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Measurement of aluminum activation cross section and gas production cross section for 0.4 and 3-GeV protons

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Abstract. To estimate the lifetime and the radiation dose of the proton beam window used in the spallation neutron source at J-PARC, it is necessary to understand the accuracy of the production cross section of 3-GeV protons. To obtain data on aluminum, the reaction cross section of aluminum was measured at the entrance of the beam dump placed in the 3-GeV proton synchrotron. Owing to the use of well-calibrated current transformers and a well-collimated beam, the present data has good accuracy. After irradiation, the cross sections of Al(p,x)^{7}Be, Al(p,x)^{22}Na-22 and Al(p,x)^{24}Na were obtained by gamma-ray spectroscopy using a Ge detector. It was found that the evaluated data of JENDL/HE-2007 agree well with the current experimental data, whereas intra-nuclear cascade models (Bertini, INCL-4.6, and JAM) with the GEM statistical decay model underestimate by about 30% in general. Moreover, gas production, such as T and He, and the cross sections were measured for carbon, which was utilized as the muon production target in J-PARC. The experiment was performed with 3-GeV proton having beam power of 0.5 MW, and the gasses emitted in the process were observed using a quadrupole mass spectrometer in the vacuum line for beam transport to the mercury target. It was found that the JENDL/HE-2007 data agree well with the present experimental data.

1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC) [1] now houses a MW-class pulsed neutron source in the Materials and Life Science Experimental Facility (MLF) within the Japan Spallation Neutron Source (JSNS) [2] and the Muon Science Facility [3]. Since 2008, the neutron source has produced a high-power proton beam of 300 kW. In 2015, we successfully ramped up the beam power to 500 kW and delivered a 1-MW beam to the target. To produce neutrons, a 3-GeV proton beam collides with a mercury target, and to produce muons, the 3-GeV proton beam collides with a 2-cm-thick carbon graphite target. To efficiently use protons 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 3 GeV RCS to neutron facility beam transport (3NBT) [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 bunches of short length and accelerated up to 3 GeV in the RCS. The extracted 3 GeV proton beam, with a 150-ns bunch width and spacing of 600 ns, is transferred to the muon production target and the spallation neutron source.

At the MLF, the target station is surrounded by helium for heat removal. To separate the vacuum area in the accelerator from the helium area of the target station, a proton beam window (PBW) made of aluminum alloy is employed. At J-PARC, another facility, called transmutation experimental facility (TEF), is planned for development of a target for the accelerator driven system (ADS) by using a 0.4-GeV proton beam, to which a similar proton beam window will be applied. The lifetime of the PBW can be estimated based on existing material properties after irradiation such as data obtained at the Paul Scherrer Institut (PSI) [6–8]. The data of post-irradiation examination at PSI are for 590-MeV protons, but there are no data for 0.4 and 3 GeV protons. To estimate the energy difference in material properties such as gas production accurately, validating the accuracy of the calculation based on the intra-nuclear cascade model and nuclear data is vital. Furthermore, for decommissioning the PBW, an accurate activation cross-section is required. In this study, the activation cross section of aluminum was measured at J-PARC.

2. Experiment

2.1. Activation cross section measurement of aluminum

To obtain the activation cross section, we performed an experiment using the beam transport from the RCS to MLF. A sample foil was placed at the beam dump line for tuning the RCS. A thin rectangular aluminum foil measuring 25 mm by 45 mm and a 0.5 mm thickness was placed at the entrance of the beam dump made of iron, which was placed 12 m downstream of the foil. For measuring the cross section, it is important to control the beam irradiation condition. To fix the irradiation condition,

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the foil was placed on the movable stage in the vacuum chamber. After irradiation, the sample and the holder were extracted from the vacuum chamber, and gamma-ray emission from the sample was measured using a high-purity Germanium (HPGe) detector. During the foil extraction and placing of the vacuum chamber, the sample foil was slowly pressed and pressed down with a slow leak valve, respectively, to avoid rupture and deformation. To estimate activation due to other radiation, some foil were placed outside of the stage.

