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Fundamental physics with cold radioactive atoms

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Abstract. 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. 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. At present, we are developing a high-intensity laser-cooled Fr factory at RIKEN accelerator facility in an attempt to evaluate the EDM of Fr to an accuracy of 10^{-30} ecm. Laser cooling is important for achieving highly accurate EDM measurements, since it allows long interaction times using an optical lattice. The current status of the laser-cooled Fr EDM experiments is presented in this paper.

PHYSICS MOTIVATIONS

Since an electron is a point particle with a non-zero spin, it may possess an intrinsic EDM, although 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 tera electron Volts or higher, which are beyond the reach of even planned high-energy particle colliders. The mass hierarchy of super-symmetry (SUSY) particles could also be studied [1]. Experimental searches for the e-EDM are currently being carried out using neutral atoms such as thallium(Tl) and francium(Fr), molecules such as ytterbium monofluoride(YbF) and thorium monoxide(ThO) [2], 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^{-29} ecm needs to be improved by almost ten orders of magnitude to test the prediction of the SM (10^{-38} ecm), which appears

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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 [3]. Under the simple SUSY model, the EDM depends on the SUSY mass and new CP phase. Francium is the heaviest alkali element and therefore its atomic EDM is most sensitive to the e-EDM because of the enhancement of the e-EDM through the relativistic effects. 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 [4], therefore Fr is one of the most promising candidates for investigating the e-EDM[5]. As the number of neutrons increases, the octupole deformation of nuclei becomes large, and as a result, nuclear EDM is amplified for ^{221}Fr etc. It is very important that the CP violating interactions between nucleon and electron can contribute to the EDM of an atomic system.

DEVELOPMENT OF THE EDM APPARATUS

The proposed facility consists of high intensity Fr ion source, beam line to transport Fr, and laser cooled Fr source trapped in the small region of the vacuum chamber as shown in Fig.1 [6]. The cold Fr source can be used for a variety of fundamental physics such as EDM, an accurate laser spectroscopy, parity non conservation experiment, and an anapole moment measurement. Low energy Fr ions are produced by nuclear fusion reactions, and transported to the EDM measurement area. They are neutralized by depositing them on a suitable neutralizing element, and then rapidly decelerated and trapped by laser cooling technique in a magneto-optical trap (MOT). They will then be transferred to an optical lattice (OL) trap equipped with electric field plates. Finally the EDM will be measured by atomic interferometry in an OL. The EDM measurement accuracy is given by

$$\delta d_e = \frac{\hbar}{2e} \cdot \frac{1}{KE} \cdot \frac{1}{\sqrt{N\tau T}}$$

where $\hbar$ is Planck's constant, e is the elementary charge, K is the e-EDM enhancement factor, E is the applied electric field, N is the number of accumulated atoms, τ is the interaction time, and T is the measurement time. The above equation shows that higher accuracy can be obtained by increasing K, E, N, and τ. Since Fr atoms exhibit the highest enhancement factor K and the OL can suppress collisions between atoms to achieve long interaction times with 1-10 s, the trapped Fr number N with 10^7 atoms for 1 cycle EDM measurement have to be achieved, to realize the EDM measurement accuracy with 10^{-30} ecm. The MOT and OL will be installed inside magnetic shielding with an active magnetic field cancellation system to suppress the effects of environmental magnetic field fluctuations. These fluctuations will be monitored using an atomic co-magnetometer installed inside an EDM measurement cell.

