

Search for a permanent EDM using laser cooled radioactive atom

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Abstract. An Electric Dipole Moment (EDM) of the elementary particle is a good probe to observe the phenomena beyond the Standard Model. A non-zero EDM shows the violation of the time reversal symmetry, and under the CPT invariance it means the CP violation. In paramagnetic atoms, an electron EDM results in an atomic EDM enhanced by the factor of the 3rd power of the charge of the nucleus due to the relativistic effects. A heaviest alkali element francium (Fr), which is the radioactive atom, has the largest enhancement factor $K \sim 895$. Then, we are developing a high intensity laser cooled Fr factory at Cyclotron and Radioisotope Center (CYRIC), Tohoku University to perform the search for the EDM of Fr with the accuracy of $10^{-29} \text{ e} \cdot \text{cm}$. The important points to overcome the current accuracy limit of the EDM are to realize the high intensity Fr source and to reduce the systematic error due to the motional magnetic field and inhomogeneous applied field. To reduce the dominant component of the systematic errors mentioned above, we will confine the Fr atoms in the small region with the Magneto-Optical Trap and optical lattice using the laser cooling and trapping techniques. The construction of the experimental apparatus is making progress, and the new thermal ionizer already produces the Fr of $\sim 10^6$ ions/s with the primary beam intensity 200 nA. The developments of the laser system and optical equipments are in progress, and the present status and future plan of the experimental project is reported.

1. Introduction

To explore the mechanism responsible for the generation of observed matter-antimatter asymmetry in the Universe, the research on fundamental symmetry violations and various fundamental interactions using the laser cooled and trapped atoms is being promoted. The understanding of how the symmetry between the matter and antimatter was broken during the evolution of the early universe requires laboratory experiments which search for symmetry violations in the elementary particles such as quarks and leptons; one such phenomenon of our interest is the intrinsic electric dipole moment (EDM) of either elementary or composite systems. The non-zero observation of EDM provides the direct and conclusive signatures of the violation of time-reversal symmetry. The study of EDM also paves a way for the continuing quest for the ultimate theory of the Universe and it has a great potential in uncovering many mysteries which have been puzzling the mankind for ages such as the very survival of ourselves amidst many cosmic catastrophes such as a complete annihilation of matter and antimatter in the Universe. Using the extreme quantum states of matter at the low-energy scales we study the high-energy physics related to the phenomena which are thought to have happened in various epochs in the very early Universe.

2. Electron EDM search with radioactive atom

The standard model (SM) predicts quite tiny value of the electron EDM with $\sim 10^{-37} \text{ e} \cdot \text{cm}$, which is appeared in the higher order diagram with gluon contribution. This means that the EDM is the good probe to search for the phenomena beyond the standard model with low background contributing from the SM process. Many theoretical works show the finite electron EDM ranging to the value which can be measured with the modern experimental technique [1]. The super symmetry (SUSY) show that the EDM depends on the mass of the SUSY particles and the new CP violating phases appeared in the SUSY, then the EDM becomes the powerful tool to explore the new symmetry such as the SUSY and its violating mechanism.

2.1. Sensitivity of the EDM measurement

Although many theoretical models predict the large EDM, but it is still tiny value to measure it with the current experimental technique. The electron EDM in paramagnetic atoms is appeared and enhanced by the relativistic effects with the 3rd power of the nuclear charge. The heaviest alkali element such as the francium (Fr) has the largest enhancement factor, and the detailed calculation with the relativistic coupled cluster model [2] shows the enhancement factor with ~ 895 [3]. The Fr atom has the function as a microscope to magnify the tiny electron EDM. Although all the Fr isotopes are

