a frequency of 46 GHz. Instead of directly generating a 46 GHz sideband as a 1st-order, we then use the EOM that can generate the 10th-order sideband components by changing the input power of a radio frequency (RF) of 4.6 GHz. The beat signal of a few hundred MHz between the 10th-order sideband component and the repumping frequency are observed for the frequency stabilization by using the delayed self-homodyne detection method. To confirm the operation of the system, we also develop the FOL system for the Rb MOT. The details of the FOL setup 2 are illustrated in Fig. 3 (a). After the trapping light passes through the EOM, the trapping and repumping lights are divided into two beams and overlapped with each other by a 50:50 non-polarizing beam splitter (NPBS). The EOM is driven at an RF of 2 GHz generated by a synthesizer. They are detected by photodetector 1 (PD1) after passing through a cavity to monitor the spectrum of the lights and by photodetector 2 (PD2) to observe the beat signal, respectively. The free spectral range (FSR) of the cavity produced by COHERENT is 7.5 GHz. The detection bandwidth of PD2 used for this detection is 1.5 GHz.

3. Result

To confirm the sideband generation for the trapping light after passing the EOM, we first measured the output powers from the cavity by PD1. The difference between the trapping and repumping frequencies for the Rb MOT is about 6.6 GHz because the frequency difference between the hyperfine splittings of $5S_{1/2}$ of a ^{87}Rb atom is about 6.83 GHz. When the RF signal of 19.0 dBm is input to the EOM, the 3rd-order sideband components appeared, as shown in Fig. 3(b). The frequency in the horizontal axis is obtained by changing the cavity length. The frequency difference between the 0th-order and 1st-order sideband component is 2.0 GHz which is generated from the synthesizer, and the frequency of the 3rd-order component is 6.0 GHz away from that of the 0th-order. As the RF power is limited by the maximum output of the synthesizer, an amplifier is needed for increasing the peak intensity of the 3rd-order sideband components. We then observed the beat signal between the 3rd-order sideband component of the trapping light and repumping light by PD2 and an RF spectrum analyzer. The beat signal of

about 540 MHz was obtained, as shown in Fig. 3. However, the obtained 3dB width of the beat signal was about 30 MHz (For Fr, the obtained width of the beat signal between the 10th-order sideband component and repumping frequency was about 1.2 MHz because the Ti:S laser and commercial ECLD are used). The resolution bandwidth and Sweep time of the analyzer was 300 kHz and 10 ms, respectively. The broadened width is because of the linewidth of ECLD made by hand laser used for the Rb MOT. The improvement of the laser sources is required for narrowing the linewidth of the beat signal. Then, the error signal for frequency stabilization is obtained using the delayed self-homodyne detection technique.

4. Conclusion

We reported the current development status of the experimental setup for the Fr and Rb MOTs. We have developed the laser light sources for trapping Fr and Rb atoms. The FOL technique for the Rb MOT is developed for confirming the operation of the locking system. We have also constructed the apparatus, including the neutralizer for the Fr and Rb ions and the MOT system for trapping the neutralized Fr and Rb atoms in lab B. We have successfully observed the neutralized Rb of 10^6 atoms in the MOT by using the Rb ion beams.

In future, we will observe the fluorescence from the Fr atoms trapped in the MOT with a single atom detection technique by the experiment using the cyclotron. We are also developing the EDM measurement systems including the electrode, magnetometer, and optical lattice. After optimization of the Fr MOT, we will perform the EDM measurement using cold Fr atoms.

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