I. 5. Extraction Time of Francium Ion Produced via a Nuclear Fusion Reaction from a Gold Surface

Kawamura H.[1,2], Ito S.[2], Dammalapati U.[2], Harada K.[2], Inoue T.[1,2], Itoh M.[2], Sakamoto K.[2], Tanaka K. S.[2], Uchiyama A.[2], Yoshioka R.[2], and Sakemi Y.[3]

[1]Frontier Research Institute for Interdisciplinary Sciences (FRIS), Tohoku University
[2]Cyclotron and Radioisotope Center, Tohoku University
[3]Center for Nuclear Study, The University of Tokyo

Experimental research is ongoing toward tests of fundamental symmetries in physics. Francium (Fr) is produced via a nuclear fusion evaporation reaction between oxygen and gold, and Fr ion can be produced through a thermal ionization on the surface of a hot gold target. Since it is empirically known that Fr ion yield depends on the temperature of the gold target, our apparatus includes a heater to heat the target. In 2011, Sakemi et al. reported that the Fr ion yield drastically increased a hundredfold after the melting of the gold target[1)]. In 2012, Hayamizu reported that the degree of increase by melting the target was about threefold, and the ion yield was different in rising or falling temperature even though the temperature was the same[2,3)]. In 2015, Arikawa reported that the drastic increase from the target melting was not observed, and the ion yield was maximized when the temperature was falling from high temperatures[4)]. In this method, the production process of Fr ion relates closely to the property of the gold surface. It is considered that such conflicting results occurred because the surface condition of the surface is easily varied by various causes. The extraction time of ion from the target was investigated as it might affect an increase or decrease of Fr ion yield[5)]. The extraction time of radioactive isotopes was often reported as a diffusion time in a metal target[6,7)].

Fr ion is produced in the following process. First, an oxygen beam ($^{18}O^{5+}$) with 100 MeV of total energy enters into the gold target (^{197}Au), and gradually loses its energy. ^{210}Fr and ^{211}Fr are produced when the oxygen beam energy is around 80–100 MeV[8,9)]. At about 8 μm of depth below the surface, the oxygen energy is less than 75 MeV and Fr is not produced. At about 30 micron of the depth, the oxygen beam stops. Since the oxygen beam irradiates the gold target at a 45-degree angle, the effective depth for Fr is $1/\sqrt{2}$ times deeper.

Therefore, the produced Fr is found in approximately Gaussian distribution at a mean depth of 3 μm from the target surface with a standard deviation of 1 μm. Next, the Fr diffuses in the gold target, arrives at the surface, and finally desorbs to vacuum. When Fr desorbs, Fr becomes a positive ion because the ionization potential of Fr is smaller than the work function of the gold surface. The ionized Fr is accelerated and shaped as a beam by applying electrostatic fields. Thus, it takes the produced Fr a finite extraction time to become an ion beam. Since Fr is a radioactive element, Fr will decay before the desorption if the extraction time is too long. If the temperature of the gold target is higher, the diffusion speed gets higher, the extraction time gets shorter, and the ion yield might increase. The extraction time was measured at different target temperatures.

The ion extraction time was measured as follows. Before the fact, the oxygen beam was stopped by a beam shutter. Then, at time $t = 0$, the shutter opened and the beam irradiation of the target started. Now, a Fr beam was produced and arrived at a beam monitor. This beam monitor was a silicon semiconductor detector to monitor the Fr ion beam by counting α particles emitted from Fr. The time evolution of the α counting by the monitor is shown in Fig. 1. As can be seen from Fig. 1, the significant counts started at $t = t_{\mathrm{A}}$. This time t_{A} includes the time of Fr production by the nuclear fusion reaction and the time of the flight of the oxygen beam and the francium beam, but they are negligibly short. Hence, t_{A} was dominated by the time that the produced Fr diffused and desorbed. The following equation was fitted to the time evolution $N(t)$ of the α counting, and t_{A} was derived:

$$N(t) \propto \begin{cases} R(t) & \text{for } t < t_A \\ R(t) + f(1 - e^{-\lambda(t-t_A)}) & \text{for } t \geq t_A \end{cases}$$

Here, $R(t)$ indicates residual components of Fr previously supplied, f indicates the Fr beam intensity, and λ indicates the decay constant of Fr. Fitting parameters are not only t_{A} but also f and λ. It was confirmed that λ was constant as it did not depend on the target temperature and roughly corresponded to literature data. The temperature of the gold target increased from the oxygen beam irradiation, but it needed a finite time to saturate the temperature rising. During the time t_{A}, the rising range was less than $50^{\mathrm{o}}\mathrm{C}$ which was sufficiently small compared to the temperature range of the measurement.