radioactive with finite lifetimes, the ^{210}Fr has a lifetime with ~ 3 minutes sufficient to produce by the nuclear reaction, extract, transport, and trap in the cell to measure the EDM. The EDM itself can be determined from the difference of the Larmor frequencies by measuring between the states with the electric field applied parallel and anti-parallel to the magnetic field. To measure it, the Ramsey resonance technique will be utilized, where the application of two successive RF pulses results in resonance signals as a sinusoidal function of the phase of the second RF pulse. The sensitivity of the EDM measurement is limited by the quantum shot noise, and depends on the enhancement factor K , applied electric field E , the number of accumulated atoms N , the spin coherence time τ , the measurement time T with the equation $\delta d = \hbar / \{ (2e \cdot K \cdot E)(N \cdot \tau \cdot T)^{1/2} \}$. The high sensitivity search of the EDM is realized by the next generation experiment using laser cooled radioactive atoms, since the Fr has the largest enhancement factor, and in the high vacuum environment of the laser trapping cell, the spin coherence time becomes longer and the high electric field can be applied. The important point is that we need the sufficient number of the accumulated Fr atoms which will be shown in the next section.

2.2. EDM search with laser cooled atoms

Up to now, the EDM measurements have been done with the accumulated atoms in the cell and the collinear atomic beam using the Cs [4] and Tl which keeps the highest accuracy data at present [5]. However there are limitations to the systematic error as follows. The motional magnetic field $B = (v \times E)/c^2$, where the v is the velocity of the atomic beam, and the E is the applied electric field, causes the false signal of the EDM. Also magnetic field generated by the leakage and/or changing currents causes the false signal. The geometric phase shifts generated by the complicated field gradients and the magnetic Johnson noise generated by traditionally used metals in electric field plates, vacuum chamber, and magnetic shield are also contributed to the systematic error. This means that the motion of the atoms and the difficulty to realize the uniform external field in the large measurement area limit the systematic error. The laser cooled and trapped atoms have the unique feature that they are confined in the small space and their kinetic energies or temperatures become very low. Then, the motional magnetic field can be highly suppressed and inhomogeneous applied field can be lowered.

3. Development of the experimental apparatus

The construction of the high intensity laser cooled Fr factory has been started from is in progress at CYRIC, Tohoku University. The experimental apparatus consists of the beam swinger system, the thermal ionizer, the Fr beam transport system, the neutralizer, the laser cooling, the magneto-optical trap (MOT), and the laser trap system with an optical lattice to detect the EDM as shown in Figure 1.

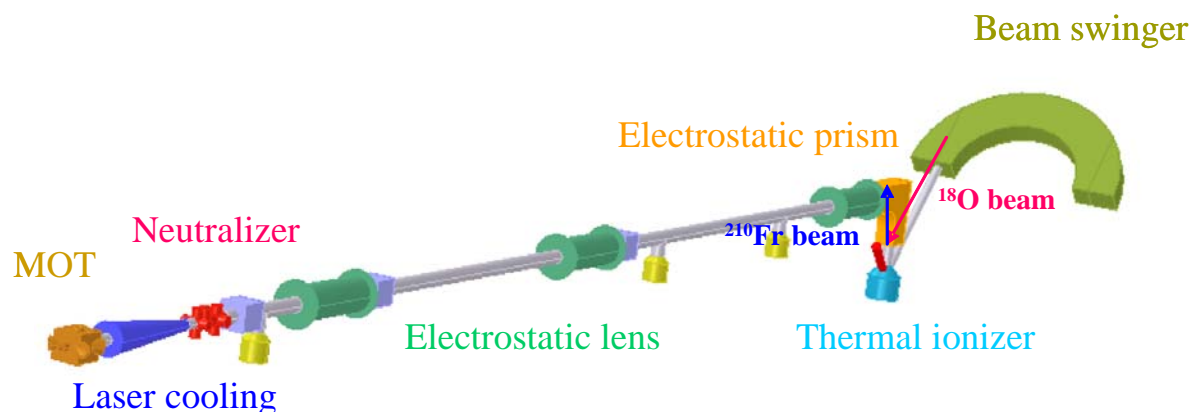


Figure 1. The overview of the experimental apparatus of the laser cooled Fr factory