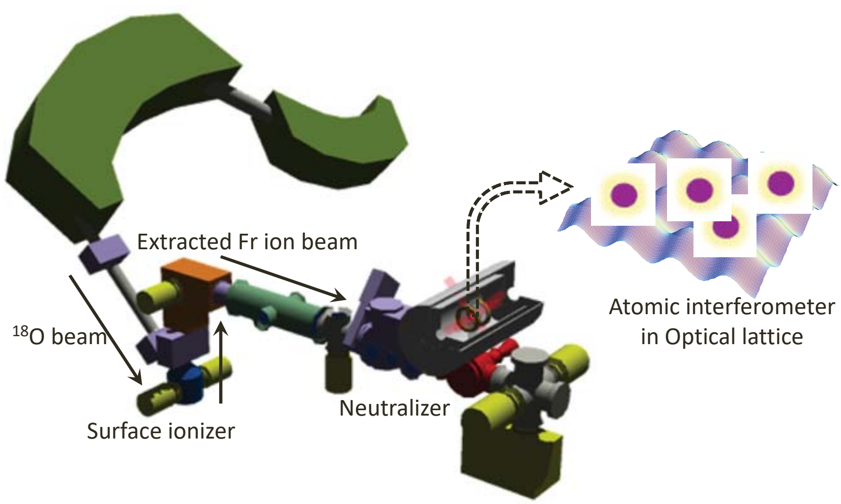

FIGURE 1. The overview of the EDM apparatus. The primary beam of ^{18}O is injected to the ^{197}Au target installed in the surface ionizer. The Fr produced in the target is extracted as ion, and transported to the neutralizer, and moved to the MOT and OL to measure the EDM with atomic interferometer.

High Intensity Fr Production

The francium is produced by a nuclear fusion reaction between ^{197}Au in the target and an ^{18}O beam supplied from an AVF cyclotron at RIKEN. The beam energy is adjusted to just above the Coulomb barrier of ~100 MeV, which yields the maximum cross section for the ^{18}O+^{197}Au reaction to produce ^{210}Fr. The Fr atoms diffuse inside the Au target, and some fractions of the produced Fr reach the target 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. We planned to operate the target above the melting point, since the Fr production yield was increased drastically. The target is heated both by the primary beam power and an additional electrical heater installed underneath the target. The target is surrounded by a parabolic electrode to confine the extracted Fr^{+} ion beam [7,8] as shown in the left of Fig.2. The extraction efficiency of Fr ion with 13 % was realized with newly developed surface ionizer at RIKEN. The construction of the cold Fr facility is in progress at RIKEN. The production of several kinds of isotopes for Fr can be seen by the typical alpha decaying spectrum shown in Fig.2. To optimize the transportation of the Fr beam and remove other background ions, we developed two dimensional beam profile monitor utilizing a microchannel plate (MCP). The fluorescence associated with α decay from Fr can be measured by comparing the image of the Fr beam in and out. In this way, the beam profile and absolute beam intensity are determined by measuring the α-decay from Fr using a solid-state detector (SSD).

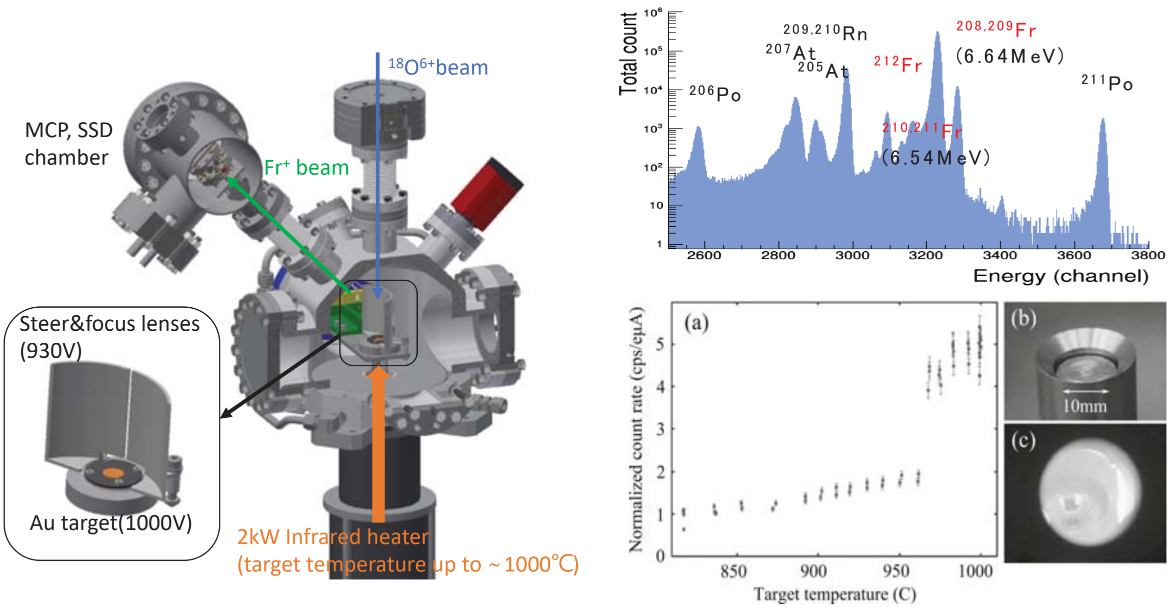

FIGURE 2. The structure of the surface ionizer is shown in the left figure. The right upper plot shows the spectrum of produced RIs measured by SSD. The right lower plot shows the temperature dependence of the produced Fr yield. Above the melting point of ^{197}Au (1064℃), the production yield is drastically increased.

