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MEASUREMENT OF DISPLACEMENT CROSS-SECTION FOR STRUCTURAL MATERIALS IN HIGH-POWER PROTON ACCELERATOR FACILITY

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Abstract

For damage estimation of structural material in the accelerator facility, displacement per atom (DPA) is widely employed as an index of the damage calculated based on the displacement cross-section obtained with the calculation model. Although the DPA is employed as the standard, the experimental data of displacement cross-section are scarce for a proton in the energy region above 20 MeV. Among the calculation models, the difference about 8 times exists so that experimental data of the displacement cross-section is crucial. To obtained the displacement cross-section, an experiment has started in J-PARC. As a preliminary result, the displacement cross-section of copper was successfully obtained for 3-GeV proton. The present results showed that the widely utilized NRT model overestimates the cross-section as suggested by the previous experiment in the lower energy region.

INTRODUCTION

As the power of accelerators is increasing, the prediction of the structural damage to materials under irradiation is essential for the design [1]. To decrease hazard of the radioactive waste produced in a nuclear reactor, Japan Atomic Energy Agency (JAEA) proposes the Accelerator Driven System (ADS) with extremely high power accelerator such as 30 MW with proton having kinetic energy about 1.5 GeV. A lead-bismuth eutectic (LBE) is one of a candidate of the target, which simultaneously plays the role of the coolant. In the design of the ADS, damage to the window material is one of a critical issue. In J-PARC, Transmutation Experimental Facility (TEF) [2] is planned to build for the study of the target material for the ADS. Beam windows play essential roles in high-power proton accelerator facilities. At Material Life science experimental Facility (MLF) [3, 4] in J-PARC [5], an aluminum alloy is utilized as beam window [6] separating between high vacuum area and target station. The T2K collaboration in J-PARC uses the titanium alloy as the beam window. To operate high power accelerator with confidence, the damage estimation of the target material is essential. For the quantitative specification of the damage to the target material, displacement per atom (DPA) is employed in general, which is widely used for the estimation of damage nuclear reactor and fusion reactor.

The DPA is estimated by the particle flux multiplied displacement cross-section, which is normally obtained by Norgertt-Robinson-Torrens (NRT) model [7]. In the lower energy region than 20 MeV, the displacement cross section for proton can predict well because the displacement is mainly caused by Coulomb force. For the neutron in lower energy, the DPA can be estimated with reasonable accuracy as well, based on elastic scattering and inelastic scattering, in which the cross-section and outgoing energy of the second particle are well known, The calculation method of displacement cross section has been established for the low-energy regions where secondary particles are not produced by nuclear reactions. However, for the protons in high energy region above 20 MeV, the experimental data of displacement cross section are so scarce that the displacement cross section has not been studied well. Since many reaction channels open above 20 MeV, the calculation codes based on the intra-nuclear cascade model are utilized to obtain the cross-section. The displacement cross-sections calculated with the MARS using several models [8] compared with the experimental data carried out Kyoto university [9] and BNL/AGS [10]. It was reported that the displacement cross section of tungsten has 8 times difference in various calculation models[1]. For validation and improvement of the estimation of the DPA, the experimental data are crucial. Since the experimental data of the DPA are, however, scarce, the experimental data are required in the proton energy region above 20 MeV for improvement of the displacement cross-section.

EXPERIMENT

For the displacement cross-section measurement, a vacuum chamber with cryocooler installed at the front of the beam dump placed beam transport, called 3NBT, at 3-GeV Rapid Cycling Synchrotron (RCS) in J-PARC. Since no space was left in the beamline dedicated for transport to the dump, all instruments for the present experiment was installed in the beamline, where the high-intensity proton beam delivers to the spallation neutron source in MLF. A very low intense beam is preferable to sustain a cryogenic temperature of the sample. Due to the safety reason, the in-

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[1] It should be noted that 8 times of ambiguity for the displacement cross-section makes 8 times uncertainty of lifetime estimation for target materials.

terlock of accelerator was modified to carry out the present experiment. The proton energy extracted by RCS can vary from injection energy of 0.4 GeV to 3 GeV with altering extraction timing by the kicker magnet. Using the RCS, the displacement cross-section between 0.4 and 3 GeV can be obtained. In next year, the similar chamber will be installed in front of abort dump of MR in J-PARC, where the proton can be utilized from 3 to 30 GeV. With compiling data obtained, the displacement cross-section will be obtained in the present experimental plan.