The measurement results of the ion extraction time are shown in Figs. 2 and 3. Figure 2 shows data for ^{210}Fr and ^{211}Fr, and Fig. 3 shows data for ^{209}Fr. The ^{210}Fr and ^{211}Fr were not able to be separated because of the detector's resolution. The extraction time is clearly small when the target temperature is higher. It seems that there is hysteresis between the situations

in rising temperature and falling temperature. This result suggests the probability that the temperature change affects the property of bulk as well as the surface of the gold target. The result of ^{209}Fr differs from the result of ^{210}Fr and ^{211}Fr in the context of the value of the extraction time and the behavior to the temperature change. Compared to ^{210}Fr and ^{211}Fr, ^{209}Fr is produced with a higher energy of the oxygen beam and at a shallower production depth. The production depth will affect the extraction time. In addition, the half-life of ^{209}Fr ($t_{1/2} = 50.0$ s) is different from that of ^{210}Fr ($t_{1/2} = 190.8$ s) and ^{211}Fr ($t_{1/2} = 186$ s). There is a possibility that the effect of the different lifetimes was not considered in the data analysis. Besides, the error tends to be large for shorter extraction times because of the properties of the measurement and analysis method. The statistical error of ^{209}Fr was larger because its ion yield was lower than that of ^{210}Fr. The measured extraction time is smaller than the lifetime of the Fr isotopes and should not affect the ion yield very much. The experimental results implied that the length of the extraction time is not an essential factor in increasing and decreasing the Fr ion yield.

The yield of Fr ion is an essential parameter to perform the test experiments of fundamental symmetries with higher precision. Subsequent development is required for increasing the ion yield.

References

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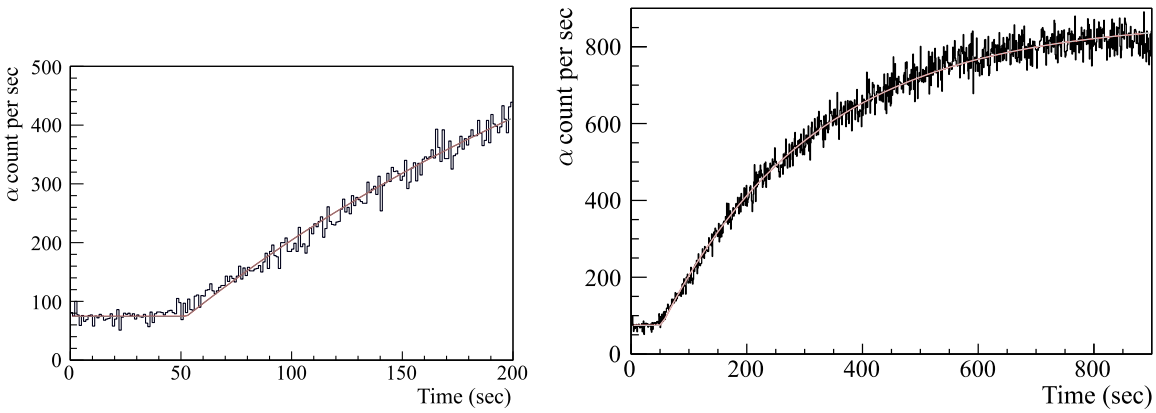

Figure 1. Typical result of the time evolution of the α counting. (Left) Time $t = 0$ to 200 sec. The counts are significantly rising up at around $t = 50$ sec. (Right) Time $t = 0$ to 900 sec for the same data.

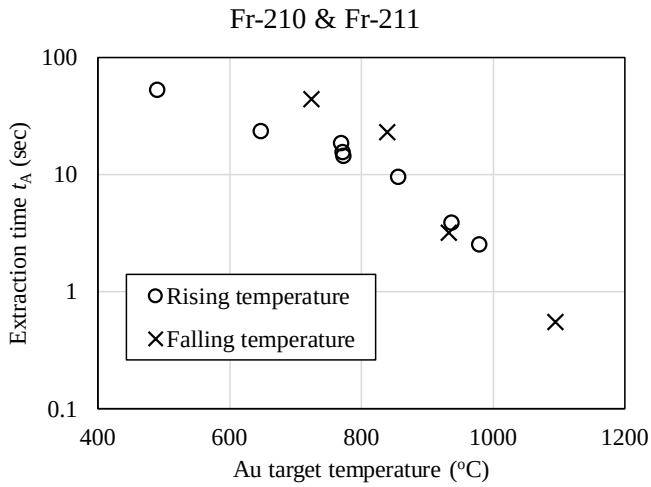

Figure 2. Preliminary result of the extraction time for the system of ^{210}Fr and ^{211}Fr.

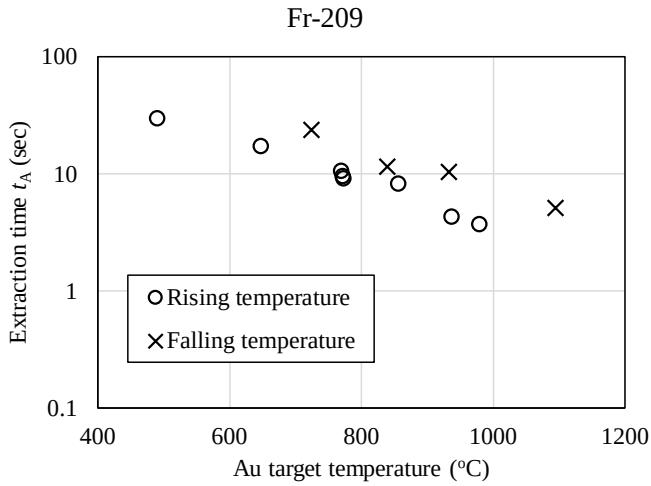

Figure 3. Preliminary result of the extraction time of the system of ^{209}Fr.