Magneto-Optical Trap of Neutral Fr atoms

One of the key issues to achieve the high intensity cold Fr source is the neutralizer, which recombine 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 [9,10]. The MOT glass cell is attached to the neutralizer directly as shown in Fig.3. 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 [11]. The trapping efficiency can be improved by the transverse cooling to collimate the Fr beam and by longitudinal laser cooling for the deceleration of the velocity (Zeeman slower). We already developed the double MOT system, which has two MOT cells. The upstream MOT (collection chamber) collects the atoms and pre-cools them, and the downstream MOT (science chamber) is used to measure the EDM based on the Ramsey resonance method, where the MOT is switched to an optical trap such as an optical dipole force trap (ODT) or an optical lattice (OL). The atoms accumulated in the collection chamber can be transported to the science chamber using a pushing laser beam. 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 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 [12]. The Fr MOT has been succeeded in the experiment at CYRIC as shown in Fig.3 [13,14,15]. The primary beam intensity at RIKEN will be increased by a factor of 10, and the number of Fr in the MOT by 10^7, which is required for the EDM accuracy 10^{-30} ecm, can be achieved in this proposed facility.

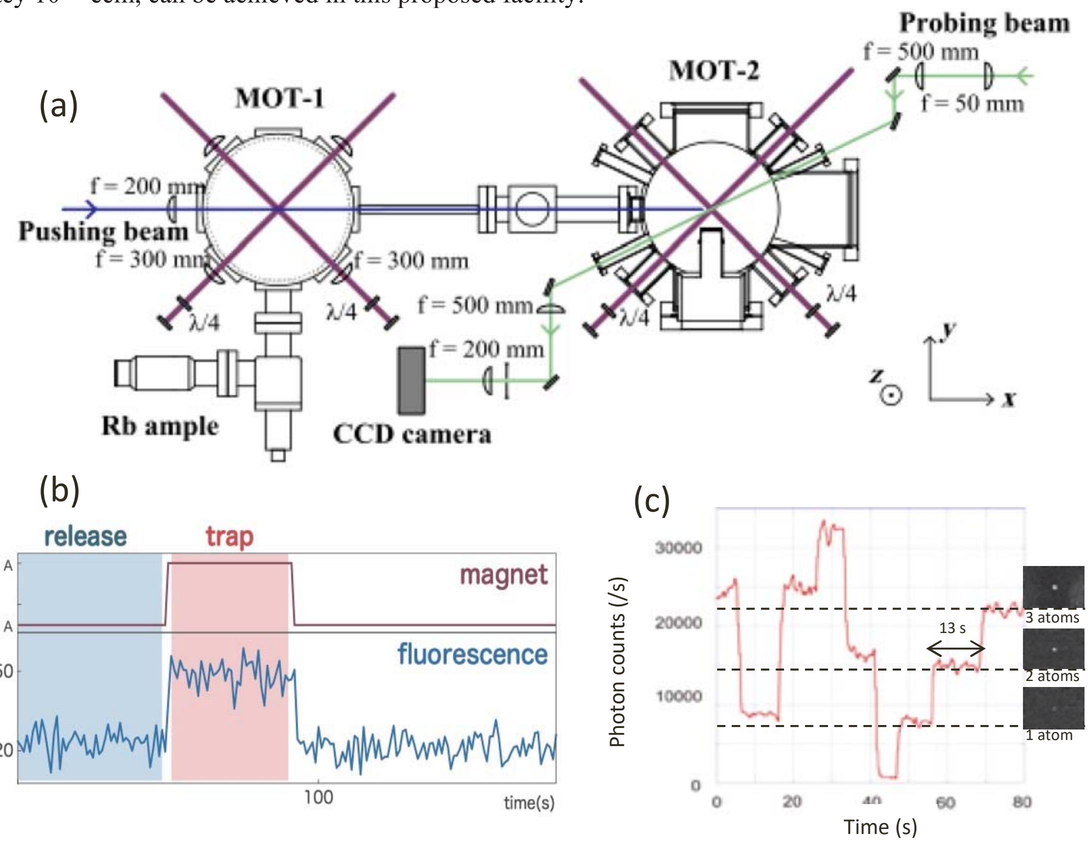

FIGURE 3. The configuration of the double MOT system is shown in (a). The MOT-1 is used for the collection of the atoms, and trapped atoms are transferred to MOT-2 by pushing beam. In the MOT-2, the trapped atoms can be monitored and also OL trap is achieved by switching off the magnetic field. The trapping of the Fr atoms can be observed by the fluorescence and shown in (b). In the same MOT-2, single atom trapping is performed as shown in (c) to check the interaction time of OL.

