Measurement of activation cross sections of the target and the proton beam window materials at J-PARC

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Abstract. To improve the accuracy of the nuclear design for spallation neutron sources and transmutation systems, nuclear reaction cross sections are required. Considering decommissioning of the accelerator facilities, accurate cross sections are mandatory. The activation cross sections have been measured in several facilities. However, they have low accuracy and precision. Especially, since there is almost no data for 3 GeV protons which are used for the spallation neutron source (MLF) in J-PARC, the experimental data is required for in order to improve the target materials. For the sake of the forthcoming full-time measurement of the activation cross sections for various nuclei, we measured the cross sections of aluminium with 0.4 GeV, 1.3 GeV, 2.2 GeV, and 3.0 GeV protons as a test case. It was found that more accurate data than current ones would be measured by using precise beam controls and highly accurate beam monitoring. We compared the experimental data, the evaluated data (JENDL-HE/2007), and the calculations with several intranuclear cascade models using the PHITS code. Although the experimental data agreed with JENDL-HE/2007, the calculations underestimated by about 40%. This arises from the evaporation model (GEM) being included in PHITS code. We found that the calculations could be made to agree with the experimental data by upgrading the PHITS code.

1. Introduction
In the Japan Proton Accelerator Research Complex (J-PARC) [1], a MW-class pulsed neutron source, the Japan Spallation Neutron Source [2], and the Muon Science facility (MUSE) [3] will be installed in the Materials and Life Science Experimental Facility (MLF). Since 2008, this source has produced a high-power proton beam of 300 kW. In 2015, we successfully ramped up beam power to 500 kW and delivered a 1-MW beam to the targets. To produce a neutron source, a 3 GeV proton beam collides with a mercury target, and to produce a muon source, the 3 GeV proton beam collides with a 2-cm thick carbon graphite target. To efficiently use the proton beam for particle production, both targets are aligned in a cascade scheme, with the graphite target placed 33 m upstream of the neutron target. For both sources, the 3 GeV proton beam is delivered from a rapid cycling synchrotron (RCS) to the targets by the 3NBT (3 GeV RCS to Neutron facility Beam Transport) [4, 5] Before injection into the RCS, the proton beam is accelerated up to 0.4 GeV by a LINAC. The beam is accumulated in two short bunches and accelerated up to 3 GeV in the RCS. The extracted 3 GeV proton beam, with a 150 ns bunch width and a spacing of 600 ns, is transferred to the muon production target and the spallation neutron source.
At J-PARC, another facility called the TEF is planned for development of the Accelerator Driven System (ADS) target system as well. A similar proton beam window will be applied at the TEF. For the decommissioning of the accelerator and TEF facilities, the activation cross sections known with high accuracy are mandatory for various materials. As a first step for further forthcoming measurements, the cross sections for aluminium with 0.4 GeV, 1.3 GeV, 2.2 GeV, and 3.0 GeV protons have been measured.

2. Experiment
2.1. Setup
In order to obtain activation cross sections, the experiment was carried out at the beam transport to the RCS and the MLF. A sample foil was placed at the beam dump line used for tuning the RCS. To estimate background radiation, some of the foils were placed at the outside of the stage. A liner stage guide was utilised to control the irradiation status. Thin aluminium foils with 0.1 mm thickness and 25 mm $\times$ 25 mm square were used as irradiation targets. Each of them was sandwiched by aluminium foils of size 38 mm $\times$ 60 mm and with the same thickness as the target. Four sets were placed at the entrance of the beam dump. The dump is made of iron, where is placed downstream at about 12 m from the foil. For the measurement of the cross section, it is important to control the beam irradiation conditions since the dump is utilised for beam tuning of the accelerator. To control the irradiation conditions, the foil was placed on a movable stage in the vacuum chamber. After irradiation, the sample holder was extracted from the vacuum chamber and then retracted from the holder. During the foil extraction and placement into the vacuum chamber, the sample was slowly depressed and pressed with slow leak valve to avoid rupture and deformation of the sample.

2.2. Irradiation
Each foil was irradiated by 0.4 GeV, 1.3 GeV, 2.2 GeV, and 3.0 GeV protons. The beam width was observed with three sets of Multi Wire Profile Monitors (MWPM), which are placed to measure the beam profile at the beam dump. In order to avoid unnecessary irradiation of the wires, the frame can retract from the beam and moves with a pendulum motion. It was shown that the beam width at the foil was smaller than 2.5 mm to 6.5 mm. It should be noted that the beam position was very stable since the RCS and the beam transport has quite good stability to avoid beam loss to deliver the beam to the spallation neutron source.

The repetition of the shots was chosen to be 0.4 Hz to avoid the samples melting. The number of protons per shot was about $6 \times 10^{12}$, which was monitored by current transformers shots by shots. The total number of protons irradiated was $1.77 \times 10^{14}$ for 0.4 GeV, $1.72 \times 10^{14}$ for 1.3 GeV, $1.78 \times 10^{14}$ for 2.2 GeV, and $2.20 \times 10^{14}$ for 3.0 GeV.

