Ultra-cold radioactive atomic isotopes produced using laser cooling and trapping methods have been in use for nuclear $\beta$-decay studies, atomic parity non conservation and for searches of a permanent electric dipole moment of a fundamental particle in atoms. Among atoms, francium, a radioactive heavy alkali atom has been identified as a promising candidate to search for an electron permanent electric dipole moment. In this context, a laser cooled francium factory is being setup at CYRIC, Tohoku University for the measurement of an electron EDM. We report on the status of the experiment and various stages of the facility such as production of francium isotopes, extraction and transportation of francium ions and conversion to atoms and finally laser cooling and trapping of francium atoms.

**KEYWORDS:** Francium, electron electric dipole moment, cold atoms

1. Introduction

The Standard Model (SM) of particle physics explains most of the observed phenomena: violation of parity symmetry in the weak interactions, nature and forces between particles and to some extent charge-parity (CP) violation. The effects of CP or T symmetry breaking are typically small compared to the dominating electromagnetic phenomena. The violation of the combined charge conjugation and parity operation, CP, is of particular importance because of the possible relation to the observed matter-antimatter asymmetry in the universe [1, 2]. A. Sakharov [3] has suggested that the asymmetry in matter-antimatter may be explained via CP-violation in the early universe in a state of thermal non-equilibrium together with baryon number violating processes [4]. CP violation has been observed in neutral K and B meson systems, however, the known sources of CP-violation in the SM are insufficient to account for it [1]. A permanent electric dipole moment (EDM) of a fundamental particle violates both parity and time reversal symmetries. In other words, from the CPT theorem, with the assumption of CPT invariance, time-reversal violation of a permanent electric dipole moment is equivalent to violation of CP symmetry. EDMs, which also violate CP, offer plausible opportunities to identify new sources of CP-violation [5, 6].

It was suggested by Sandars [7] that in heavy atoms, atomic EDMs increases as a function of $Z^3$. Detailed calculations show that the atomic EDM can actually be several hundred times larger than the EDM of a bare electron. The EDM of a fundamental particle can induce an EDM into a composite...
Paramagnetic atoms and molecules are sensitive to the EDM which arises from an unpaired electron. In heavy paramagnetic atoms a possible EDM of the electron is enhanced by a factor $R = d_{\text{atom}}/d_e$ and is given by \[ R = 10 \frac{Z^2 \alpha^2}{J(J + 1/2)(J + 1)^2} \] where $Z$ is the atomic number, $\alpha$ is the polarizability of the atom and $J$ is the angular momentum. For a large $Z$ this factor can provide a few orders of magnitude enhancement of the electric field inside the atom.

Experimental searches for permanent electric dipole moments are in progress using various systems such as neutron, electron and nucleons through atoms and molecules \[9\]. Our interest is in francium (Fr), a paramagnetic atom for the electron EDM experiment. From the theoretical predictions francium atom is a better atomic system for electron EDM studies compared to Thallium (Tl) and Cesium (Cs) \[10–12\].

Francium ($Z = 87$), a group I element is a radioactive heavy metal and is being used for different experimental investigations such as atomic parity violation \[13, 14\], search for an electron permanent electric dipole moment \[15\] and anapole moment \[16, 17\]. Laser cooling and trapping of different Fr isotopes have been demonstrated \[13, 14, 18, 19\]. The advantages of laser cooled and trapped atoms for EDM studies have been discussed \[20–22\]. We intend to use ultracold Fr atoms for EDM measurement in an optical dipole trap \[23\]. In this context, construction of a laser cooled francium factory has almost completed and the status of various sections is presented.

2. Experimental setup

2.1 Francium production and extraction

The different sections of the francium EDM experimental setup located at cyclotron and radioisotope center (CYRIC), Tohoku University can be broadly divided into four stages: production and transportation of francium isotopes; conversion of francium ions to neutral atoms; laser cooling and trapping of Fr atoms and EDM experiment in an optical dipole trap. At present most of the components of the first three stages are in place and preliminary measurements have been completed.

