I. 4. Development of an Ion-to-Atom Converter Based on the Orthotropic Source for a Magneto-Optical Trapping of Francium

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A device converting ions to neutral atoms has been developed for a magneto-optical trapping of francium toward a test of fundamental symmetries. The neutralized francium atoms were successfully observed and the parameter dependence of the device was studied. The current value of the ion-to-atom conversion efficiency does not reach our goal. Hence, further developments are required for the achievement of the magneto-optical trapping of francium.

Introduction

Francium (Fr), which is the heaviest alkali element, is a promising candidate for the precise testing of physics models[1)]. We plan to discover the new physics beyond the standard model through a test of fundamental symmetries using Fr atoms. A pending problem is to capture the Fr, produced via a nuclear reaction, in a magneto-optical trap (MOT).

The first issue confronting the laser cooling of radioactive isotopes produced using an accelerator is how to extract the objective element from a production target. In cases where Fr is produced by the reaction between oxygen beam and gold target, most Fr produced is desorbed as univalent positive ions. In fact, the groups employing this reaction extract and transport the Fr ions using electrostatic fields[2,3)].

When the Fr is extracted as an ion, the next issue is the neutralization of the ion. For the purpose of our Fr project, a positive Fr ion is not useful at all, because we utilize the

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interaction of the heavy nucleus and the outermost unpaired electron. Therefore, the neutralization process of Fr ions is necessary. In experiments performing MOT of radioactive isotopes, the general method is thermal neutralization using a metal target with a small work function, such as yttrium (Y). Since the atoms are emitted diffusely from the metal surface, some artifice is required in order to use these atoms as an atomic beam.

To form an atomic beam from an ion beam, we developed an ion-to-atom converter (KNB-01 from Kitano Seiki Co., Ltd.) based on the orthotropic source[4]. This converter consists of a small Y target and a platinum oven surrounding the target. In principle, the converter can make a collimated atomic beam that suppresses the loss of the incident ions. With a collimated beam, it is expected that the efficient MOT will be realized using Zeeman slowing.

In a pilot setup where the converter was combined with a dedicated Rb ion source[5], ^{87}Rb was neutralized and captured in MOT (without Zeeman slowing). After the pilot experiment, the converter was installed on the 51 course in target room No. 5 and in the TOF room, where the secondary Fr beam line is located[6]. In this beam line, the ^{87}Rb produced by the Fr ion source was neutralized with this converter and captured in the same way. After that, the experiment using Fr was performed to be sure of the neutralization of the Fr[7].

Experiment and results

The experiment challenged with Fr after the operation test and performance estimate with Rb. Before Fr MOT, the neutralization of Fr was confirmed using a solid state detector (SSD) that identified the particle by measuring decay-α particles. An ion reflector electrode was placed in front of the SSD to sweep out stray ions as shown in Fig. 1.

SSD is susceptible to heat and light. In this experiment, this SSD was cooled using a Peltier device and water chiller. Water leakage inside the vacuum chamber worsened the vacuum pressure on the order of 10^{-3} Pa, but this was not critical for this neutralization experiment. The temperature of the SSD did not rise above 15^{o}C and it worked well, even though the converter was heated to 1000^{o}C. To overcome the light problem, a thin aluminum foil (800 nm) cover was placed on the SSD. Accordingly, it was expected that the energy resolution of the detector would be ~100 keV. Since the α-particle energies of ^{209}Fr and ^{210}Fr are 6.646 MeV and 6.543 MeV, respectively, a better resolution is desired

in order to resolve these energies.

Figure 2 shows an acquired α spectrum. There are clearly different events, with a peak of ^{241}Am as the source for an energy calibration. Owing to the low resolution, these events do not contradict α particles of $^{208\text{-}211}$Fr. Considering the original production yield, ^{210}Fr should dominate. In the following analyses, the event number in this peak was counted.

The ion-to-atom converter and the detector based on SSD have adjustable parameters: that include the temperature of the converter, the neutralizer target voltage, the ionizer oven voltage, the shield voltage, and the voltage of the ion reflector in front of the SSD. The standard operation parameter settings are the temperature at 1000^{o}C, the neutralizer at -2000 V, the ionizer at 0 V, the shield at +1 V and the reflector at +100 V. If not specified in the text, these parameters were used. The count rate increases as the temperature rises, as shown in Fig. 3a. It suggests that the diffusion and desorption of the particles are enhanced due to the high temperature of the material surface. The count rate also increases as the voltage of the neutralizer target rises, as shown in Fig. 3b. These data imply that higher voltage attracts more ions, and also that ions that are not attracted are still present. Other parameter dependences shown in Figs. 3c and 4 include some difficult-to-grasp behaviors. One of the reasons for this could be the complex electric fields formed by a complex internal configuration. Another reason might be the energy dependence of the ion implantation. Some ions with energy around 1 keV do not adsorb on the surface of a material[8)]. It is possible that such circumstances make for further complicated conditions.

Assuming that all the events in a certain peak of the α spectrum are from ^{210}Fr, the ratio of the incident ^{210}Fr going into the converter to the ^{210}Fr leaving the converter is estimated at ~0.1% under the best of conditions. This conversion efficiency is quite low in comparison with the estimation in the pilot Rb experiment. In the Rb case, the conversion efficiency might be overrated because the measurement method of the Rb experiment was quite different from that of the Fr case. Furthermore, the principle of this ion-to-atom conversion is no problem for stable Rb isotopes, but could be a fatal problem for radioactive Fr isotopes, because of the time it takes to output from the converter after the cycles of ionization and neutralization.