PRESENT STATUS OF THE SEARCH FOR THE EDM

The MOT gives trapping force by a combination of gradient magnetic field and laser light, but this magnetic field is not suitable for the EDM measurement. We have developed an ODT, which can be interpreted as one dimensional 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. 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. To measure a shift of an energy due to the EDM coupled with external electric field, an atomic interferometer has been developed.

Spin polarized Rb atoms are irradiated with an RF pulse to rotate the spin to a plane perpendicular to the external field, and is irradiated again with the RF to measure polarization in the final state. The interference pattern is generated by detuning the RF from the resonance frequency. The width of the pattern corresponds to the frequency measurement resolution, and it depends on the inverse proportion to the interaction time. We obtained a resolution of ~10^2 Hz with the interaction time of 300 μs as shown in Fig.4. Considering an interaction time of 10 seconds in OL, the resolution required for EDM measurement ~ mHz can be realized.

In the EDM experiment, we measure two atomic resonance frequencies that are in the electric field parallel and anti-parallel to the magnetic field in the OL. The frequency difference is generated by the interaction between the applied electric field and the EDM. The fluctuation of the Zeeman shift, which is caused by the interaction between the magnetic moment and the magnetic field, and the vector light shift (VLS) caused by the high intensity laser field in the OL will lead to dominant components of systematic errors. The VLS can be changed due to the fluctuations of the power and the polarization of the laser source for the OL. The unique solution to eliminate these errors are to monitor the spin frequencies of two atomic species, which have no EDM contribution compared with Fr, and measure the magnetic field and VLS explicitly. Based on this idea, the dual species co-magnetometer is now developed for evaluating the fluctuations of the Zeeman shift and VLS with two rubidium isotopes of ^{85}Rb and ^{87}Rb as shown in Fig.4. Four different frequencies of lights were required for the dual-Rb-isotope MOT. An external cavity diode laser (ECDL) serves as the master laser. The typical output power of the ECDL is 50mW. After passing through a Faraday isolator (FI), the laser light is split to monitor the wavelength, for frequency modulation spectroscopy (FMS) and for the EOM by polarizing beam splitters (PBSs). The frequency of the ECDL is stabilized using FMS to the ^{87}Rb repumping frequency. To obtain sufficient power for the cooling and trapping experiment, the laser light power is amplified with a tapered amplifier (TA) that generates a total output power of 1.5 W. After passing through another FI, part of the laser beam is reflected by a PBS and input into a Fabry–Perot interferometer (FPI). The layout of the electronics and the RF signals used for the generation of sidebands in the EOM for the dual-Rb isotope MOT are shown in Fig. 4. In total, three RF frequencies, 6586 MHz, 5460 MHz and 2527 MHz, and the carrier frequency are needed for the trapping of two isotopes and are obtained through multiple sideband generation. We already demonstrated to measure the magnetic field and VLS with this developed dual species co-magnetometer, and this technique can be applied to reduce the dominant systematic error for the magnetic field change and VLS [16].

