

I. 2. Development of High Quality Francium Ion Beam to Search for the Permanent Electron Electric Dipole Moment

*Yoshida H.¹, Hayamizu T.¹, Liu S.², Oikawa A.¹, Saito M.¹, Aoki T.³, Ezure S.¹,
Furukawa T.⁴, Harada K.¹, Hatakeyama A.⁵, Hatanaka K.⁶, Imai K.⁷,
Itoh M.¹, Kawamura H.¹, Kato T.¹, Murakami T.⁷, Nataraj S. H.¹,
Sato T.¹, Shimizu Y.⁸, Uchida M.⁹, Wakasa T.¹⁰, and Sakemi Y.¹*

¹*Cyclotron and Radioisotope Center, Tohoku University*

²*Department of Physics, Jilin University*

³*Graduate School of Arts and Sciences, University of Tokyo*

⁴*Department of Physics, Tokyo Metropolitan University*

⁵*Department of Applied Physics, Tokyo University of Agriculture and Technology*

⁶*Research Center for Nuclear Physics, Osaka University*

⁷*Department of Physics, Kyoto University*

⁸*Department of Physics, Tohoku University*

⁹*Department of Physics, Tokyo Institute of Technology*

¹⁰*Department of Physics, Kyusyu University*

Introduction

The non-zero observation of electric dipole moment (EDM) of the elementary particle provides the direct signature of the violation of the time-reversal (T) symmetry. Under the CPT theorem the T-violation means the CP violation. The Standard Model shows that the electron EDM (e-EDM) appears only in the higher-order diagram with gluon exchange and predicts a quite small value of less than 10^{-38} e cm^1 , which is many orders of magnitude below the current experimental limit. On the other hand, several theoretical models beyond the Standard Model predict much larger e-EDM values as $10^{-26} \sim 10^{-29} \text{ e cm}^2$. This means that e-EDM is a good probe to search for the phenomena beyond the Standard Model.

In paramagnetic atoms an electron EDM results in an atomic EDM enhanced by the factor $\sim Z^3 \alpha^2$ ³⁾, where Z and α are the atomic number and the fine structure constant, respectively, due to the relativistic effects. A heaviest alkali element francium (Fr) has the largest enhancement factor $R \sim 895$ ⁴⁾. The electron EDM for Fr atom has not yet been measured because Fr is a radioactive element with no stable isotopes, and it is difficult to make a concentrated sample due to a short life time (1~20 min) for the standard experiment.

Then, we are developing a high intensity laser cooled Fr factory at CYRIC, to perform the search for the unstable atom Fr with the online Fr production, cooling and trapping.

Figure 1 shows the overview of the high intensity laser cooled Francium factory. The Fr is produced by a heavy-ion fusion reaction with an oxygen beam and a gold target ($^{18}\text{O} + ^{197}\text{Au} \rightarrow ^{210}\text{Fr} + 5\text{n}$ etc.) with the primary beam energy $E \sim 100$ MeV just above the coulomb barrier. The feature and details for each apparatus of this factory are reported^{5,6}. In these reports the experiment for Fr production and ion transport system are described.

Experimental Apparatus

For the primary beam of ^{18}O , the new 10 GHz ECR ion source (ECR10) was prepared for higher intensity and heavy nuclide and the beam current of $^{18}\text{O}^{5+}$ with 2 electric μA has been achieved. We utilize the beam swinger system to inject oxygen beam into the gold target in Thermal Ionizer downward. The angle of the swinger system is fixed at 45 deg. In the Thermal Ionizer, francium atom produced by fusion reactions are ionized and extracted. To realize more than 10^6 of Fr^+/sec yield, the thermal ionizer was designed to expect over 10% of extraction efficiency and stable heating operation during long term measurement. The features of the thermal ionizer are as follows;

- The Au target is held upper side of rod to prevent the outflow of melted gold.
- The direction of Fr extraction is vertical to the gold surface to be maximum of the extraction yield.
- The thermal ionizer has a focusing lens system just after the extract electrode to achieve a small emittance of Fr ion beam.
- The target and oven temperature can be kept over 110°C , stably by using a radiant heating type tungsten heater.
- Rb atomic beam is used for the development and performance evaluation of each apparatus. Rb is also alkali element atom and Rb ion beam extracted by the thermal ionizer is available to test and improve ion optics and transport parameter without accelerated beam.

The detail of this thermal ionizer and Rb beam was reported⁷.

To avoid radioactive damage of laser trap detectors, especially optical devices, Fr beam should be transported to trapping area far from the nuclear reaction region. We need not only to transport Fr beam with high transmission rate so far but also to diagnose the Fr beam profile and the number of Fr ion passed. The high vacuum of transportation area is

needed for heavy ion beam. This system consists of one electrostatic deflector, three sets of electrostatic Quadrupole triplets and four diagnosis chambers⁸⁾. Each diagnosis chamber has one semiconductor detector (SSD) for decayed alpha particles from unstable Fr reached a catcher foil after a slit and one ZnS viewer for Rb ion beam profile. The catcher foil is also used for Faraday Cup to measure the current of Rb ion beam.

