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Search for permanent EDM using laser cooled Fr atoms

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Abstract The existence of a non-zero electric dipole moment (EDM) implies the violation of time reversal symmetry. As the time-reversal symmetry violation predicted by the Standard Model (SM) for the electron EDM is too small to be observed with current experimental techniques and any a non-zero EDM would indicate new physics beyond the SM. The tiny signal from the electron EDM is enhanced in the heavy atoms such as francium (Fr). We are constructing the laser-cooled Fr factory to search for the electron EDM.

Keywords Electric dipole moment · Radioactive francium · Laser cooling and trapping

1 Introduction

New physics that can generate CP-violation beyond what is already observed in K and B mesons is needed to explain the preponderance of matter over an-

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timatter in our current universe and it has been the subject ongoing research from astrophysics to high energy physics. One of the most promising routes to access CP-violaion is the search for permanent EDMs of fundamental elementary particles. The existence of a non-zero EDM implies that parity and time reversal symmetry are simultaneously violated and it indicates the CP-violation under the assumption of CPT invariance. The search for finite EDMs of various elementary particles and atoms has been pursued for more than half a century; however, one has not suceeded in the measurement of a finite EDM and only upper limits are set; for the electron EDM $|d_e| < 10.5 \times 10^{-28}\,e$cm by YbF-beam experiment [1]. Permanent EDMs of elementary particles should be described by a new theoretical model beyond the SM. Accordingly, the several experiments are required to understand a fundamental theory since each particle yields its EDM through different sources. A nucleon EDM arises from quark EDMs, and a diamagnetic atomic EDM could arise from quark chromo EDM. The EDMs in paramagnetic atoms or polar molecules are mainly from electron EDM, although the enhancement mechanisms of the EDMs in the many body systems such as the nucleus, atoms, and molecules are different.

The EDM of an unpaired electron in an orbit close to the nucleus can induce a net atomic EDM because the magnetic force in addition to the electrostatic force is considerable. In fact, the net EDM of a heavy atom can be many times larger than the electron EDM. Fr, being the heaviest alkali atom, has a large EDM enhancement factor, $K(\mathrm{Fr}) = 895$ [2]. Since its electronic structure is simple, the enhancement mechanism is relatively easy to understand. This permits the calculation of the enhancement factor more reliably. Fr is a radioactive element with no stable isotopes and it can be produced by a nuclear fusion reaction [3]. Fortunately, several isotopes have lifetimes long enough to carry out the experiments. In addition, the laser cooling technique of alkali atoms is well established and even Fr has be captured in a magneto-optical trap [4]. The use of the laser-cooled Fr in the EDM experiment promises an efficient reduction of the systematic effects which limited the sensitivities of previous measurements.

In atomic EDM experiments, the effects originating from the atomic motion would be serious problems. In particular, to get the long coherence time, a measurement region tends to be so large that it is difficult for the external fields to be uniform over the full volume. Trapped atoms can be confined in a small area by laser cooling. In addition, this enables longer coherence time. Consequently, it seems that both statistical and systematic errors can be greatly reduced.

2 Development status of experimental apparatus

A factory of laser-cooled Fr atoms is currently being constructed at the Cyclotron and Radioisotope Center, Tohoku University. The ^{18}O beam from the AVF cyclotron bombards a gold target in a thermal ionizer and produces Fr by a fusion reaction as $^{18}\mathrm{O} + {}^{197}\mathrm{Au} \rightarrow {}^{215-x}\mathrm{Fr} + x\mathrm{n}$. A high precision measurement of an EDM must be performed in a separate room away from the radiation controlled area to avoid the stray neutrons and gamma rays produced in the nuclear reaction, that would damage the electronics and also introduce the noise signals. The transported Fr ions must be neutralized and decelerated to enable the laser cooling. To efficiently load Fr to an optical trap, the neutralized Fr would additionally be slowed down by laser cooling as follows: two-dimensional cooling to reduce the transverse momentum of the beam, Zeeman slowing to reduce the longitudinal momentum, and magneto-optical trapping to confine atoms in vacuum. The atoms trapped in a small volume of a few mm^3 have a low temperature of less than 1 mK.