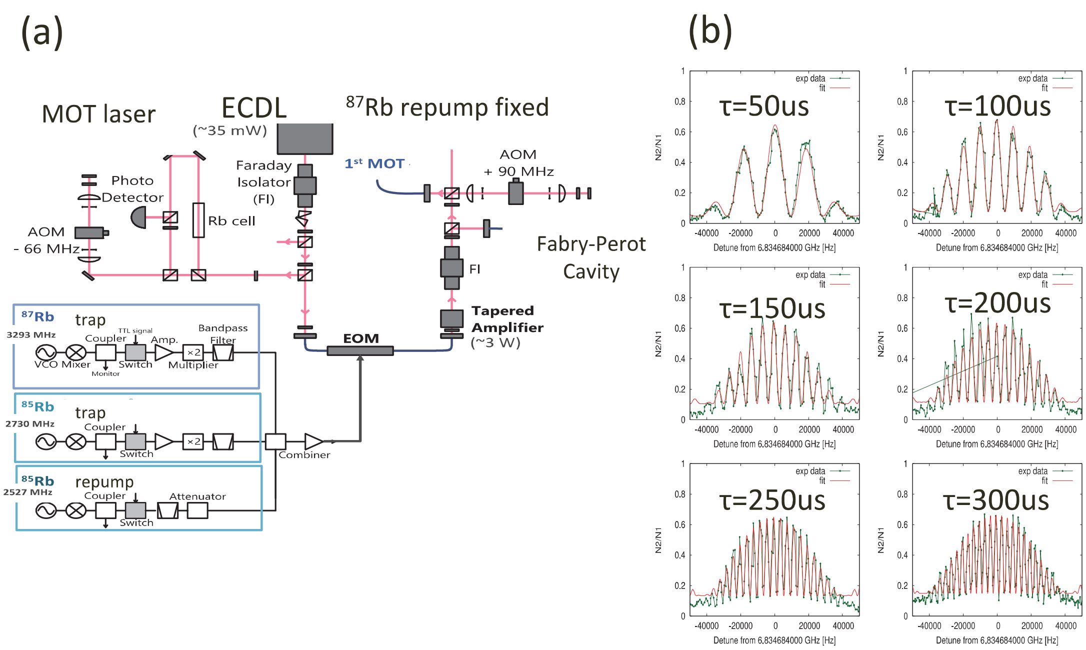

FIGURE 4. The left figure shows the laser optics for the MOT to trap the dual species atoms such as ^{85}Rb and ^{87}Rb with an ECDL. The right plots show the interference pattern of Ramsay resonance with the change of interaction time from 50 us to 300 us. The peak width corresponds to the resolution of the EDM measurement, and to achieve the sensitivity 10^{-30}ecm, interaction time of 1~10 s will be required.

SUMMARY

The cold Fr source can expand new physics search by high-precision measurement of quantum correction effect. In particular, atoms and molecules trapped in the optical lattice can prolong the interaction time with an external field, and reduce collisions with other atoms and molecules to suppress spin depolarization. The experimental technique and each component to achieve the measurement accuracy of 10^{-30} ecm are almost ready now. The installation of MOT and atomic interferometer will be done in 2021, and the experiment for the study of the systematic error will be started within 3 years. In order to further improve the sensitivity of EDM, we are developing the technique to produce the cold polar molecules of Fr-Sr using Feshbach resonance. We have already succeeded in trapping coexistence of Rb and Sr in MOT, and the development to produce the Fr-Sr molecules in progress by using the high intensity Fr source, which was achieved by newly developed surface ionizer at RIKEN, to realize the search of the EDM with the accuracy 10^{-31} ecm for the next generation experiment.

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REFERENCES

1. Maxim Pospelov, Adam Ritz, Annals Phys. **318** (2005) 119-169.
2. V. Andreev *et al.*, Nature, **562**, 355 (2018).
3. W. Altmannshofer, R. Harnik, J. Zupan, JHEP**11** (2013) 202.
4. B.K. Sahoo, T. Aoki, B.P. Das, Y. Sakemi, Phys.Rev. A**93** (2016) 032520.
5. B.K. Sahoo, D.K. Nandy, B.P. Das, Y. Sakemi, Phys.Rev. A**91** (2015) 042507.
6. Y. Sakemi *et al.*, J.Phys.Conf.Ser. **302** (2011) 012051.
7. H.Kawamura *et al.*, Nucl.Instrum.Meth. B**317** (2013) 582-585.
8. H.Kawamura *et al.*, Hyperfine Interact. **214**(2013)133-139.
9. H.Kawamura *et al.*,Rev.Sci.Instrum**.87**(2015)02B921.
10. H.Arikawa *et al.*, Rev.Sci.Instrum. **85** (2014) 02A732.
11. H.Kawamura *et al.*, Hyperfine Interact.**236**(2915)53-58.
12. K.Harada *et al.* , Appl.Opt. **55**(2016)1164-1169.
13. T.Aoki *et al.*, Phys.Rev.A**87**(2013)0642426.
14. U.Dammalapati, K.Harada, Y.Sakemi, Phys.Rev.A**93**(2016)043407.
15. K.Harada *et al.*, JPS Conf.Proc. **6** (2015) 030128.
16. A.Uchiyama *et al*., Rev.Sci.Instrum.**89**(2018) 123111.