Procedure of Displacement Cross-Section Measurement

To observe the defect of damage in the sample, the irradiated sample is required to be cooled cryogenic temperature (around 10 K), where recombination of Frenkel pairs by thermal motion is well suppressed. With the observation resistivity change $\Delta\rho_u$ due to irradiation under cryogenic temperature, the experimental displacement cross-section $_{exp}(E)$is given by the following,

$$\sigma_{exp}(E) = \Delta\rho_{Cu}/(\overline{\phi(E)}\rho_{FP}), \tag{1}$$

where $\overline{\phi(E)}$ is average proton flux over the sample surface accumulated for irradiation time, ρ_{FP} is the resistivity change per Frenkel-pair density for a particular metal. In this work, ρ_{FP} was defined to 2.2×10^{-6} Ωm.

It should be noted that the increase in electrical resistivity due to high-energy protons provides straightforward information such as degradation of the stabilizer of the superconductor, which compromises quench protection and increases magnetothermal instability, for the superconducting accelerator magnet utilized in the hadron collider such as High-Luminosity LHC in CERN.

Measurement of Displacement Cross Section at 3-GeV Beam Dump in J-PARC

A vacuum chamber, as shown in Fig. 1 was installed in front of the 3-GeV beam dump. The chamber was deployed Gifford-McMahon (GM) cryocooler (Sumitomo Heavy Industries RDK-408D2) which cooled the sample through a copper rod and sample holder made of aluminum. The assembly of cryocooler and sample was placed on a movable stage to avoid unexpected irradiation of proton. In order to compare the previous experiments, copper was selected as the sample. Before installation sample of copper, summarized characteristics in Table 1, was annelid about 800℃to eliminate the defect of the lattice. To hold the sample with electrical isolation, Kapton foil was inserted between the sample and the holder. The resistance of the sample was measured by the voltmeter (Keithley 6221) and current source (Keithley 2185). The sample wire at the terminal (i.e., potential point) was connected to both current source and voltmeter for compensation of cable resistance between the sample and the instruments. A current of ±100 mA was fed into the copper wire with the polarity changing at a frequency of 10 Hz. The voltage of the copper wire was read once every minute. The precision of this resistance measurement was ±0.01 μΩ, corresponding to a resistivity of ±3 fΩm.

The residual resistivity ratio (RRR) of the sample was measured between a room and cryogenic temperature. Table 1 also summarizes the electrical resistivity measurements. The CX1050-SD Cernox resistance thermometer on the sample holder was calibrated in the temperature region 4-100 K and the silicon thermometer on the copper column was calibrated between 4 K and room temperature. The electrical resistivity of the sample ρ_{Cu} is expressed as follows:

$$\rho_{Cu} = RL/A \tag{2}$$

where $R[\Omega]$ is the measured electrical resistance, L[m] is the length between two potential points (40 mm), and A is the area of the sample (4.9×10^{-2} [mm^2]). The minimum temperature on the sample holder was 20 K, although the temperature of near the cold head was 4.6 K. The main reason for the different temperatures is insufficient thermal contact between the copper column and the holder.

The beam intensity was observed by the well-calibrated current transformer. The beam width was observed with the multi-wire-profile-monitor (MWPM) [11, 12] placed near the sample, which was 4.0 and 5.0 mm for horizontal and vertical direction, respectively, in 1. From the result of the beam measurement, the average flux was derived as1.98×18 m^{-2}.

Table 1: Characteristics of Copper Sample

Shape	Single wire
Diameter [μm]	250
Length between potential points [mm]	40
Purity [%]	99.999
Resistivity at 298 K [Ωm]	1.67×10^{-8}
Resistivity at 20 K [Ωm]	7.36×10^{-11}

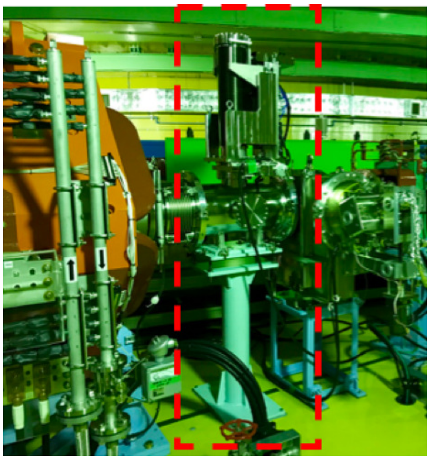

Figure 1: Vacuum chamber for the measurement displacement cross-section placed at the beam line with GM cryocooler and movable stage.

RESULT AND DISCUSSION

Result of Present Experiment

The damage rate of copper irradiated with a proton of present result is shown in Table 2 compared with the previous experiment carried out for lower energy proton. Using the present damage rate and Eq. (1), the displacement cross-section of the proton was obtained, which was 1070 b of Cu at 3 GeV.