In the original experiment, the gas production cross section of the aluminum had to be planned by using a quadrupole mass spectrometer (Q-mass) placed in the vacuum chamber. However, the Q-mass malfunctioned owing to radiation damage, possibly due to the single-channel effect. By using Q-mass with a heavy shield, measurement of gas production in the carbon muon-production target was carried out, as described in Sect. 2.3.

2.2. Proton beam tuning for irradiation

Each aluminum foil was irradiated by 400 MeV and 3-GeV protons. Without acceleration at the RCS, the 400-MeV beam can be delivered to the beam dump placed at the exit, which is called the 3NBT dump 1/3rd mode. The 3 GeV protons are extracted from the RCS with acceleration. The beam width was observed with the multi-wire profile monitor (MWPM). Along the 3NBT to the beam dump, three sets of movable MWPMs were placed to measure the beam profile to the beam dump. The MWPM frame has 31 wires of silicon carbide (SiC) with a spacing pitch of 6 mm along both the horizontal and the vertical directions. We employed SiC wires having a diameter of 0.1 mm, which have a tungsten core of 0.01 mm and are coated with 1 μm of pyrolytic carbon. A wireframe made of >95% aluminum oxide was selected given its high resistance to radiation. The wireframe was placed in a vacuum chamber made of titanium, which was selected because of its good vacuum characteristics and low activation. To avoid unnecessary irradiation to the wires, the frame was built to be retractable from the beam.

By observing the beam width using MWPMs, the emittance and the Twiss parameter of beam emittance were acquired. It was shown that the beam width at the foil was 3 and 7 mm in 1σ for 0.4 and 3-GeV protons, respectively. It should be noted that the beam position was very stable because the RCS and the beam transport must have high stability to avoid beam loss and deliver the beam to the spallation neutron source.

2.3. Measurement production cross section of H and He for carbon

In MLF, a 20-mm-thick rotating carbon graphite target, which is target cooled mainly by heat radiation, was placed at the proton beam line for muon production. The quadrupole mass spectrometer (Q-mass), which obtains gas production cross section, was placed in the vacuum chamber for beam transport. To avoid the single event effect due to neutrons, the Q-mass was surrounded by boron-loaded polyethylene blocks. The sensitivity of the Q-mass was calibrated using a standard helium leak source (1.5×10^{-7} Pam^3/s) placed atop the muon target chamber.

Table 1. Production cross section of aluminum obtained in present experiment.

	Proton energy [MeV]	Energy width [MeV]	Cross section [mb]	Total uncertainty [mb]
^{7}Be	400	1.08	2.96	0.11
	2984	8.06	8.50	0.31
^{22}Na	400	1.08	15.42	0.56
	2984	8.06	10.57	0.38
^{24}Na	400	1.08	11.25	0.41
	2984	8.06	9.54	0.34

Table 2. Mass number 3 and 4 production cross section for carbon obtained in present experiment.

Reaction	Proton energy [MeV]	Error energy [MeV]	Cross section [mb]	Error [mb]
C(p,xt)+C(p,x^{3}He)	2984	8.06	53.2	20
C(p,xα)	2984	8.06	141.0	35

3. Result

3.1. Activation cross section measurement of aluminum

The aluminum activation results obtained herein are summarized in Table 1, in which the experimental errors are given as well. In analyzing the data, the escape of residual nuclides from the sample was calculated with PHITS code[9] using the cascade model of INCL-4.6[10], and it was found to be lower than a few percent. In this experiment, the beam current was observed using the current transformer placed at RCS and along the beam transport line. Because well-calibrated proton intensity monitors were utilized, the accuracy of the beam monitor was estimated to be better than 1%. Furthermore, the intensity was observed many times at RCS, in which the beam loss was smaller than 0.1% and very accurate beam intensity was obtained. The detection efficiency of the HPGe detector was calibrated using a radiation source. In the analysis, 3% of uncertainty was estimated for absolute detection efficiency. By including of uncertainties of proton intensity, detection efficiency, and statistical errors, the total uncertainty of the cross section was less than 4%.

3.2. Production cross section of H and He for carbon

The gas production cross section was measured under the condition of 0.5 MW continuous beam operation at MLF. It was found that the partial pressure for mass numbers of 3 and 4 saturated after 1 h of irradiation. The partial pressure, which saturated after beam operation, was considered to represent the amount of particles produced of each mass number. Mass numbers 3 and 4 were considered as the sum of ^{3}He and triton and ^{4}He, respectively. The results of the gas production cross section are summarized in Table 2. The error of the cross section was derived from the fluctuation of saturated pressure.

