I. 4. Toward Magneto-Optical Trap of Fr Atoms for EDM Search

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A permanent electric dipole moment (EDM) of the fundamental particles serves as the direct signature of the violation of Time-reversal symmetry (T). The existence of the EDM also suggests a charge-parity (CP) violation on the basis of CPT theorem, and it is important key for understanding the observed matter-antimatter asymmetry in the universe. The Standard Model (SM) predicts the value of 10^{-38} e cm for the electron EDM (e-EDM)[1)], however this value is extremely small and far below the current detection limit. On the other hand, several theoretical models beyond the SM predict much larger e-EDM values (10^{-26} ~ 10^{-29} e cm)[2)], which can be observed by current experiments.

The e-EDM measurement using Thallium (Tl) atomic beam is well known as the most precise measurement in the paramagnetic atoms and the upper limit of e-EDM obtained from the experiment is 1.6×10^{-27} e cm [3)]. The EDM enhancement factor of Tl atom is R = -585. In this experiment, the interaction time between Tl atoms and the external electric field is almost 2.5 ms. Moreover, for thermal beams the significant systematic effect is caused by the motional magnetic field $v \times E/c^2$ that comes from the atoms moving with velocity v through an electric field E. This systematic error mimics the true EDM signal and limits the accuracy of measurement of atomic EDM.

Laser cooling and trapping of atoms such as a Magneto-optical trap (MOT) is useful technique to overcome these problems. The velocity of laser cooled atoms dramatically decreases, and therefore the motion-induced magnetic field is strongly suppressed. In particular, the blue-detuned optical lattice trap caused by optical dipole force suppresses the detrimental effects induced by the atomic collision and the atom-light interaction, which reduces the systematic errors of the EDM signal[4)].

Additionally, the interaction time is elongated to about 1 s by using laser cooled atoms, which is much longer than that of Tl atomic 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 the measurement of atomic EDM. Additionally, Francium (Fr) being the heaviest alkali atom has a large enhancement factor, R = 895 [5]. The EDM experiment using laser cooled Fr atoms promises, to reach sensitivities even with their upper bounds, thus better than that of Tl atomic beam experiment. However, Fr atom poses an experimental challenge as there is no stable isotope of half-life longer than 22 min and it is radioactive.

In this report, we describe the current status of the experimental apparatus for trapping Rb and Fr atoms at Cyclotron and Radioisotope Center (CYRIC), Tohoku University. We have two experimental areas for the experiment at CYRIC; one is a general laser experimental room where the development of laser sources and its frequency stabilization for Rb and Fr MOTs are performed. We also designed the unique MOT chamber to observe the fluorescence of single atoms trapped in MOT, the other is in the radiation controlled area. Here, the preparation of experiment of Fr MOT and EDM measurement are in progress. As the operation of the cyclotron is needed for Fr production, it becomes expensive to use it for optimizing the operation parameters of the apparatus such as the ion source, beam transport system, neutralizer, and optical devices, and hence Rb atom is used.

A trapping laser light generated by external cavity laser diode (ECLD) is tuned to the $5S_{1/2}$ (F=2) → $5P_{3/2}$ (F=3) transition of ^{87}Rb atom at a wavelength of 780 nm and the output is amplified up to 1 W by tapered amplifier (TA) as shown in Fig. 1. The frequency of the light is modulated by an acousto-optic modulator in a double-pass configuration for operating the frequency precisely and it is then input into a polarization maintaining fiber (PMF). The trapping light of a few mW is divided by a polarization beam splitter (PBS) and it is utilized for the frequency stabilization of the laser sources by using frequency modulation spectroscopy method. After passing through the PMF, the light is adjusted to circular polarization and injected into a vacuum chamber in a six-beam counter-propagating MOT configuration. The power of each trapping beam is 5 mW. The axial gradient of the magnetic quadrupole field induced by anti-Helmholtz coils is about 10 G/cm at the center of the chamber. On the other hand, a second ECLD system provides 6 mW of laser light tuned to the $5S_{1/2}$ (F=1) → $5P_{3/2}$ (F=2) for repumping transition. The diameters of both lights are 20 mm.

