I. 3. **RI-production Experiment for “Basic Research in Physics” at Physics Department, Tohoku University**

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A course of “Basic Research in Physics (Butsurigaku-kiso-kenkyu)” is opened for third graders at Physics Department in Tohoku University. We carried out the production of radioactive isotopes (RI) at CYRIC, Tohoku University. In general, sealed RI sources were used in the educational experiments in the nuclear or particle physics because of safety and easiness in handling of them. However, there were some anxieties that easiness of their handling mislead students to regard the experiments as “well-made” and boring. By using an accelerator, we can demonstrate “on-going” experiments to the students. From many kinds of simple and educational experiments in the nuclear physics that can be done with use of the accelerator, we chose the production of RI in consideration of the impression to the students and the connection of the measuring techniques to other experiments. Ordinary metal plates turned to be radioactive after irradiation of proton beam. It is the transformation of the element that medieval alchemists could never accomplish. After the irradiation, the students tried to obtain the energy spectrum of the $\gamma$-rays for the identification of the produced RI in the irradiated target. In subsequent 4 weeks after the RI-production, they carried out 9 times of measurements of the intensity of the $\gamma$-rays. The measurement of half-life of the RI in four weeks requires short lifetime compared with the course period. It is one of the experiments that are made available only by use of the accelerator.

We chose usual carbon steel as the target. The fraction of the natural iron in the carbon steel is more than 98%. The iron has four natural stable isotopes (and the relative abundances): $^{54}$Fe(5.8%), $^{56}$Fe(91.72%), $^{57}$Fe(2.2%), and $^{58}$Fe(0.28%). The most abundant product of the (p, n) reaction with $E_p < 20$ MeV is $^{56}$Co by considering the abundance of
isotopes in the natural iron, their cross sections of the reactions by incident proton of 20 MeV, and the half-lives of the radioactive products. It can be easily identified by the $\gamma$-rays with characteristic energies more than 3 MeV. The energy dependence of the cross section of $^{56}$Fe(p, n)$^{56}$Co reaction is shown in Figure 1. With use of proton of 20 MeV and 1 $\mu$A incident on a steel target of 1 mm thick, the yield of $^{56}$Co is estimated as 220 kBq after irradiation of 5 minutes. The half-life of $^{56}$Co is 77.27 days. After 4 weeks, the radioactivity of produced $^{56}$Co decreases into 171 kBq, which is 78% of the original radioactivity. Measurements with accuracy less than 5% will reveal the exponential nature of the decay rate and the life of the $^{56}$Co.

The irradiation of proton was performed in the first target room (TR-1) at CYRIC, Tohoku University. Proton beam of 20 MeV from the AVF-Cyclotron was incident on the target with use of the target conveyer system for the RI production. Before irradiation, students participated in the guided tours through the AVF-Cyclotron room, ion-source room and TR-1. They seemed to be interested in the instruments and machines and asked some questions to the guides: Dr. Fujita M. for the AVF-Cyclotron and ion-source and Dr. Ohtsuki T. for TR-1. After the irradiation, the steel plate was conveyed from the TR-1 to the hot-lab-1. We monitored the radiation by a Geiger counter. It started to beep frequently as the steel plate approached us. It was the efficient occasion for the students to feel the radiation more realistic and consider the radiation protection more severely. The steel plate was packed and sealed in a plastic vessel for easy handling for the subsequent $\gamma$-ray measurements. The measurements were carried out in the measurement room in the RI-building. A radiation counter: RC-101A (OKEN) and a sodium iodide probe were used for the measurement. A discriminator in RC-101A can be used both as the leading-edge discriminator and the window discriminator that is also known as the single channel analyzer (SCA). Using the SCA and scanning the threshold, students were able to obtain the energy spectrum of the $\gamma$-ray. The energy calibration was done with $^{60}$Co source. The obtained energy spectrum is shown in Figure 2. We could find the correspondence of the peaks to the known energies of $\gamma$-rays emitted from $^{56}$Fe. For 4 weeks after the irradiation, we continued to count the $\gamma$-rays with energy threshold higher than 3 MeV in 10 minutes. The background in the same energy range was counted in 1 minute in each measurement. It was multiplied by 10 and subtracted from the count of the $\gamma$-ray. The result is shown in Figure 3. Only statistical error is shown in each data point, however, it is not as large as the size of the circles. From the attenuation of the counts
with respect to the time after irradiation, the half-life of the produced RI was obtained as 72.5±2.4 days, which was within 2σ errors from the known half-life of $^{56}$Co. As can be seen in Figure 3, the data points deviate more significantly than its statistical error. We suspect some unknown conditions that we could not control in each measurement, affected the results. However, we consider that this kind of uncertainties is essential for the students to inspect the experimental methods and conditions by themselves.

We carried out RI-production experiments in the course of “Basic Research in Physics” for third graders. Teaching staffs and an assistant, planned and prepared the tools and instruments, however, the students arranged and carried out all these measurements by themselves. In the trials and errors to make the measurements as good as possible, the students understood the necessity of the energy calibration of the scintillation probes for the determination of the absolute energies of the γ-rays, the necessity of the identical conditions for each measurement in order to reduce the systematic errors, and the impacts of the errors and uncertainties to the interpretation of the results. All these considerations are required for all the experimental researches. They will be helpful not only for the students who major in the experimental nuclear physics but for all the students who major in other fields of science and technology.

**References**

1) Table of Isotopes, 8th Ed. (1996).

![Figure 1. Total cross sections of $^{56}$Fe(p, n)$^{56}$Co taken from Experimental Nuclear Reaction Data library in NNDC](http://www.nndc.bnl.gov/exfor/exfor00.htm)
Figure 2. Energy spectrum of emitted $\gamma$-ray from the irradiated steel plate measured with the SCA of RC-101A. From the energies of the peaks, we were able to identify $^{56}$Co. The energies assigned to the peaks are known energies of the $\gamma$-ray of $^{56}$Fe$^0$.

Figure 3. Counts of $\gamma$-ray with energy more than 3 MeV with respect to the time after irradiation. By fitting the exponential curve to the data points, half-life of 72.5±2.4 days was obtained.