Development of a Neutralizer for the Search of an Electron EDM

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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 the current experimental technique, an observation of the EDM indicates new physics beyond the SM. The tiny signal of the electron EDM is enhanced in the heavy atoms such as francium (Fr)1), which is an unstable nucleus. We are constructing the laser-cooled Fr factory to search for the electron EDM at the Cyclotron Radioisotope Center (CYRIC) at Tohoku University.

The ^{18}O beam from the AVF cyclotron bombards a gold target in a thermal ionizer, and produces Fr ions by a nuclear fusion reaction. To achieve a high precision measurement, we must perform the EDM experiment in a separate room away from the radiation controlled area to avoid stray neutrons and gamma rays produced in the nuclear reaction, which could damage the electronics. We plan to perform a high-precision EDM measurement using laser cooling and trapping techniques. Therefore, the transported Fr ion is required 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. In our factory, the production of a very slow and fine neutral atomic beam is essential for an efficient optical trap. We have developed two methods of neutralization in order to choose the best method for our experiment.

The neutralization could be achieved using the electron-ion recombination process. The ion beam is neutralized by passing through electron plasma and recombining with an electron. This method has a good track record in the semiconductor industry, for example, to make a neutral gas atom soft-landing on substrate. The electron plasma is produced by a ring filament, developed by Omegatron Co., Ltd.[2)]. In February 2011, the Fr neutralization test using this device was performed at the CYRIC 51-course beam line. The Fr ion produced in the thermal ionizer was transported into the neutralization device, and the neutralized Fr was identified by detecting alpha particles from unstable nuclei. There was a reflector electrode in front of the alpha-particle detector (solid-state detector) to separate stray ions from neutral atoms. Figure 1b shows the alpha-particle count rate as a function of the ring-filament current I_{FN} and the voltage V_{N} applied to form the electron plasma (Fig. 1a). The count rate increased with the increase on I_{FN} and V_{N}. The plasma density would be increased with the increase in these as well. Consequently, it could be considered that the probability of the recombination process was increased by increasing the electron plasma density and the number of Fr neutralized with plasma was increased. In this test experiment, it could be estimated that the maximum neutralization efficiency was around 20%. At the time, the acceleration voltage of the ion beam was 1.0 kV. However, a significant signal of neutralization was not detected when the acceleration voltage was 2.5 kV. This could be due to the ion energy dependence of the recombination-process cross section. The ion beam is required to be decelerated to less than 1 eV for laser cooling. Such a low energy ion beam is easy to spread, however, and the efficient transportation of the ion beam is very difficult. As we could not balance efficient beam transport of ion and adequate deceleration, it is nearly impossible to achieve the slow and fine Fr atom beam using this method.

Another way to achieve neutralization is to use the thermal neutralization. If the beam enters certain heated material, thermal ionization or neutralization would arise depending on the work function of the material. Yttrium has a smaller work function (3.1 eV) than the ionization energy of Fr (4.0 eV), and hence is generally used to neutralize Fr. We employ a method to form a collimated beam of Fr atoms, which is based on the principle of the orthotropic source[3)]. The source consists of an yttrium-neutralizer target and platinum-ionizer oven surrounding the target. Platinum has so large of a work function (5.6 eV) that it can ionize Fr. As a negative voltage is applied to the target, particles ionized on the surface of the oven are attracted to it. The particles are 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 atom beam. 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 converted into atomic beam, minimizing the loss of Fr. In our factory, the oven must also have a large hole to accept the incident ion beam. To realize an efficient conversion, it is essential to minimize the particles that escape through the 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 shown in Fig. 2a has been developed. The neutralizer target and the ionizer oven are made by tantalum coated with yttrium and platinum, respectively. So far, the test experiment of rubidium (Rb) conversion has been done for a performance evaluation. The ionization energy of Rb that is a stable element is close to that of Fr. The temperature of the oven is typically 1,000°C, and the voltage applied to the target is -1,000 V. The Rb converted into a neutral atom is ionized on a filament in a detection region and is detected by an electron multiplier. There is a reflector electrode in front of the filament. Figure 2b shows the neutralizer voltage dependence of the detected count rate. The count rate increases with an increase in the applied voltage. It seems that the conversion probability is increased because the ion is more strongly attracted and confined. More detailed studies are required for the optimization of the conversion efficiency. When Fr is fed to this converter, the alpha-particle detection allows us to perform a more reliable measurement of the conversion efficiency.