The francium isotopes, for example, $^{210}\text{Fr}$ is produced using an oxygen ($^{18}\text{O}^{5+}$) beam of total energy 100 MeV (5.6 MeV/nucleon) from ECR ion source of AVF ($K = 100$ MeV) cyclotron. The oxygen beam is passed through a swinger magnet and impinge on the gold (Au) target at an angle of 45 degrees. The Au target is placed in a cup like arrangement inside a thermal ionizer that can be heated to 1300 K. The advantage of this setup is that the gold does not overflow when it is heated to the melting point and because the diffusion time is faster in a liquid. The francium isotopes are produced by the $^{18}\text{O} + ^{197}\text{Au} \rightarrow ^{215-\delta}\text{Fr} + \alpha n$, (nuclear) fusion evaporation reaction \[24, 25\].

The production of Fr ions in the Au target is based on the principle of surface ionization described by the Saha-Langmuir equation \[26\]
\[ \alpha = \frac{n_+}{n_0} = \frac{g_+}{g_0} \exp \left( \frac{\phi - V}{k_B T} \right) \] where $\alpha$ is the fraction of ionized particles, $n_+$ and $n_0$ are the respective densities of ions and atoms near the surface, $g_+$ and $g_0$ are statistical weights of the ionic and atomic states based on the angular momentum of the states, $\phi$, the work function of the ionizing material, Au target (5.1 eV) and $V$, the first ionization potential of the element produced, Fr (4.08 eV), $k_B$ is Boltzmann’s constant and $T$ is the absolute temperature, respectively. The efficiency, $\epsilon$ for surface ionization can be written as \[27\]
\[ \epsilon = \frac{n_+}{(n_+ + n_0)} = \frac{\alpha}{1 + \alpha} \]
The ionization efficiency for Fr on an Au target surface is about 100% for the temperature between 950 and 1100 K.

The produced Fr isotopes are extracted perpendicular to the production target from the thermal ionizer as singly charged low energy ions by applying an electrostatic potential of 3 kV and are deflected horizontally with an electrostatic prism. These ions are transported to the deposition chamber, located ten meters away from the production target using three sections of quadrupole focusing electrodes and a Wien filter [28]. They are deposited on a 25 micron thick yttrium (Y) neutralizer foil placed inside the deposition chamber. The neutralizer foil is mounted such that it can be rotated up while heating for the release of Fr as an atom into the glass cell for magneto-optical trapping (MOT) and down while depositing the Fr ions (see Fig. 2(right)). The yttrium metal is known to have a good conversion efficiency for Fr compared to other metals like zirconium (Zr) and Gadolinium (Gd) [29].

Recently, a modified thermal ionizer is installed in order to achieve higher extraction and transportation efficiency than that of the previous ionizer [30]. Preliminary results of the operation of the thermal ionizer are presented here. The variation of the emission of background ions as a function of temperature of the Au target is shown in Fig. 1(a). The red full circle corresponds to the increase in temperature of the Au target for the 950 to 1300 °C range. The blue full circle corresponds to the decrease in temperature of the Au target. The sharp increase in the ion current observed at about 1150 °C is due to the liquid Au target after reaching the melting point of gold. In Fig. 1(b), the increase in the background ion current as a function of the extraction voltage of the Au target is shown. Here, the Au target temperature is kept constant, which is 1120 °C. The application of extraction voltage to the target also leads to the focusing of background ions from the Au target or impurities inside the target [30].

![Fig. 1.](image)

**Fig. 1.** (a) The background ion current as a function of Au target temperature. *Inset:* Enlarged view of the Au target temperature from 970 °C to 1140 °C. (b) Dependence of the background ion beam current on extraction voltage of the Au target.

### 2.2 Magneto-optical trap

An anti-reflection (AR) coated glass cell made of quartz is located above the deposition chamber for magneto-optical trapping of francium atoms, which is shown Fig. 2(left). The inside walls of the cell are coated with octadecyltrichlorosilane (OTS) to minimize sticking of Fr atoms (as well as Rb) on the glass surface. After deposition of Fr ions, the yttrium foil is heated to about 1000 K to extract them as neutral atoms, a necessary requisite for collecting atoms in a MOT, which is a combination of red detuned laser beams in three dimensions with respect to the atomic transition and a quadrupole magnetic field produced by a pair of anti-Helmholtz coils. The apparatus has been optimized using
$^{87}\text{Rb}$ ions during off-line measurements and magneto-optical trapping of about $10^6$ $^{87}\text{Rb}$ atoms has been achieved [31, 32]. In Fig. 2(right), the loading time of the $^{87}\text{Rb}$ atoms in the MOT when the yttrium neutralizer heats to about 1000 K and decay time of the atoms is shown after the neutralizer is switched off.

