Present status of EDM experiment with laser cooled radioactive atoms


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The fundamental symmetries, charge conjugation (C), parity (P) and time reversal (T), play a significant role in the Standard Model (SM) of elementary particle physics. Of these, T symmetry and the combined CP symmetry are the least well understood, and they hold valuable clues for unraveling the secrets of nature. All subatomic particles are postulated to possess an intrinsic property known as a permanent electric dipole moment (EDM). The EDM of an atom is a combination of those of each constituent particle and also CP-violating interactions between the particles [1]. Being many-particle systems, atoms and molecules are ideal candidates for probing a rich variety of both T- and CP-violating interactions. Paramagnetic atoms, which have a single valence electron in their outer shell, are sensitive to subtle signals associated with CP violations in the leptonic sector, i.e., the EDM of the electron.

Since an electron is a point particle with a non-zero spin, it may possess an intrinsic EDM. However, the electron EDM (e-EDM) is predicted to be very small by many particle physics models. The magnetic dipole moment of the electron has been measured to a precision of just a few parts in a hundred trillion, which is the most accurate verification of a quantum electrodynamics prediction in the history of physics. However, its counterpart, the e-EDM, is still speculative. If the e-EDM was identified, it could be used to indirectly investigate particles with masses of ten electron Volts or higher, which are beyond the reach of even planned high-energy particle colliders [2]. Experimental searches for the e-EDM are currently being carried out using neutral atoms such as thallium (Tl) and francium(Fr), molecules such as YbF and ThO, and solid-state materials. Although no conclusive result has yet been obtained, some upper limits have been established.

The magnitude of the coupling constant is so small that the current experimental sensitivity about 10^{-30} ecm needs to be improved by almost ten orders of magnitude to test the prediction of the SM (10^{-38} ecm), which appears impossible in the foreseeable future. However, there are many extended versions of the SM that predict the e-EDM to be within the reach of current or proposed EDM experiments. This allows the predictions of various models of particle physics to be tested, including the most attractive SUSY models. Under the simple SUSY model, the EDM for an unknown particle can be expressed as

\[ d_e \sim \frac{\alpha m_e e}{4\pi M_i^2} \sin \theta_\mu \tan \beta, \]  

where \( \theta_\mu \) is the CP phase, \( M_i \) is the SUSY particle mass, \( \alpha \) is a fine structure constant. Francium is the heaviest alkali element and is therefore its atomic EDM is therefore most sensitive to the e-EDM. It thus provides a rich laboratory for investigating CP violation arising from the leptonic sector.

The high nuclear charge of Fr significantly enhances the atomic EDM to approximately 895 times that of a free electron, which is calculated very accurately with a relativistic couple cluster model [3,4], therefore Fr is one of the most promising candidates for investigating the e-EDM. At RIBF, many kinds of isotopes of Fr can be produced, and we can study the EDM for many Fr isotopes. The Fr has high sensitivity to electron EDM. As the number of neutrons increases, the octupole deformation of nuclei becomes large, and as a result, nuclear EDM is amplified for Fr etc. It is very important that the CP violating interactions between nucleon and electron can be contributed to the EDM of an atomic system, and it can be extracted from atomic EDM measurement.

The francium is produced by a nuclear fusion reaction between \(^{187}\text{Au}\) in the target and an \(^{16}\text{O}\) beam produced by an AVF cyclotron. The beam energy is adjusted to just above the coulomb barrier of \(\sim 100\) MeV, which yields the maximum cross section for the \(^{16}\text{O}^{187}\text{Au}\) reaction to produce \(^{205}\text{Fr}\). The Fr atoms diffuse inside the Au target, and some reach the surface, where a certain fraction are desorbed. In this process, an electron is stripped away to produce a Fr+ ion with a surface ionization process. One of the key issues to achieve the high intensity cold Fr source is the neutralizer, which reflects the electron to the Fr ion to produce the neutral Fr atom with high neutralization efficiency. The Fr ion is injected to the target, yttrium (Y) that has the work function smaller than the ionization potential of Fr. The injected Fr ion becomes a neutral atom and it will be desorbed from the target surface when the Y target is heated. The Magneto-Optical Trap (MOT) glass cell is attached to the neutralizer directly. The trapping efficiency is less than 1% at present, due to the loss of the atoms by sticking to the inner wall of the tube connected from the neutralizer to the MOT cell, and the velocity of the atoms are too fast compared to the capture range of the MOT. The trapping efficiency can be improved by longitudinal laser cooling for the deceleration of the velocity.
We developed the MOT system shown in Fig. 1, which was directly attached to the chambers for the neutralizer. We have succeeded in developing a frequency-offset locking technique that can adjust the resonance frequency while keeping the two kinds of light sources (trapping and repumping) needed for Fr trapping [5] at a constant frequency difference of 46 GHz. Furthermore, a frequency stabilization technique using iodine (I$_2$) molecules has been established as a secondary frequency reference for which excitation levels exist near the Fr resonance frequency. The Fr MOT has been succeeded in the experiment at CYRIC, Tohoku University as shown in Fig.1 and 2 [6]. The primary beam intensity at RIKEN will be increased with 10 times, and the number of Fr in the MOT with $10^7$, which is required for the EDM accuracy $10^{-30}$ ecm, can be achieved at RIKEN.

We introduced high-intensity fiber laser and confirmed the formation of ODT/OL with stable atom Rb as shown in Fig. 3. Moreover, lifetime was measured by single atom trap, and the lifetime of 10 seconds or more can be achieved in OL with no disturbance of adjacent atoms as shown in Fig.1.

Fig.1. The MOT overview. The result of coherence time with single atom trap (left) and the Fr trap result with the time dependence (Fr in/out) (right).

Fig.2. Fluorescence image of MOT containing Fr atoms (left) and background image without Fr atoms (center). The trapped Fr can be observed from the difference of these images (right), although the number of the Fr atom is limited and less than $10^2$.

Since MOT gives trapping force by a combination of gradient magnetic field and laser light, this magnetic field is not suitable for the EDM measurement. We have developed an optical dipole force trap (ODT), which can be interpreted as one dimensional optical lattice (OL) that traps the atoms with the potential formed by the standing wave of laser light with the lattice shaped potential. Since the OL has a lattice spacing of about the wavelength of laser light of ~ 100 nm, atomic collisions are suppressed and interaction time can be prolonged. We introduced high-intensity fiber laser and confirmed the formation of ODT/OL with stable atom Rb as shown in Fig.3. Moreover, lifetime was measured by single atom trap, and the lifetime of 10 seconds or more can be achieved in OL with no disturbance of adjacent atoms as shown in Fig.1.

Fig.3. ODT and OL setup. The right plot shows the ODT trapping for Rb atoms.

The cold Fr facility utilizes the high intensity heavy ion beam supplied by AVF cyclotron to produce high flux of Fr isotopes of interest and applies laser cooling techniques on these radioactive isotopes (RI). This cold Fr source has a function capable of investigating various fundamental symmetries. The development of laser apparatus and the construction of the experimental room for the laser are in progress.

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