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Measurement of Neutron Spectrum using Activation Method in Deuterium Plasma Experiment at LHD

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In the Large Helical Device (LHD) of the National Institute for Fusion Science, the experiments using deuterium plasma were performed from March 2017. Neutrons with the energy of 2.45 MeV are generated by d (d, n) ^{3}He reactions. The evaluation of the neutron flux in the torus hall as well as the LHD body is very important for designing the decommissioning of the LHD in the future, and the radiation shielding for workers and components around LHD. In this study, we performed the activation experiments using multiple activation foils to obtain a neutron spectrum in the vacuum vessel of the LHD. The reaction rate of each activation foil was generally consistent with the calculation result by MCNP6. As a result of the unfolding with SAND-II code, we experimentally obtained the neutron spectrum in the vacuum vessel of the LHD for the first time.

Keywords: LHD, Neutron spectrum measurement, Activation method, MCNP6

1. Introduction

At the National Institute for Fusion Science (NIFS), deuterium plasma experiments at the Large Helical Device (LHD) are performed in order to obtain the fundamental data for the design of nuclear fusion power plants. In commercial fusion reactors, neutrons generated by the nuclear fusion reaction will be utilized as thermal energy in fusion power generation. On the other hand, the neutron activates devices of fusion reactor composed of several materials. Therefore, it is one of the important tasks in nuclear fusion reactor development to understand the behavior of neutrons for the radiation protection for the safe operation of facilities and for future decommissioning.

The first deuterium plasma experiment series was performed from March to July of 2017 at the LHD. It is known that neutrons with the energy of 2.45 MeV are generated by d (d, n)^{3}He (DD) reactions. Neutrons with the energy of 14 MeV are also generated by secondary t (d, n) ^{4}He (DT) reactions accompanying DD reaction. Because those fast neutrons scattered in the LHD are moderated and become thermal and epi-thermal neutrons, the neutrons are expected to have a wide energy spectrum. It is necessary to know the radio-activation inside of the vacuum vessel of the LHD because workers enter into the vacuum vessel for maintenance. It is, therefore, necessary to obtain the energy spectrum of neutrons.

One of the methods to measure the neutron spectrum is a multi-foil activation method. It can provide the neutron spectrum by using reaction rates for several kinds of activated foils having different reaction cross sections, and an unfolding technique. The activation foil method was widely used for the fusion reactor of tokamak type. In the experiments of the DT discharge at the Joint European Torus (JET) [1], the neutron energy spectrum in the high-energy range was acquired using 15 types of activated reactions.

On the other hand, the neutron energy spectrum in the LHD was estimated using the neutron transport Monte Carlo simulation code. Due to the complexity of the LHD structure, it is simulated by the simple model by dividing the LHD in the toroidal direction and imitating helical structures [2, 3]. The validity of model should be evaluated by the actual neutron spectrum obtained experimentally. In this study, we employed the multi-foil activation method to experimentally obtain the neutron spectrum during the deuterium plasma experiment. As shown in Table 1, 10 kinds of activated reactions were selected in this experiment. The energy peaks of the DD and DT neutrons in the spectra can be distinguished by using reactions with different threshold energies such as ^{115}In (n, n')^{115m}In, ^{64}Zn (n, p)^{64}Cu, ^{27}Al (n, p)^{27}Mg, ^{27}Al (n, α)^{24}Na, ^{28}Si (n, p)^{28}Al and ^{64}Zn (n, 2n)^{63}Zn. Other reactions are mainly induced by thermal neutrons. Thus, the neutron energy spectrum with wide energy range can be acquired.