2.1 Fr-ion source

A thermal ionizer has been developed for the production of Fr. Fr produced by the fusion reaction inside the target is desorbed from the gold surface as a positive ion or neutral atom according to the Saha-Langmuir equation. In this case, since the work function of the gold target ($E_{\mathrm{WF}}(\mathrm{Au}) = 5.1\,\mathrm{eV}$) is larger than the ionization energy of Fr ($E_{\mathrm{IE}}(\mathrm{Fr}) = 4.0\,\mathrm{eV}$), Fr is emitted as an ion that can be controlled by electromagnetic fields. A molten gold target can be used for the production of Fr. In general the diffusion coefficient in liquids is much larger than in solids. In addition the transport is also driven by convection flow. These processes are essential for the efficient extraction of the short lived Fr isotopes. This is one of the most notable features of this ionizer, which is made by Omegatron Co., Ltd. Another feature of the ionizer is that it is possible to convert a rubidium (Rb) atomic beam into a Rb ion beam. The Rb beam is utilized in development phase since Rb is a stable element and is chemically similar to Fr. This minimizes the use of beam time at cyclotron facilities and hence is cost effective.

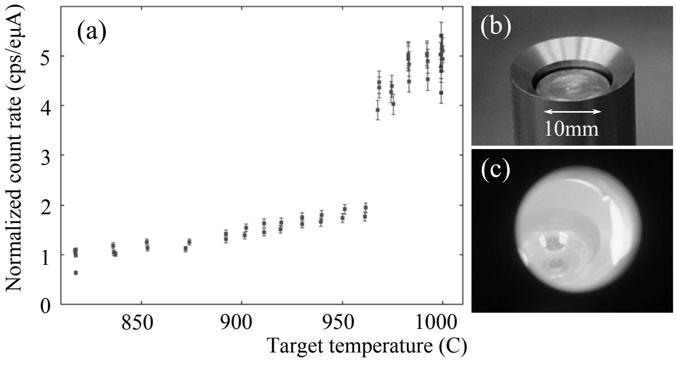

Fig. 1 (a) The Fr count rate dependence on the temperature of the ionizer. The vertical axis that describes the count rate measured by a SSD is normalized by the primary beam intensity, (b) the photograph of the gold target before installation, and (c) the photograph of the high temperature target installed in the vacuum chamber.

We have already produced Fr in accelerator experiments. Fr was identified using a solid state detector (SSD) that measures the energies of α particles from unstable nuclei. It was confirmed that the extraction yield of Fr was mostly proportional to the primary ^{18}O beam intensity. The dependence of the yield on the temperature of the ionizer is shown in Fig. 1. The yield significantly increased when the target temperature was close to the melting point of gold. In these experiments, the maximum yield of ^{210}Fr extraction was about 6×10^5 ions per second. There are two plans to increase the ion yield: the renewal of the Fr extraction electrode and the optimization of the primary beam transport parameters. Owing to these improvements, we can expect a tenfold increase of the Fr yield.

2.2 Magneto-optical trap

Magneto-optical trapping is one of the most standard techniques to trap neutral atoms. It requires a pair of anti-Helmholtz coils producing a quadrupole magnetic field and two lasers that are detuned slightly to red of the atomic transition and stabilized to less than its natural linewidth. We have built a magneto optical trap (MOT) in an experimental room outside the radiation controlled area. The pilot experiment of MOT is currently being performed using Rb. We use 780 nm laser light corresponding to the ^{87}Rb D_2 line for trapping and repumping lasers. Each laser is an external-cavity laser diode (ECLD) [5] The trapping laser light is amplified up to 1 W by a tapered amplifier. Figure 2 shows an image of trapped Rb atoms in our double MOT setup. In the next stage, the experiment of the single atoms trapping will be performed. That experiment requires highly-efficient imaging optics to collect low levels of fluorescence [6]. Such an optical technique is useful to the early Fr-MOT experiment where the number of atoms may be too small.