![Fig. 2. Left: The quartz glass cell for magneto-optical trapping of Fr (and Rb) atoms. Right: The fluorescence of the magneto-optically trapped $^{87}\text{Rb}$ atoms. The yttrium neutralizer foil is heated to about 1000 K for 30 seconds, releasing rubidium as neutral atoms, which are captured in the MOT [32].](image)

Further, saturated absorption spectroscopy of $\text{I}_2$ molecule, a widely used secondary frequency standard in the 500-900 nm wavelength region is realized employing the frequency modulation technique. It is used as a reference for laser frequency stabilization of the electric dipole allowed $7s^2S_{1/2} - 7p^2P_{3/2}$ transition at 718 nm in francium and for frequency offset locking of the laser frequencies needed for trapping as well as repumping of francium atoms in a MOT [31]. Frequency offset locking of two laser frequencies separated by 46.8 GHz, corresponding to the hyperfine splitting of the francium ground state has been demonstrated with a commercial waveguide type electro-optical modulator (EOM) by generating a tenth order sideband frequency [33]. Additionally, frequency dependent polarizabilities of the $7s^2S_{1/2}$ and $7p^2P_{3/2,1/2}$ levels of the electric dipole allowed $7s^2S_{1/2} - 7p^2P_{3/2,1/2}$ transitions are calculated from which magic wavelengths are identified for state insensitive optical dipole trapping of francium atoms [34].

### 2.3 Rubidium magnetometer

In parallel, an atomic magnetometer using rubidium is being developed, which will be used as a magnetometer for Fr-EDM experiment [35]. The principle of non-linear magneto-optical rotation (NMOR) of laser light is used to detect the magnetic component parallel to the direction of the laser light [36]. Employing frequency modulation (FM) technique the strength of the applied magnetic field is determined from the rotation angle of the linearly polarized laser light [37]. From the relation

$$\delta B = \left( \frac{\partial \phi}{\partial B} \right)^{-1} \delta \phi$$  \hspace{1cm} (4)


where $\frac{\partial \phi}{\partial B}$ is the slope of the measured NMOR signal and $\phi$, measured power density of the spectrum, the sensitivity of the magnetometer is determined. The best sensitivity achieved so far with the Rb magnetometer is 50 pT/\sqrt{Hz} [38].

2.4 Development of electrodes for electric field application

Application of high electric fields of about 100 kV/cm is required for the EDM measurement using cold atoms. For this, glass electrodes coated by tin doped indium oxide (ITO - $\text{In}_2\text{O}_3$:Sn) are being developed and are tested placing inside a MOT chamber. The advantages of ITO are high transparency to light in the visible region, 400-700 nm (transmission $\sim$ 80%) and good conductivity (resistivity ($\rho$) $\sim$ 1 $\times$ 10$^{-4}$ $\Omega$cm) to apply high electric fields [39]. Preliminary measurements of the Stark shift of D1 line in $^{87}$Rb atom employing ITO coated glass electrodes on magneto-optical trapped $^{87}$Rb atoms using the D2 transition are shown in Fig. 3. A maximum of 40 kV could be applied without any discharge [40].

![Fig. 3. Absorption of spectrum of the F=2 to F'=1 transition (right peak) and the F=2 to F'=2 transition (left peak), D1 line of $^{87}$Rb atom at 0 kV and 15 kV DC electric field. The difference frequency of the two spectra is used to determine the magnitude of the applied electric field.](image)

3. Summary

In summary, francium atom is being used for fundamental symmetry investigations such as searches for an electron permanent electric dipole moment and atomic parity non conservation. The francium facility at CYRIC, Tohoku University has almost been completed for an experiment to search for an electron electric dipole moment using laser cooled and trapped francium atoms. Test runs of different experimental stages using both Rb and Fr have been carried out. The former has been successfully magneto-optically trapped. Further improvement of various sections of the experimental facility to magneto-optically trap francium is in progress.

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