Table 2: Experimental Resistance Change Rate to One Proton Induced

Experiment	Energy [GeV]	Damage rate [$\times 10^{-31}\,\Omega m^3$/proton]
KURRI	0.13	3.41
AGS	1.94	3.66
Present(J-PARC)	3.0	2.35

Calculation of Displacement Cross-Section

The displacement cross section, which is defined as following equation obtained with the calculation based on intra-nuclear cascade model,

$$\sigma_{disp-calc}(E) = \sum_i \int_{E_d}^{T_i^{max}} \nu(T_i) d\sigma/dT_i, \qquad (3)$$

where E is the kinetic energy of irradiation, d/dT_i is recoil atom kinetic energy distribution, T_i is the kinetic energy of recoil particle i valid to maximum of T_i^{max} , E_d is the effective threshold displacement energy, and $\nu(T_i)$ is the number of defects (Frenkel pairs) showing the defect production efficiency defining by a vacancy and a self-interstitial atom in the irradiated material, which is widely utilized by Norgertt-Robinson-Torrens (NRT) model [7]. Calculation result was obtained with PHITS code [9].

Comparison Between Experiment and Calculation

In Fig. 2, the present preliminary result of the displacement cross-section is compared with the previous experimental data and the calculation. The present data showed overestimation about 4 times of the calculation with the NRT model as similar to the previous experiment carried out lower energy [9, 10]. It was also shown that the PHITS with the improved model of Nordlund showed remarkably good agreement with the experimental data. By accumulation of the experimental data in the future work, the accuracy of the calculation can be expected to be improved.

CONCLUSION

For estimation of target materials, displacement cross-section experiment was carried out in J-PARC. As a preliminary result, the displacement cross-section of copper for 3-GeV proton was successfully obtained. The present results showed an overestimation of the cross-section with widely utilized the NRT calculation model, which was suggested by the previous experiment in the lower energy. In next year, the similar chamber will be installed in front of beam dump for the 30-GeV synchrotron to obtain the cross-section up to 30 GeV. After compiling the data, the cross-section from 0.4 to 30 GeV, which will help improve the damage estimation of the proton accelerator.

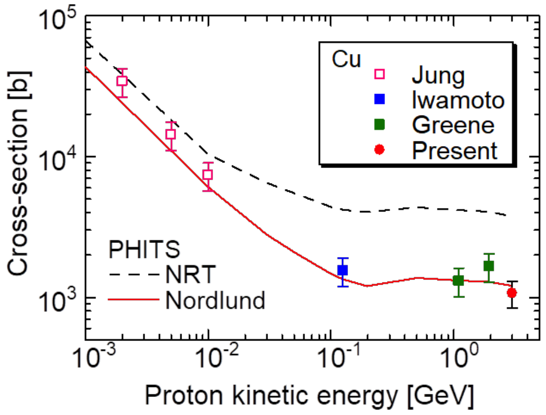

Figure 2: Comparison of the present experiment data with the previous experiment [9, 10, 13] and calculation results with PHITS as a function of kinetic energy.

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REFERENCES

[1] D. Filges, F. Goldenbaum, Handbook of Spallation Research, Theory, Experiments and Applications, Wiley-VCH Verlag GmbH KGaA, Berlin, Germany, pp. 215-232 (2009).
[2] H. Oigawa et al., “Conceptual Design of Transmutation Experimental Facility”, Proc. Global2001, Paris, France (2001).
[3] Y. Ikeda, Nucl. Instrum. Meth. **A600**, (2009) 1.
[4] Y. Miyake, et al., Physica B **404** (2009) 957.
[5] The Joint Project Team of JAERI and KEK, JAERI-Tech 99-56, 1999.
[6] S. Meigo, et al., J. Nucl. Mater. , **450**, 141 (2014).
[7] M. J. Norgett, M. T. Robinson, I. M. Torrens, Nucl. Eng. Des. **33** , 50-54, (1975).
[8] N. Mokhov, et al.,“MARS15 Developments Related to Beam-Induced Effects in Targets”, 6th High-Power Targetry Workshop, Oxford, UK, April 11-15 (2016).
[9] Y. Iwamoto, et al., J. Nucl. Mater. , **458**, 1551 (1998).
[10] G. A. Greene, et al., Proc. of 6th Int. Meet. on Nucl. Application of Accel. Tech. (AccApp’03), Ja Grange Park, Illinois, USA, pp.881-892, (2004).
[11] S. Meigo, et al., Nucl. Instrum. Meth. **A562**, (2006) 569.
[12] S. Meigo, et al., Nucl. Instrum. Meth. **A600**, (2009) 41.
[13] P. Jung, J. Nucl. Mater. , **117**, 70 (1983).