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I. 6. Upgrade of Thermal Ionizer for the Production of High Intensity Francium Beam

Liu S., Yoshida H., Hayamizu T., Saito M., and Sakemi Y.

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Introduction

The non-zero permanent electric dipole moment (EDM) of an elementary particle implies simultaneous violation of both parity (P) and time-reversal (T) symmetries and its search is in the forefront of the T-violation experiments. Assuming CPT invariance, T-violation involves an associated CP violation; the latter is the key to explain the observed matter-antimatter asymmetry in the universe.

The magnitude of the electron EDM is predicted to be of the order of $10^{-38}$ e·cm within the Standard Model of elementary particle physics, which is far below the current experimental reach. However, many extensions of the Standard Model such as for example, supersymmetry, multi-Higgs physics, left-right symmetry etc. predict much larger EDMs, which therefore can be verified with the ongoing and/or the proposed experiments.

Experiment

Francium (Fr) being the heaviest alkali and radioactive atom is a suitable candidate for the research of the electron EDM. Despite Fr being radioactive, we use $^{210}$Fr with a half-life of about 3 min for the EDM experiment for the reason that it has large EDM enhancement factor as the latter scales as the cube of the atomic number: $K \sim Z^3 \alpha^2$. The relativistic coupled cluster theory predicts the enhancement factor of Fr with 895 at present. In addition, the energy level structure of Fr is such that it can be easily subjected to laser cooling and trapping.

In our experiment, we produce Fr by the nuclear fusion reaction: $^{18}$O+$^{197}$Au→$^{210}$Fr+5n. The $^{18}$O beam from AVF cyclotron at CYRIC, Tohoku University with the beam energy of 100 MeV, which is just above the coulomb barrier and chosen so as to maximize
the production of Fr, is bombarded on the gold target at an angle of 45°. The target is being heated to a temperature of more than the melting point of the gold 1337K. After the reaction, the produced Fr atoms move to the surface by diffusion. Then the Fr desorbs from the target surface as atoms and ions. After surface ionization in the Thermal Ionizer (TI) the produced Fr⁺ ion beam is extracted by the extraction electrode and focused by the two einzel lenses subsequently and transported up to the deflector, which will bend the beam line from vertical to horizontal direction, and transport further to the three sets of quadrupole triplets. At the end of this beam line, we have a neutralizer to neutralize the ions back into atoms. These atoms are slowed down using Zeeman cooling system and further transported to the laser room, where these atoms are cooled to velocities as low as a few μK using Magneto-optical trap and eventually measure the Fr EDM in the optical lattice. Thus, we have obtained $10^6$Fr⁺/sec yield²).

To improve the sensitivity of the EDM measurement, one needs to improve both extraction and transportation efficiency of the Fr⁺ ion beam to obtain much more Fr production yields. The transverse beam emittance also needs to be improved to prevent further losses; the smaller the emittance better would be the beam quality. The transportation efficiency, the beam profile and the beam emittance depend highly on the geometry of the lens system and the shape of the electric field.

In our experiment, the Fr⁺ ion beam is transported up to the length of 11 m from TI to neutralizer, thus a parallel beam is required to maintain high transportation efficiency with small beam size. To achieve this, an electrostatic lens system having five or higher number of lens elements is desirable since only they have afocal zoom. The conditions for “afocal zoom lens” are given in the following equations:

$$M = \left(\frac{V_5}{V_1}\right)^{1/4}, \quad \frac{V_5}{V_3} = \frac{V_3}{V_1}, \quad \frac{V_4}{V_3} = \frac{V_2}{V_1}$$  \hspace{1cm} (1)

where $M$ is the magnification and $V_1$ to $V_5$ are the voltage potentials applied for the first to the fifth element³).

**Lens design and Simulation**

Modeling of electrostatic lenses is carried out using the charged particle optics simulation software called SIMION. By replacing the present two einzel lenses with a five-element lens system and modifying the geometry of extraction electrode and lens system, we aim to obtain high extraction and transportation efficiency with small beam emittance and beam size.
One of the most important parameters which affect both beam emittance and beam focal point is the opening angle of target rod. To optimize the electric field distribution around the target rod, we have studied the effect due to variation in the rod angle on beam emittance and focal point. We have varied the opening angle from 73 degree to 85 degree, and at 82 degree we have observed the farthest focal point of ion beam with relatively low beam emittance (Fig. 1 (a)). Thus, we have chosen 82 degree as the new opening angle of target rod. Another important parameter on which both beam emittance and beam diameter depend is the distance between target and extraction electrode. By changing the distance from 14.5 mm to 16.5 mm we have found that between 14.6 and 14.8 mm both the beam emittance and beam diameter have the lowest values (Fig.1 (b)). Considering the fact that during the experiment the gold target melts thereby increasing the distance in the process, we decided to choose 14.6 mm as the distance between target and extraction electrode. The dependence of beam emittance and beam diameter on the distance between target surface and lens system has also been studied. As shown in Fig 1 (c), the beam emittance remains more or less constant where as the beam diameter decreases as the distance increases. Thus we have chosen the middle point-101 mm, which is the beam focal point after extraction electrode to make sure the stability of both beam emittance and beam size.

**Results and Conclusion**

We have upgraded the TI based on the design mentioned above. We have performed the test experiments with the upgraded TI using stable rubidium beam. We can see that the forms of distribution of the extraction efficiency in simulation shown in Figs. 2 (a) and (c) are very close to the form of distribution of the beam current in experiment, shown in Figs. 2 (b) and (d). We have improved the transportation efficiency from 50% to more than 80% with the highest value being 91.4%. We presume that this improvement is due to the optimized beam emittance, the simulated value of which had been minimized from 36.1 mm•mrad to 18.3 mm•mrad.

We expect to perform the experiment using Fr beam next and improve the transportation efficiency up to 94% by applying a higher voltage (up to 5 kV) to gold target and oven. The Fr beam intensity will hopefully reach $10^7$ Fr$^+$ /sec with the $^{18}$O beam intensity of 2 eμA using the upgraded ECR ion source and with the upgraded TI.
References


Figure 1. Effect of opening angle change on beam emittance and focal point (a); Dependence of beam emittance and beam diameter on the distance between target surface and extraction electrode to beam emittance and beam diameter (b) and on the distance between target surface and lens system (c).

Figure 2. Distribution of the extraction efficiency in simulation (a),(c) and beam current in experiment (b),(d) at SSD1 and SSD2 for two einzel lens system with the voltage applied for oven and target VA=1kV. X axis shows the voltage applied for VL4 and Y axis shows the voltage applied for VL2.