2.3. Analysis
Decay gamma rays from irradiated samples were measured by the HPGe immediately to survey short-lived nuclei. The main activation products in aluminium are $^7$Be (life-time: 53.22 d), $^{22}$Na (life-time: 2.6018 y), and $^{24}$Na (life-time: 14.997 h). Disintegration data were taken from the latest IAEA Nuclear Data Services [6].

Since there was only one HPGe, each of samples were periodically measured at intervals from two hours to a day. The samples were mounted on an acrylic spacer to keep the detector-to-sample geometry rigidly. Radioactivity for each product was deduced using the following equation:

$$A = \frac{\lambda N}{(1 - e^{-\lambda t_m})t} \exp(\lambda t_m)$$

(1)
Table 1: The activation cross sections

| Proton energy GeV | $^7$Be (mb) | $^{22}$Na (mb) | $^{24}$Na (mb) |
|------------------|-------------|---------------|---------------|
| 0.4              | 3.55 ± 0.45 | 16.2 ± 1.0    | 11.5 ± 0.8    |
| 1.3              | 7.10 ± 0.66 | 11.9 ± 0.9    | 10.4 ± 0.8    |
| 2.2              | 8.77 ± 0.73 | 11.7 ± 0.8    | 9.80 ± 0.77   |
| 3.0              | 8.76 ± 0.73 | 11.0 ± 0.8    | 10.4 ± 0.8    |

where $N$: count of $\gamma$-rays peak, $\lambda$: decay constant, $t_m$: measurement time, $\epsilon$: detection efficiency, and $I$: absolute $\gamma$-rays intensity, respectively. The production cross section was derived from the following equation:

$$\sigma = \frac{A}{\lambda N_p n} \text{ barn} \quad (2)$$

where $N_p$ is the number of protons irradiated, and $n$ is the number density of the sample.

The obtained cross sections are shown in table 1. Both statistical and systematic uncertainties are included. The main contribution to the uncertainty is the number density which is 5%. The next one is detection efficiency (5%). The others (the number of protons, self-absorption of gamma-rays, decay gammas) are about 1%. In total, the systematic uncertainty is estimated as 6.1%.

It is estimated that the contribution of sodium production by neutron and other charged particles is negligible since there was no gamma rays observed in the samples used for background measurement.

3. Discussion

In figure 1, the measured, calculated, and evaluated activation cross sections for $^{27}$Al$(p, X)^7$Be, $^{27}$Al$(p, 3p3n)^{22}$Na, and $^{27}$Al$(p, 3p1n)^{24}$Na are shown. Comparing with other experimental data, the present data have smaller uncertainties than others thanks to the highly stabilised and controlled proton beam. Their values are also consistent with others. Thus the irradiation experiment at the 3NBT beam dump line produces valid results and is ready for full-time measurements with various materials.

It was found that the GEM code in the PHITS code slightly differs from the original one [9]. Thus we implemented the original one in the PHITS code, then calculated the activation cross sections. They are superposed in figures 1b, 1d and 1f respectively. It is clearly shown that especially for $^7$Be production the calculated ones are drastically improved by about 40% (see figures 1a and 1b) though the one with INCL still underestimates above 2 GeV. On the other hand, the ones for $^{22}$Na and $^{24}$Na production are less affected since Na comes from fission products rather evaporation products. This indicates that improvement of the intranuclear cascade model is required.

4. Conclusion

In order to improve the accuracy of the nuclear design for spallation neutron sources and transmutation systems, nuclear cross sections are important. Prior to the forthcoming full-time measurement with various materials, the activation cross sections of aluminium for $^7$Be, $^{22}$Na, and $^{24}$Na with 0.4 GeV, 1.3 GeV, 2.2 GeV, and 3.0 GeV protons were measured to validate the availability of the irradiation place at the 3NBT beam dump line in J-PARC. The present experimental results are in good agreement with other experimental ones and have less uncertainty than other experimental ones.
Figure 1: Comparison of the present production cross sections with other experiments, the evaluated data, and the calculations of the original PHITS [7] code and the upgraded one. Figures 1a, 1c and 1e are compared to the calculation done by the original PHITS. Others (figures 1b, 1d and 1f) are to the one done by the upgraded PHITS (labeled by Gen.GEM). The present results (full circle) and other experiments (other symbols) taken from EXFOR [10] data are plotted.

It was shown that the calculation by the PHITS code underestimates the present measurements. By implementing the original GEM code to the PHITS code, $^7$Be production cross section were improved drastically. However, this is not so for sodium production which is mainly produced by direct reaction.

In future works, measurement of the activation cross sections for noble gases (especially Xe) with Pb and Bi materials for parameter determination of TEF facilities is planned.

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