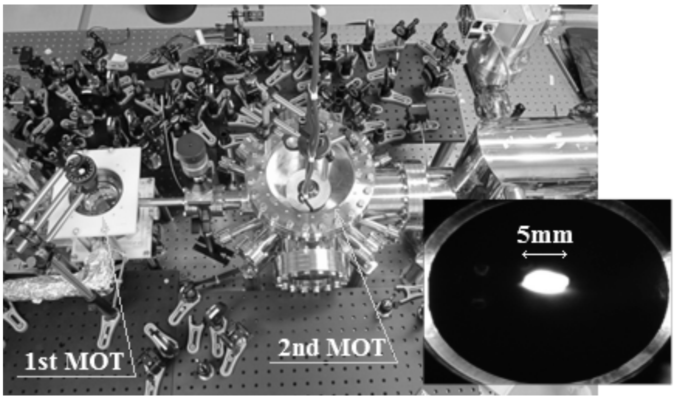

Fig. 2 The double MOT chamber consisting of 1st and 2nd MOT chambers. The inset shows the fluorescence image from Rb atoms trapped in the 2nd MOT.

The laser light sources for a Fr atom MOT are in preparation. Light at 718 nm of up to 3.5 W corresponding to ^{210}Fr D_2 transition is generated by Ti:Sapphire laser (Coherent MBR110), which is pumped by 532 nm laser (Verdi-V18) for the trapping. The repumping laser is also 718 nm generated by an ECLD (custom-ordered Toptica DL100). A spectroscopy experiment using an iodine vapor cell is ongoing to develop the frequency stabilization circuit of the laser source because a Fr vapor cell cannot be prepared. A new vacuum chamber for the Fr trap will be designed based on the study of a Rb trap.

2.3 Ion to neutral atom converter

Although Fr is produced and extracted as positive ions, the particles must be electrically neutral atoms for the laser cooling and the EDM measurement. Therefore, the transported Fr ions need to be neutralized. The energy of the ion beam during transportation is a few keV. However, the energy of a neutral atom must be less than 1 eV for effective cooling. Fr must not only be neutralized but also decelerated.

The most general method for MOT is to use the thermal neutralization. The probability of the release as a neutral atom from a hot surface depends on the work function of the hot surface. Yttrium has a small work function ($E_{\mathrm{WF}}(\mathrm{Y}) = 3.1\,\mathrm{eV}$) and hence is generally used to neutralize Fr. The neutralized atoms are emitted diffusely in Maxwell-Boltzmann velocity from the yttrium surface. The MOT of Fr is often performed close to heated yttrium. In that case, the vacuum tends to be high pressure and therefore the trapping time would be too short with the collisions of the residual atoms.

We employ a method to form a collimated beam of Fr atoms to achieve more efficient trap, which is based on the principle of the orthotropic source [7]. The original orthotropic source had been developed to realize highly-efficient MOT [8]. The source consists of a yttrium-neutralizer target and platinum-ionizer oven surrounding the target. Platinum has such a large work function ($E_{\mathrm{WF}}(\mathrm{Pt}) = 5.6\,\mathrm{eV}$) that it can ionize Fr. As a negative voltage is applied to the yttrium coated target, particles ionized on the surface of the oven get attracted to it. The particles get neutralized on the surface of the yttrium, and some of the particles go out through the small aperture of the oven. Thus, we can produce the collimated neutral atomic beam. The other particles interrupted by the wall of the oven would be ionized on the platinum, and would be attracted to the yttrium again. Because of such a recirculating process, the ionic beam can be efficiently converted into an atomic beam, minimizing the loss of Fr. In this experiment, the oven must also have a large hole to accept the incident ion beam. To realize an efficient conversion, it is essential that the particles do not escape through the entrance hole. Therefore, an additional electrode is placed around the ionizer oven. This electrode applied with positive voltage can confine the ion to the oven.

Based on this concept, a device as shown in Fig. 3 has been developed (Kitano Seiki KNB-01). The neutralizer target and the ionizer oven are made from tantalum coated with yttrium and platinum, respectively. So far, the test experiment of Rb neutralization has been done for a performance evaluation. The temperature of the oven is typically $1,000°$C, and the voltage applied to the target is $-1,000$ V. The neutral Rb beam exciting the device is ionized on a hot filament and detected by an electron multiplier. The count rate on the electron multiplier increases with the increase in the applied voltage. It seems that the neutralization probability is increased because the ion is attracted and confined more strongly. More detailed studies are required for the improvement of the neutralization efficiency. When Fr is fed to the neutralizer, the α-particle detection allows us to perform a more reliable measurement of the neutralization efficiency.