Summary and plans

This project aimed to search for the violation of fundamental symmetries using Fr. A device to convert ions into atoms was developed to apply MOT to Fr produced as ions. However, the conversion efficiency of Fr was too low, and further improvements are needed for the implementation of MOT. Reducing the diameter of the ion entrance could lead to an increase in conversion efficiency. To realize this, the size of the ion beam spot must be minimized by improving the beam transportation. There should be still room for the optimization of the size and configuration of the whole device. Moreover, the materials of this device will be selected to have better ionization and neutralization efficiencies. A device that produces a fine atomic beam must be developed in order to apply Zeeman slowing and achieve an efficient MOT of Fr.

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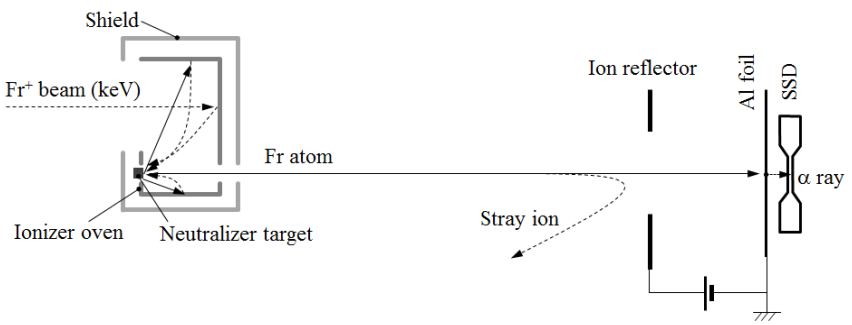

Figure 1. Schematic of the ion-to-atom converter and the detector based on SSD.

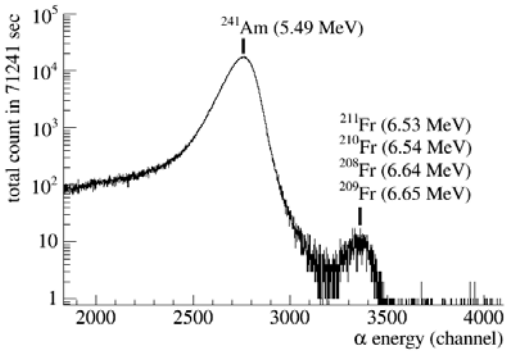

Figure 2. Total α spectrum acquired by the SSD after the ion-to-atom converter.

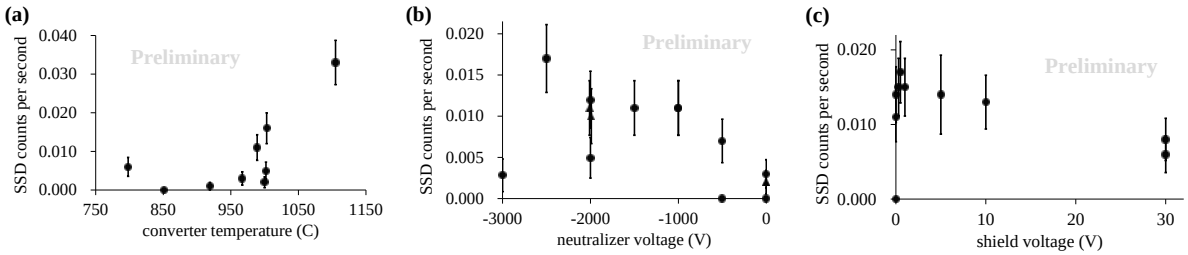

Figure 3. (a) Converter temperature dependence of the SSD count rate. (b) Neutralizer target voltage dependence. The shape of the plot indicates different runs under the same condition. (c) Shield voltage dependence of the SSD count rate. The shield voltage is used to confine ions to the oven. It looks like it has an optimum voltage.

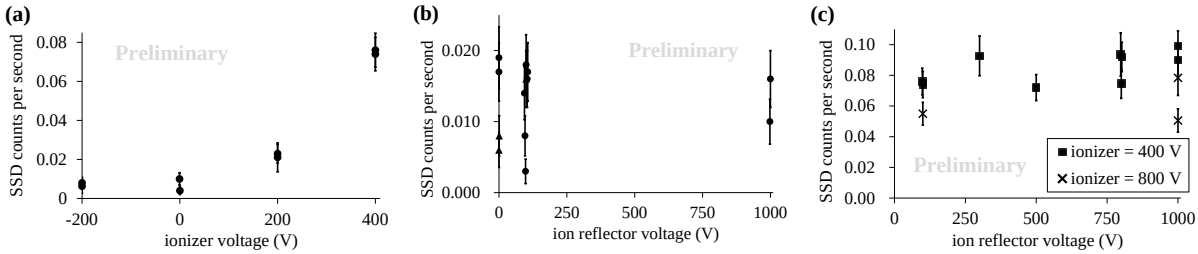

Figure 4. (a) Ionizer oven voltage dependence of the SSD count rate. This is an unexplained reaction. (b, c) Ion reflector voltage dependence. Ionizer dependence of (a) is difficult to understand. It might show that the output at higher ionizer voltages could include many charged components. However, from these figures, no significant dependence on the ion reflector is seen. This means that the dominant component must be electrically neutral.