Our experimental apparatus is based on a double MOT chamber system which is connected by 16 cm long differential pumping tube. The photograph of the MOT apparatus is shown in Fig. 2. The cross section of the tube is kept as 6 mm to maintain the pressure difference between the two chambers. The first MOT chamber is made of 316L stainless steel and the inside is evacuated by an ion pump (IP), a turbo molecular pump (TMP) and a rotary pump (RP). The vacuum pressure of the first MOT chamber is 4.2×10^{-9} torr. We have already achieved the trapping of Rb atoms in the first chamber. Figure 3 shows the Rb atomic cloud trapped in MOT which is obtained by monitoring the fluorescence from the atoms on the charge coupled device camera. The number of atoms is estimated to be about 10^8. The vertical and horizontal sizes of the atomic cloud are 3 and 4 mm, respectively. We have also designed the unique MOT chamber as a second MOT chamber, which can be used to observe the fluorescence of single atoms trapped in MOT. The view port of 1 inch diameter to observe atoms is placed at 21 mm from the center of the chamber. In this port, the lens system that consists of four spherical lenses is installed and advantageously used for high resolution imaging of single atoms[6)]. For Rb atom, the fluorescence intensity from an atom in MOT is calculated to be 3.6 fW, which can be detected by an avalanche photo diode. The vacuum system of 2nd MOT chamber consists of a titanium sublimation pump, an IP, a TMP and a RP. The vacuum degree of the 2nd MOT chamber reaches 2.0×10^{-11} torr and it is enough for trapping the single atoms. The experimental result will be reported soon.

On the other hand, a 718 nm laser light generated by Ti:Sapphire laser (MBR110), which is pumped by 532 nm laser (Verdi-V18), is employed for trapping of Fr atoms. The frequency of the laser is tuned to the $7S_{1/2}$ (F=13/2) → $7P_{3/2}$ (F=15/2) D2 transition of ^{210}Fr atoms. Figure 4 shows the output power of the Ti:Sapphire laser as a function of the pump power. The maximum output power of the laser is 3.5 W when the pump laser is 18 W. We also use a repumping laser light with a wavelength of 817 nm generated by ECLD for $7S_{1/2}$ (F=11/2) → $7P_{1/2}$ (F=13/2) D1 transition. The two laser lights are then carried by single mode optical fibers whose length is 150 m to the radiation controlled area where Fr atoms are laser cooled and trapped by MOT. The trapping laser light is also divided by a PBS and is used for the frequency stabilization of laser sources.

We are constructing the MOT apparatus of Fr atoms at the 51 course beam line in the radiation controlled area. In the case of Fr, the number of atoms depends on the efficiencies of production, transportation and neutralization of Fr ions. The probability of getting large number of Fr atoms for being trapped in MOT is less. Therefore, we need the chamber such as the second MOT chamber used for Rb MOT to observe down to single atoms. In future, we would like to observe the fluorescence from single Rb atoms trapped in MOT, and we then utilize this technique for trapping Fr atoms. After optimization of Fr MOT, especially the number of atoms, we will perform EDM measurement using cold Fr atoms in optical lattice.

References

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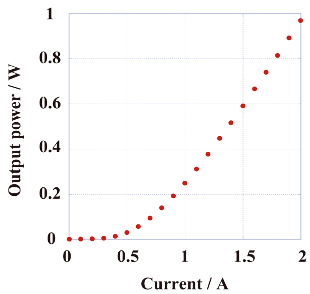

Figure 1. Output power of the trapping light amplified by the TA. The maximum output power is about 1W when the injection current is 2 A.

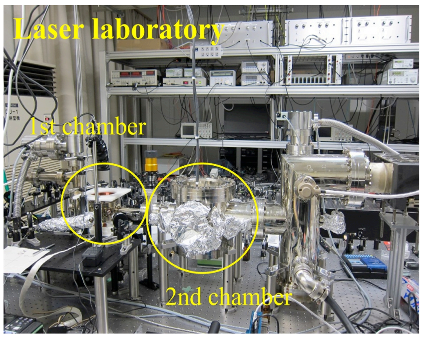

Figure 2. Photograph of the laser laboratory.

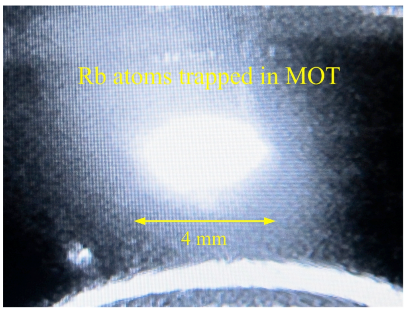

Figure 3. Fluorescence image of Rb atomic cloud trapped by MOT. Vertical size of the atomic cloud is 3 mm, and horizontal is 4 mm.

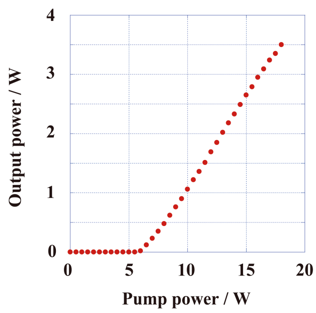

Figure 4. Output power of Ti:Sapphire laser as a function of pump power. The maximum output power of 3.5 W is obtained when the pump power is 18 W.