II. 6. Development of an Optical Dipole Force Trap System for the Search of an Electron Electric Dipole Moment

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In its present state, the universe is mostly occupied by matter, and it is thought that there are few antiparticles having the same mass and spin but with a different electric charge. It is a significant mystery why matter and antimatter, which are considered to have existed in equal number in the early universe, presently show such a large difference in their amounts. The violation of the combined operator of Charge conjugation (C) and parity (P) is thought to be necessary to explain the matter-anti-matter asymmetry, and it is provided by the finite value of an electric dipole moment (EDM) as the combined operator of C, P and time-reversal (T) is expected to be invariance. The EDM is a physical quantity that breaks the T and P symmetry. However, the value of the EDM predicted in the framework of the standard model is quite small, and is difficult to measure. However, if the EDM is measured as a finite value whose value is larger than that predicted, it will lead to a new physics beyond the standard model.

The upper limit of an electron EDM obtained from a thorium monoxide (ThO) experiment was shown to be 8.7×10^{-29} ecm[1)]. A ThO molecule has a large effective internal electric field, and is an advantageous material for an EDM search. However, in atomic or molecular beam experiments, a significant systematic effect is caused by the moving magnetic field effect. Owing to the geometric phase shift generated by the field gradient, these systematic errors mimic the true EDM signal and limit the measurement accuracy of the EDM.

Francium (Fr) atom, which has a large enhancement factor, are very useful for the search of an electron EDM. Because Fr is an alkali atom, it is possible to slow down the atomic velocity, greatly extending the interaction time, and to localize the atoms within a small space using laser cooling and a trapping technique. This technique can also reduce the influence of non-uniformity of the applied electric and magnetic fields in an EDM search experiment. Moreover, a longer interaction between the atoms and applied electric field increases the sensitivity of an EDM signal as compared with an EDM search experiment using atomic and molecular beams.

The development of an optical dipole force trap (ODT) and optical lattice systems for an electron EDM search using Fr and rubidium (Rb) atoms is progressing at the Cyclotron and Radioisotope Center (CYRIC) of Tohoku University. Because Rb atoms have chemical properties similar to those of Fr atoms, Rb atoms have been mainly used in the development of ODT systems. The use of an ODT is a variegated technique for the trapping of neutral atoms within a region with high electric field strength, and is useful for EDM measurements. A magneto-optical trap (MOT) is widely used as a precooling method before atoms are loaded into an ODT. Details regarding the development of a MOT system for the trapping of Rb and Fr atoms have been reported[2,3)]. The typical density and number of Rb atoms in the magneto-magnetic trap were estimated through absorption imaging to be approximately 10^{10} atoms/cm^3 and 10^9 atoms. For a transfer from an MOT to an ODT, it is important that the temperature of the atomic cloud be sufficiently lower than the potential produced by the ODT light. In a previous study, it was shown that the temperature of the atomic cloud was higher than the potential of the ODT light, and the efficiency of the transfer to the ODT was poor. Therefore, we investigated whether an atomic cloud is cooled to below the Doppler cooling limit temperature through polarization gradient cooling (PGC) using the time of flight (TOF). To allow PGC to work well, a precise adjustment of the ambient magnetic field is needed. The results are shown in Fig. 1, where the vertical axis indicates the radius of the atomic cloud, and the horizontal axis indicates the time after turning off the MOT light. The spread of the atom cloud is observed through absorption imaging using a camera with a cooled charge-coupled device (CCD). The estimated temperatures of the atoms were 800 (red circle) and 20 (blue rectangle) μK, respectively, which indicates that the temperature decreases when PGC is added, and the value is also lower than the Doppler cooling limit temperature, as compared with the MOT.

We introduced a new light source for the optical dipole force trapping of atoms trapped using an MOT with PGC. The light source consists of a seed light and a fiber amplifier. The wavelength of the light was 1,064 nm. The output power was approximately

50 W after passing through the fiber amplifier when inputting a seed light power of 120 mW. After passing through the isolator for the prevention of a return light, the light enters an acousto-optic modulator (AOM) for switching. First-order light diffracted by the AOM is extracted based on the aperture, and magnified using f = 50 and f = 300 lenses. Thereafter, the light passes through a f = 250 lens installed in front of the port of the vacuum chamber, and becomes incident inside the chamber. The ODT light passing through the chamber is blocked using a beam dumper to prevent scattering into the surroundings. The atomic cloud trapped in the ODT is observed from a photograph taken using the cooled CCD camera. To prevent the ODT light from entering the camera as stray light, a filter for blocking light with a wavelength of 1,064 nm is attached to the camera. When the light intensity reached 35 W, the number of atoms captured by the ODT was confirmed, as shown in Fig. 2, which is an image taken after 35 ms of holding only ODT light. The number of atoms was evaluated by taking the sum of the optical density around the image of the ODT, the estimated number of which was approximately 10^6.

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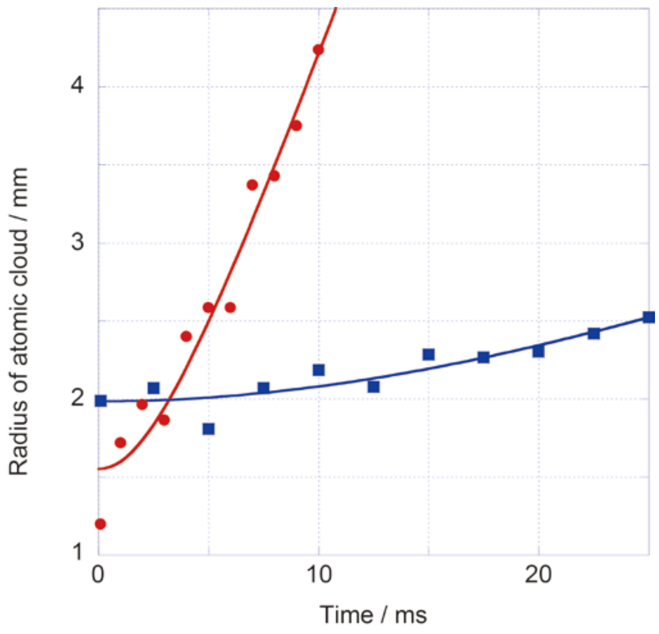

Figure 1. Time of flight. The blue rectangle and red circle indicate the results with and without PGC, respectively. The lines are the fitting curves.

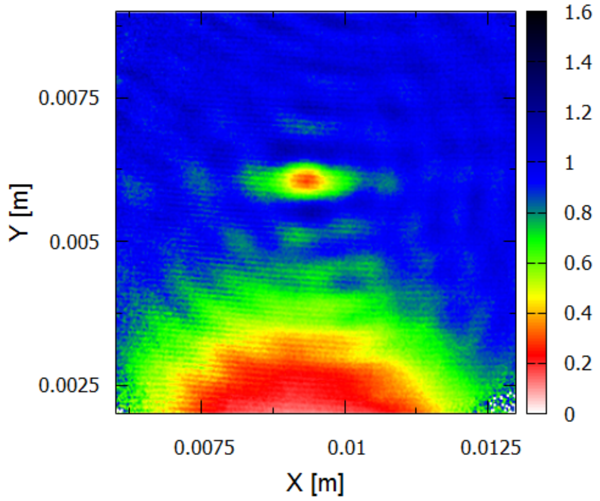

Figure 2. Absorption imaging of atoms after being captured by an ODT for 35 ms. The large absorption shown at the bottom of the image is an atomic cloud under a free-fall without being captured by the ODT.