Concerning the Fr EDM experiment, two methods of the Fr neutralization have been developed: the electron-ion recombination method and the orthotropic source method. According to studies up to now, the latter method would be more appropriate to our experiment. In addition to the neutralization device, the laser cooling devices such as laser lens and Zeeman slower will be developed. We will study the laser cooling of the neutralized atomic beam. This work was partially supported by Science research grant-in-aid (Nos. 21104005 and 23740166) and Tohoku University’s Focused Research Project.

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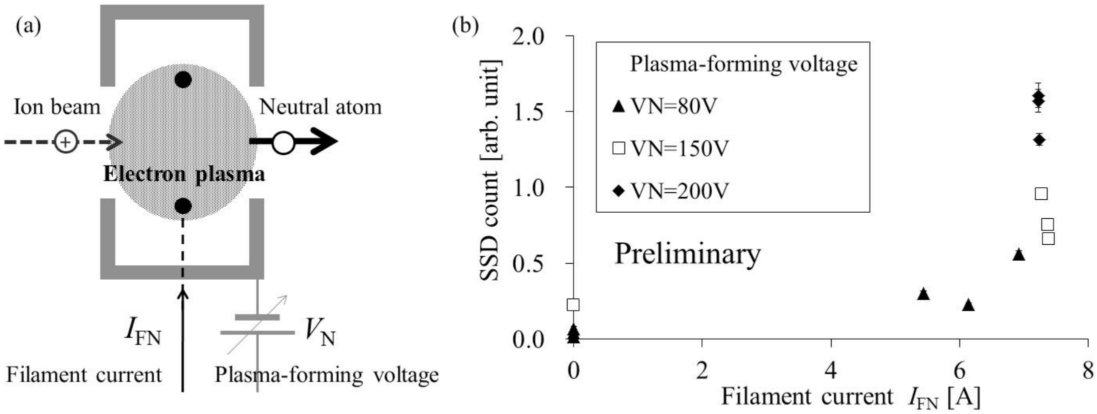

Figure 1. (a) Electron-plasma generator with a ring filament and a plasma-forming electrode. (b) The filament-current dependence of the Fr count rate.

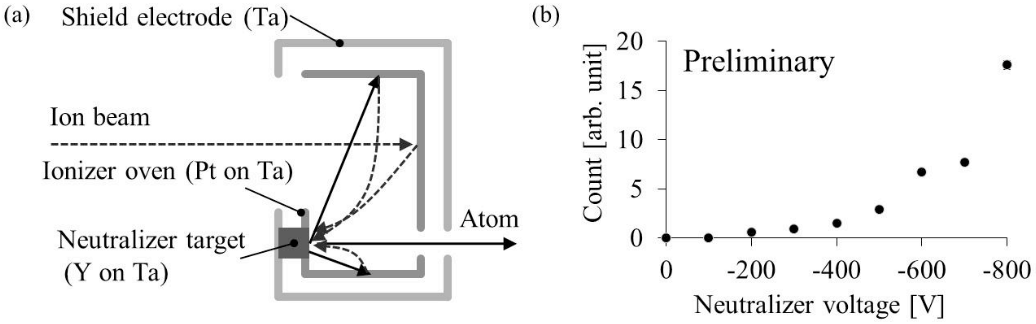

Figure 2. (a) Orthotropic source type ion-to-atom beam converter. (b) The neutralizer-voltage dependence of the Rb count rate.