Experiment and Results

The experiment of Fr production has been performed at CYRIC by using the thermal ionizer and the beam transport and diagnosis system with the accelerated $^{18}\text{O}^{+5}$ beam up to 100 MeV. The accelerated oxygen beam was transported on the center of the thermal ionizer where there was the gold target with a size of $\phi 12.5$ mm diameter and 1mm thickness. Though the beam current was about 2 eμA at the monitor just after the accelerator, the typical beam current injected on the target was estimated at about 250 enA because the parameters of the primary beam transport wasn't optimized and a slit on the primary beam course cut off the beam to avoid activating materials around the thermal ionizer and to clear up problems of optimization of the beam transport parameters.

Figure 2 shows the alpha decaying spectrum obtained by the SSD in the diagnosis chamber directly above the thermal ionizer. The highest peak at the energy 6.54 MeV is to be the alpha decaying energy from $^{210,211}\text{Fr}$ and other peaks are the energies from other produced isotopes $^{208,209}\text{Fr}$ and daughter nucleus from Fr.

We observed the target temperature dependence of the Fr yield as shown in Fig. 3, by monitoring with the thermocouple (W/Re) attached below of the target. It is found that over 970°C which is near the melting point of the gold 1064°C, the yield is increased, drastically. Assuming that the highest peak is almost from $^{210}\text{Fr}^{9)}$, the ^{210}Fr extraction yield rate was estimated from Fr detection and efficiency calculated by Monte-Carlo simulation. The maximum value is about $7 \times 10^5/\text{sec}$ with the primary beam current of about 250 enA. Calculating the total production with the primary beam current, the maximum extraction efficiency of the Fr ion from the thermal ionizer is evaluated at about 40%, which is the highest extraction efficiency of Fr. The primary beam current dependence of Fr production is shown in Fig. 4, thus Fr production rate is almost increased as a linear function of the beam current. The transport efficiency of the Fr beam course from the diagnosis system directly above the thermal ionizer to other diagnosis system after one electrostatics deflector and one quadropole triplet were measured. The maximum

efficiency is about 20% even though design values expected was over 90%. This means that the emittance of the Fr ion beam after the thermal ionizer was worse than our assumption.

Next Step and Plan

The current experimental limit of the e-EDM value is less than $1.05 \times 10^{-27} \text{ e cm}^{10}$, therefore the target of the measurement precision of e-EDM is less than 10^{-28} . To achieve our aim, about $10^7/\text{sec}$ of Fr for the injection rate into the Neutralizer is required by roughly estimation. To attain this production rate, we have some plans. One is to increase the current of primary beam by the optimization of beam transport and the development of the extraction of the ECR10 ion source because from our data the Fr production rate might be almost in proportion to the primary beam current. Transport efficiency is already increased about twice and the result of the ECR10 ion source development is expected to increase it by a few times. Therefore, totally about 2 euA of the primary beam current is expected on the target. Another plan is to replace the focusing lens system in the thermal ionizer. The new focusing lens system is already installed and the test experiment was performed¹¹⁾. This lens system has five-element lens, which has five sequential electrodes capable of being applied voltages independently and the high efficiency extraction electrode those shapes are optimized by the simulation software SIMION. In Fig. 5, the experimental result by using Rb beam as same setting of the Fr experiment show that the beam transport efficiency are improved about 90%.

After repairing of the accelerator and primary beam courses of CYRIC from the earthquake disaster, we will perform the experiment by high intense $^{18}\text{O}^{+5}$ beam about 2 euA with upgrade ECR10 ion source, then the $^{210}\text{Fr}^{+}$ rate of the entry of the Neutralizer is expected to achieve $10^7/\text{sec}$.

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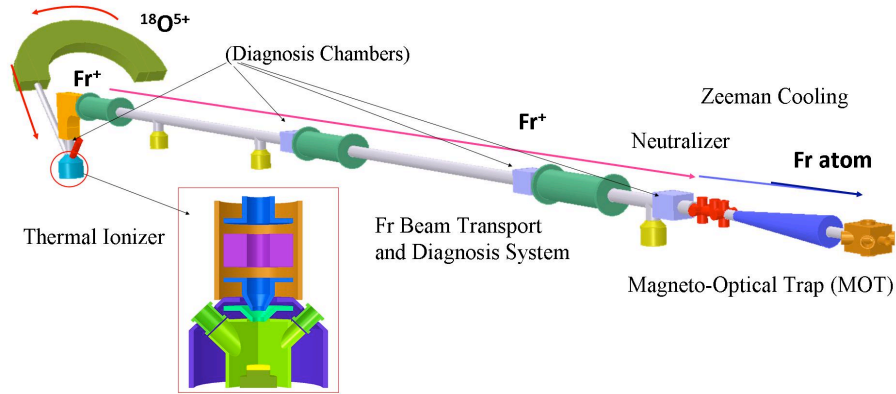


Figure 1. Schematic view of a high intensity laser cooled Francium factory at Cyclotron and Radioisotope Center (CYRIC), Tohoku Univ. The trap and measurement area to measure the EDM for Fr atom trapped by using Magneto-Optical Trap (MOT) after Fr atom slows down through Zeeman slower.