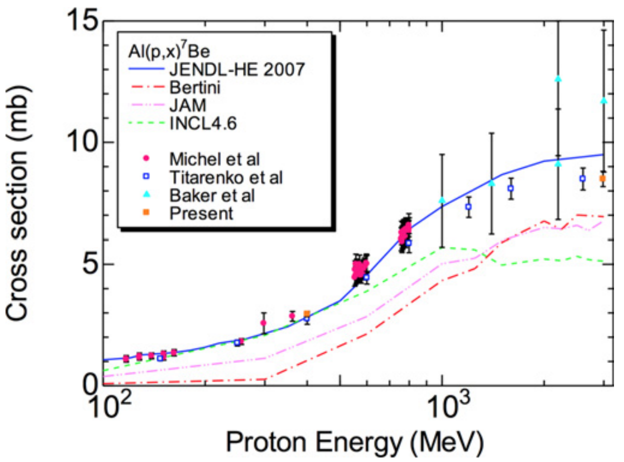

Figure 1. Comparison of Al(p,x)^{7}Be cross section data from other experiments, evaluation, and calculation.

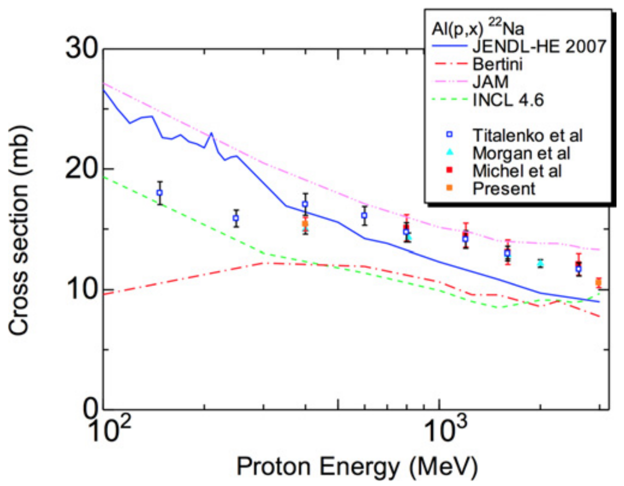

Figure 2. Comparison of Al(p,x)^{22}Na cross section data from other experiments, evaluation, and calculation.

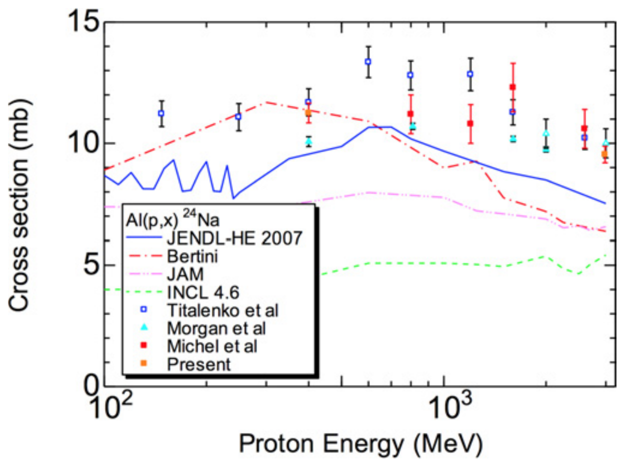

Figure 3. Comparison of Al(p,x)^{24}Na cross section data from other experiments, evaluation, and calculation.

4. Discussion

4.1. Calculation and evaluated data

The present experimental results were compared with the calculation results as follows. The calculation was performed using the PHITS [9] code and various intra-nuclear cascade models, namely, Bertini, JAM, and INCL-4.6 [10], coupled with the statistical decay model of GEM [11]. The present experimental results were compared with the evaluation data of JENDL High Energy File 2007 (JENDL/HE-2007) [12] and with ENDF/HE-VI [13] for carbon.

4.2. Comparison of aluminum activation cross section

Figure 1 shows a comparison of the Al(p,x)^{7}Be reaction. The present result for 400 MeV shows good agreement with other experimental data. Since the current results have good accuracy in terms of proton numbers, the overall error is smaller than that in the other experiment.