3.1. Thermal ionizer

The Fr is produced in a heavy-ion fusion reaction using an oxygen beam and a gold target ($^{18}\text{O} + ^{197}\text{Au} \rightarrow ^{210}\text{Fr} + 5n$ etc.) with the beam energy of 100 MeV just above the coulomb barrier. The target consists of a lump of gold melted and flattened onto the end of a tungsten rod with a thickness of 50 μm . The target rod is surrounded by an oven which is heated by the coil heater, and the target material is heated by the radiation from the oven. The target temperature can be controlled precisely with the additional heater installed around the rod. The embedded Fr produced by fusion reaction diffuses rapidly to the surface and evaporates. The francium desorbs from the target surface as atoms and ions according to the Langmuir-Saha equation: $n_+/n_0 = (w_+/w_0) \cdot \exp\{(E_{\text{WF}} - E_{\text{IP}})/kT\}$, where n_+/n_0 is the ratio of ions to atoms desorbed, w_+/w_0 is the ratio of the statistical weights and equals 1/2 for alkali atoms, E_{WF} is the work function of the surface, and E_{IP} is the ionization potential of the desorbed atom. Since for gold E_{WF} is 5.1 eV and 4.08 eV for E_{IP} , we have $E_{\text{WF}} > E_{\text{IP}}$, and consequently the target emits primarily Fr ions. While Fr isotopes can be produced in other fusion reaction, the gold is used as a target since it is a noble metal, naturally monoisotopic, and provides an ionizing surface for alkali atoms. The structure of the thermal ionizer is shown in the Figure 2. The unique point of this system is to use the swinger system to inject the beam to the target from the upper direction with the target configured upward to be able to keep it with melting to realize the high extraction efficiency. The extracted Fr beam is bended to 90 degree with the electrostatic prism and transported with three sets of the lens systems along about 10 m from the vertex region to the MOT.

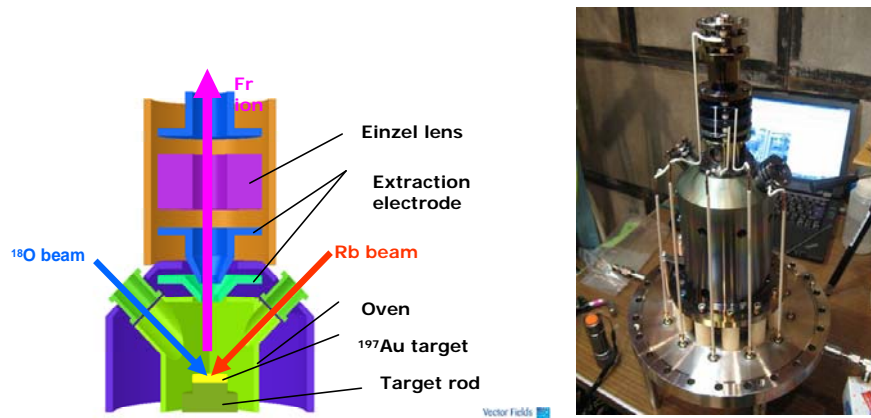


Figure 2. The structure of the newly developed thermal ionizer.