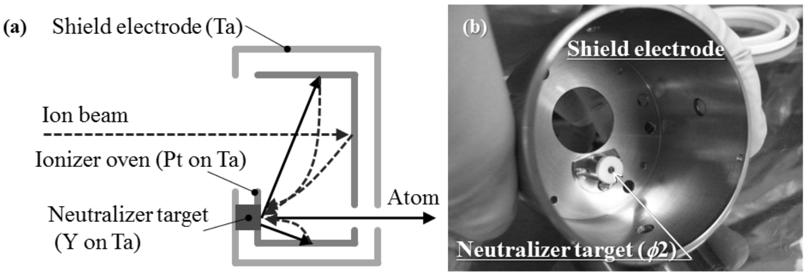

Fig. 3 (a) The basic concept of the beam converter based on the orthotropic source, (b) the photograph of the converter. The ionizer oven is not installed yet in this picture.

To advance the development of the converter without a cyclotron, we have built a mini laser-cooled ‘Rb’ factory based on the described design that consists of a Rb-ion source, ion-beam focus lens, ion diagnosis system, ion-to-atom converter and MOT chamber. They are the minimal components of the laser-cooled Fr factory. If we succeed in trapping the neutralized Rb in this Rb factory, it encourages us to complete the Fr factory.

2.4 EDM measurement system

Static external electric and magnetic fields will be applied to the trapped atoms. Atoms should be polarized with the magnetic field and the difference of the energy shifts would be measured when the electric fields (anti)parallel to the polarization axis are applied. The EDM measurement requires a homogeneous magnetic field to polarize atoms, while MOT uses an inhomogeneous field with zero amplitude at the center. In other words, one cannot measure the EDM of atoms during a trap in MOT.

We plan to employ an optical trap without any magnetic field. An optical lattice trap can be formed by the interference of laser beams. Since each atom would be individually trapped in a lattice-like potential, atomic collisions could be extremely suppressed and the coherence time could be greatly lengthened.

The fluctuation of the magnetic field in the measurement period poses the largest systematic effect. The stability and monitoring of the external field are quite important to realize the high precision measurement. Therefore, a magnetometer using Rb vapor cells has been developed. In parallel, a static magnetic shield and an active-feedback magnetic-field canceller have been designed. Moreover, the optical lattice can also simultaneously trap auxiliary atoms that could be utilized as co-magnetometers to precisely monitor the magnetic field. Therefore, the EDM measurement with the highest precision will be achieved using the optical lattice trap [9].

3 Summary and outlook

Concerning the Fr-EDM experiment, the developments of apparatuses are in progress. In the near future, the Fr-ion beam line will be completed and the MOT of Fr will be achieved. The measurement system of the atomic EDM will be developed using stable Rb. Finally, all the apparatuses and techniques must be integrated for the Fr-EDM measurement.

References

1. J. J. Hudson *et al.*, Improved measurement of the shape of the electron, Nature, 473, 493-496 (2011)
2. D. Mukherjee, B. K. Sahoo, H. S. Nataraj and B. P. Das, Relativistic Coupled Cluster (RCC) Computation of the Electric Dipole Moment Enhancement Factor of Francium Due to the Violation of Time Reversal Symmetry, J. Phys. Chem. A, 113, 12549-12557 (2009)
3. J. A. Behr *et al.*, Possibilities for francium spectroscopy in a light trap, Hyperfine Interactions 81 197-202 (1993)
4. J. E. Simsarian *et al.*, Magneto-Optic Trapping of ^{210}Fr, Phys. Rev. Lett. 76, 3522-3525 (1996)
5. C. E. Wieman and L. Hollberg, Using diode lasers for atomic physics, Rev. Sci. Instrum., 62, 1-20 (1991)
6. W. Alt, An objective lens for efficient fluorescence detection of single atoms, Optik, 113, 142-144 (2002)
7. T. Dinneen, A. Ghiorso, and H. Gould, An orthotropic source of thermal atoms, Rev. Sci. Instrum., 67, 752-755 (1996)
8. Z.-T. Lu *et al.*, Efficient Collection of ^{221}Fr into a Vapor Cell Magneto-optical Trap, Phys. Rev. Lett., 79, 994-997 (1997)
9. C. Chin *et al.*, Measurement of an electron's electric dipole moment using Cs atoms trapped in optical lattices, Phys. Rev. A, 63, 033401 (2001)