It was found that JENDL/HE-2007 showed remarkably good agreement with the present results and those of other experiments. Since JENDL/HE-2007 was normalized using the Bertini cascade and GEM to fit the other experimental data, JENDL/HE-2007 showed good agreement. It was also found that all PHITS calculations with many types of intra-nuclear cascade models showed underestimation in general. Although the INCL-4.6 model showed good agreement in the energy region lower than 500 MeV, it underestimated at energies higher than 500 MeV. It should be noted that the calculation of Furihata using the GEM and the Bertini cascade models implemented in LAHET showed remarkably good agreement [11]. Since the PHITS code applies the same model, it should yield similar good agreement. However, it underestimated the value by 20%, and we will look into this matter in future work.

Figures 2 and 3 show sodium production cross sections of ^{22}Na and ^{24}Na, respectively. For ^{22}Na, JENDL-HE 2007 showed remarkably good agreement for 0.4 GeV, but slight underestimation for 3 GeV. JENDL-HE 2007 for ^{24}Na production showed underestimation over the entire energy range. Although the PHITS shows agreement within 20%, except for the INCL-4.6, it underestimated the ^{22}Na and ^{24}Na results in general, except the result of the JAM model for ^{22}Na, which was slightly an overestimate. It should be noted that the new cascade model of INCL-4.6 underestimated remarkably, especially for ^{24}Na production.

4.3. Comparison of C(p,xα) cross section

Figure 4 shows a comparison of the C(p,xα) reaction results with data from other experiments and calculations. JENDL-HE 2007, ENDF/HE-VI and the Bertini cascade model in PHITS showed remarkably good agreement with the present result. On the contrary, the JAM and the INCL-4.6 cascade models in the PHITS code overestimated compared to the present result. It is curious that the similar reaction channel of Al(p,x)^{24}Na was underestimated by the INCL-4.6 model, whereas the C(n,xα) reaction was overestimated. This may be solved by performing systematic studies in future. It should be noted that in the energy region lower than 500 MeV, ENDF/HE-VI showed different behavior than JENDL-HE 2007 and the Bertini cascade model. Given that there is no experimental data on EXFOR[14], further discussion is not possible. For the sake of evaluation, it is interesting to measure the C(n,xα) cross section.

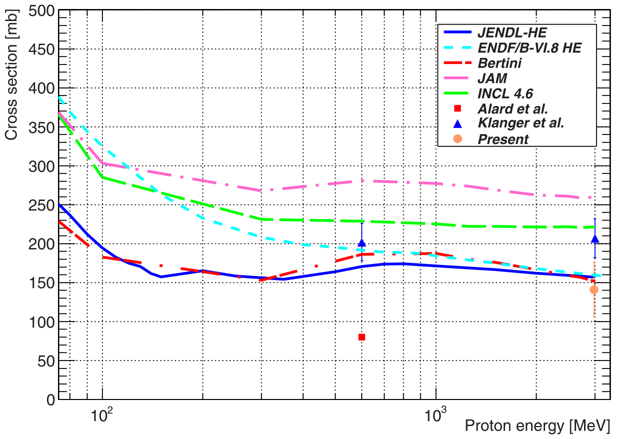

Figure 4. Comparison of present C(p,xα) cross section with those from other experiments, evaluation, and calculation.

5. Conclusion

For estimation the lifetime of the proton beam window, we obtained the activation cross section of aluminum. The activation cross sections of Al(p,x)^{7}Be, Al(p,x)^{22}Na, and Al(p,x)^{24}Na were obtained for 0.4 GeV and 3 GeV protons by observing gamma rays with an HPGe detector. The present experimental results have a good accuracy of less than 4% in total uncertainty. The amount of residual nuclides escaped from the sample was compensated for in the calculation with the PHITS code, and the amount was less than a few percent. The present results showed good agreement with other experimental results.

The present experimental results were compared with the nuclear data and the calculation results. It was found that JENDL-HE/2007 shows good agreement with the present results. The intra-nuclear cascade (INC) models also show good agreement within 20%, but improvement of the INCs for accurate estimation of window lifetime is essential.

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