3.2. Magneto-optical trap system

The Fr ions will be neutralized by the neutralizer and injected to the Zeeman slower to slow down the Fr atomic beam to be trapped efficiently into the MOT. The neutralizer consists of the filament to emit the high density electrons and the electrode to control the position of the electron distribution. The Fr ion beam is decelerated up to the kinetic energy of 0.1 ~ 1 eV which is suitable for the efficient cooling with the Zeeman slower and injected into the high density electron distribution and neutralized with the electron recombination. The low speed Fr atomic beam is injected into Zeeman slower and loaded into the MOT. The Zeeman slower and the MOT require the high intensity laser light sources, which cool and trap not only the Fr but also the Rb, since the chemical properties of Fr and Rb are similar and all the parameters to operate the experimental apparatus can be adjusted with the high intensity Rb beam in the offline experiment. The Fr needs the laser with a wavelength of 718 nm for the trapping and the high power ~3W is realized by the Ti:S laser supplied by COHERENT with the combination of Verdi V18 and MBR-110. The repump light source 817 nm is prepared by the external cavity laser diode (ECLD). The laser with a wavelength of 780 nm is prepared by the ECLD and tapered amplifier for the Rb trapping and the output power of 1 W is achieved. The repump laser of a wavelength 795 nm is also prepared with the ECLD. All the light sources are ready at present and the MOT vacuum chamber will be installed soon.

4. Present status of the high intensity laser cooled Fr factory

4.1. Test experiment at CYRIC

The test experiments to check the performance of the new thermal ionizer has been performed at the newly constructed beam line for the Fr production in the CYRIC. The configuration of the experimental setup was minimized to study the Fr production rate, the transmission efficiency, and the neutralization efficiency efficiently, where only one electrostatic lens system consisting of three sets of the quadrupole lenses were installed to focus the Fr ion beam to the neutralizer. The two sets of the beam diagnosis system with the SSD were installed just after the thermal ionizer and the downstream of the beam line just before the neutralizer. The primary ^{18}O beam supplied from the AVF cyclotron was injected to the ^{197}Au target installed inside the thermal ionizer. The beam profile, observed by the ZnS beam viewer installed just before the thermal ionizer, was about 10mm diameter which was almost same size of the target. The beam intensity was ~ 200 nA on target, which was the highest intensity at present due to the low transmission efficiency between the ECR ion source and the AVF cyclotron although the beam intensity from ECR ion source was much higher. The temperature of the target was monitored with the thermocouple (W/Re) attached to the below of the target. The extraction voltage of the thermal ionizer was applied up to 2kV for the stable operation, although the design value was 5 kV but the leakage current became large due to the spattered materials from the target or other reasons. The operation parameters of the beam transport system were optimized using the Rb beam in advance based on the simulation of the ion optics.

4.2. Experimental results

The alpha decaying spectrum obtained by the SSD installed just after the thermal ionizer was shown in the Figure 3. The prominent peak from the alpha decay of ^{210}Fr can be seen at the energy of 6.543 MeV, and other peaks are from other produced isotopes ^{209}Fr and daughter nucleus decayed from Fr. The left peak is the reference alpha source of ^{241}Am with 5.486 MeV. It can be seen clearly that there are almost no backgrounds from other radioactive atoms produced in the fusion reaction with ^{18}O and ^{197}Au due to the condition on the surface ionization, and we can expect that the Fr can be transported to the final stage MOT with high purity.

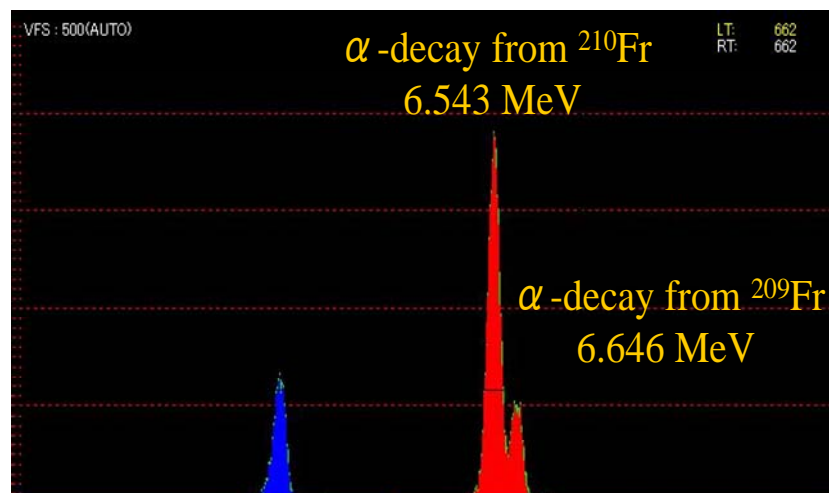


Figure 3. The horizontal axis shows the energy of the alpha particles decaying from ^{209}Fr , ^{210}Fr , and ^{241}Am obtained by the SSD. The vertical axis shows the number of the alpha particles. The ^{241}Am source is installed in the beam diagnosis system for the energy calibration.