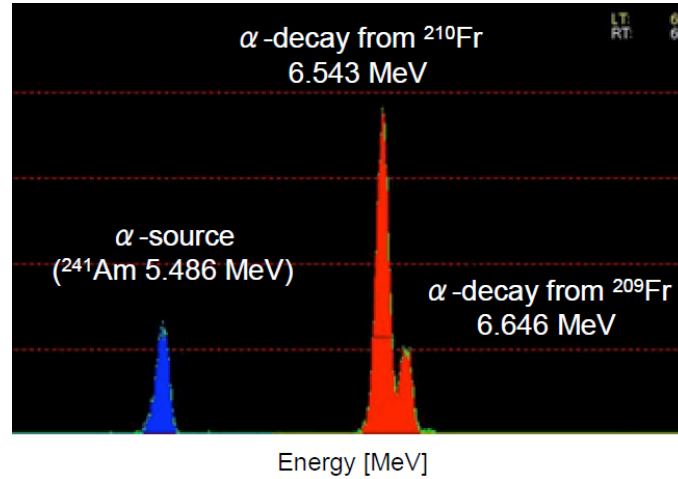


Figure 2. The horizontal axis corresponds to the energy of the alpha particles decaying from $^{208,209}\text{Fr}$, $^{210,211}\text{Fr}$ and ^{241}Am obtained by the SSD. The vertical axis shows the number of the alpha particles. The left peak at 5.486MeV is the alpha source of ^{241}Am installed in the diagnosis chamber for the energy calibration.

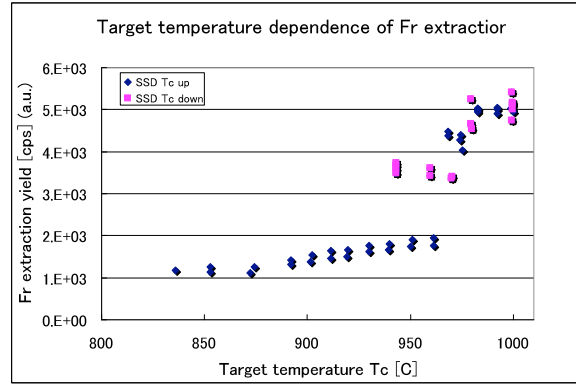


Figure 3. The target temperature dependence of Fr extraction yield: The target temperature is monitored by the thermocouple (W/Re) set near target inside the target rod.

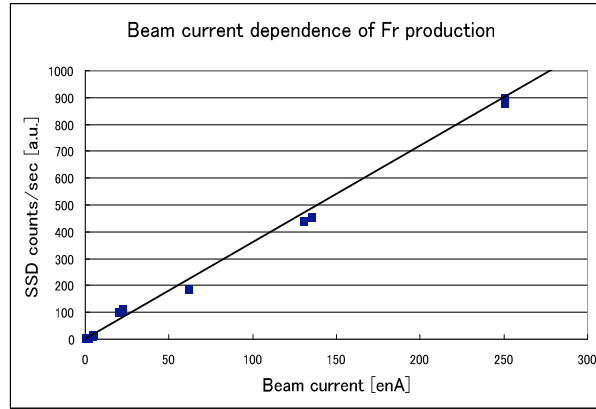


Figure 4. Beam current dependence of Fr detection rate: “SSD counts” is corrected by subtracting background, which are daughter nucleus with long life times decayed from Fr.

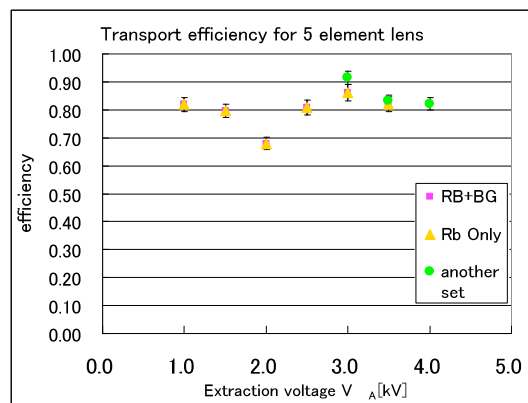


Figure 5. The transport efficiency for new focusing lens system with 5-element lens by using Rb beam: The efficiency is defined as the current ratio of Faraday Cup 2 (FC2), which is located at after the quadrupole triplet downstream from the deflector from FC1, which is located just above the thermal ionizer.