The temperature dependence of the Fr yield is shown in the Figure 4. It should be noted that the vertical axis shows the number of alpha particles decaying from ^{210}Fr atoms which are caught by the catcher foil installed in the Fr beam line and detected by the SSD installed about 60 mm far from the catcher. The Fr yield has been evaluated with the correction of the detector acceptance in the final analysis. The yield is drastically increased at 970 degree, which is around the melting point of the gold 1064 degree. This similar feature was also observed at other institutes such as SUNY [6] and LNL [7], and also we observed that the extraction time of the Fr ions became short when the thermal ionizer was operated at the temperature higher than the melting point. The stable production yield of ^{210}Fr with $\sim 10^6 \text{ Fr}^+/\text{sec}$ was achieved successfully with the primary beam ^{18}O intensity of 200 nA. The evaluated extraction efficiency is more than 30 %. This yield is sufficient to search for the EDM as far as the design value of the efficiency of the neutralization and trapping is achieved.

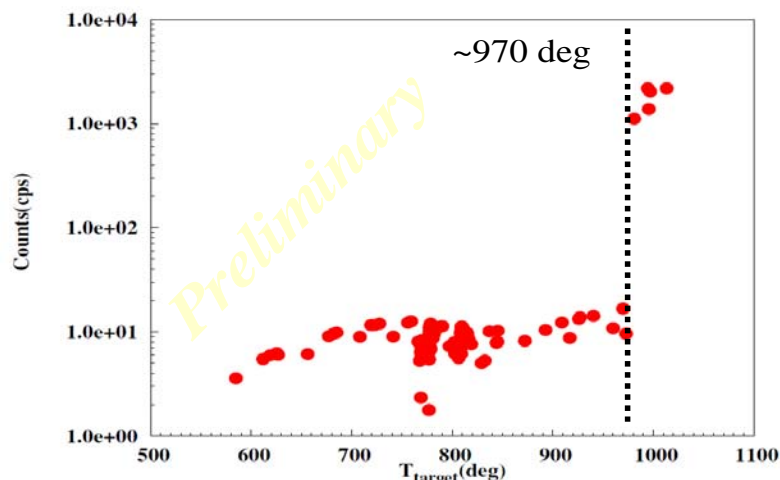


Figure 4. The temperature dependence of the number of the alpha particles decaying from ^{210}Fr . The horizontal axis is the target temperature. The vertical shows the number of the detected alpha particles.

5. Summary

The construction of the laser cooled Fr factory is in progress at CYRIC to search for the electron EDM with the sensitivity $10^{-29} \text{ e} \cdot \text{cm}$. We developed the new thermal ionizer and succeeded to produce the $10^6 \text{ Fr}^+/\text{sec}$ with the primary beam intensity of 200 nA. The expected Fr intensity will be $10^7 \text{ Fr}^+/\text{sec}$ with the ^{18}O beam intensity 2 uA using the upgraded ECR ion source. We can realize the high intensity Fr source at a small scale accelerator facility compared with the TRIUMF ISAC and CERN ISOLDE, where the high energy proton beam is injected to the targets such as UO_2 / UCx which need the careful treatments to produce the Fr at the large scale facilities. This research was partially supported by Grant-in-Aid for Scientific Research on Innovative Areas "Extreme quantum world opened up by atoms" (No.21104005) and Grant-in-Aid for Scientific Research (A) (No.21244026) from the Ministry of Education, Culture, Sports, Science, and Technology.

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