2. Experimental Setup

The Neutron Activation System [4] installed at measurement ports on the outside of the LHD body was used in activation experiments. We used 8-O port located at the outboard side of the horizontally elongated poloidal cross section of the plasma as shown in Figure 1. As a result, the metal foil can be sufficiently activated. The measurement station is located in the basement. At first, the metal foils were packed in a capsule made of polyethylene and, transferred to the vicinity of the plasma in the vacuum vessel of the LHD through a pneumatic

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Table 1. Selected activation foils and nuclear reactions

Reactions	Threshold [MeV]	Half-life	E_γ [MeV]
$^{197}Au\ (n, \gamma)^{198}Au$		2.69day	0.412
$^{115}In\ (n, \gamma)^{116m}In$		54.3 min	1.294
$^{64}Zn\ (n, \gamma)^{65}Zn$		244 day	1.116
$^{68}Zn\ (n, \gamma)^{69m}Zn$		13.8 h	0.439
$^{115}In\ (n, n')^{115m}In$	0.5	4.49 h	0.336
$^{64}Zn\ (n, p)^{64}Cu$	0.6	2.52 h	1.346
$^{27}Al\ (n, p)^{27}Mg$	1.9	9.46 min	0.844
$^{27}Al\ (n, \alpha)^{24}Na$	3.1	15.02 h	1.369
$^{28}Si\ (n, p)^{28}Al$	4.0	2.24 min	1.779
$^{64}Zn\ (n, 2n)^{63}Zn$	12	38.5 min	0.670

tube before the plasma shot. The foils were irradiated during the plasma shot and returned to the measurement station after the shot. This operation was repeated several times in order to sufficiently activate the foils. The neutron yields in each plasma shot were measured by the fission chamber [5] and the triton burn-up ratio, which represents the ratio of neutron yield by DT reaction to neutron yield by DD reaction, was measured by the scintillating fiber detector [6].

Finally, gamma-rays from the activated foils were counted using a high-purity germanium (HPGe) detector. The HPGe detector was Model GX3018/CP5-PLUS-U of Canberra Industries, Inc. Because the detector was in the lead shield with a thickness of 100 mm, the counting rate of the background was sufficiently low. From the obtained gamma-ray counts, the reaction rate, R, per source neutron was calculated using equation (1).

$$\mathrm{R} = \mathrm{N}\sum_{E} \sigma(E)\cdot\varphi(E) = \frac{\lambda\cdot C}{S_n\cdot\alpha_\gamma\cdot\varepsilon\cdot(e^{-\lambda t_1}-e^{-\lambda t_2})\cdot(1-e^{-\lambda t_0})} \quad (1)$$

Here, $\sigma(E)$ is a cross-section of the reaction [barn], $\varphi(E)$ is the neutron spectrum at the irradiation end per source neutron [$cm^{-2}\bullet s^{-1}$], E is neutron energy, S_n is neutron yield [s^{-1}], N is the number of nuclei in the foil, α_γ is the gamma-ray emission yield, t_0 is the end time of irradiation [s], t_1 is the start time of the gamma-ray measurement from the start of the irradiation [s], t_2 is the end time of the gamma-ray measurement from the start of the irradiation [s], λ is the decay constant of activated nuclide in the sample [s^{-1}], C is the gamma-ray count under the specific gamma-ray peak measured during t_1 to t_2, and ε is the efficiency of the HPGe detector for the specific gamma-ray peak.

3. Results and discussion

3.1 Reaction rate

The reaction rate of each reaction with the neutrons was obtained by Eq.1 using the experimental data. Figure 2 shows the ratio of the simulation results of the reaction rate using MCNP6 [7], which is a Monte Carlo N-particle code, to the experimental results. The uncertainties in Figure 2 are mainly due to the statistical error in the counts of gamma rays. The horizontal axis shows the triton burn-up ratio that is different in each plasma shot. The ratios of the simulation results using MCNP6 to the experimental ones for the reaction rate were close to unity. The result of (n, γ) reactions which were represented by the open symbols in the legend of the figure 2 were smaller than 1. This result indicated that the thermal neutron flux by the simulation was underestimated. It was because the modeling of surrounding equipment in the irradiation field of NAS is not complete in the simulation and neutrons generated in the simulation process are not decelerated by the surrounding equipment. On the other hand, the result of reactions with threshold energy which were represented by the closed symbols in the legend of the figure 2 were almost 1.

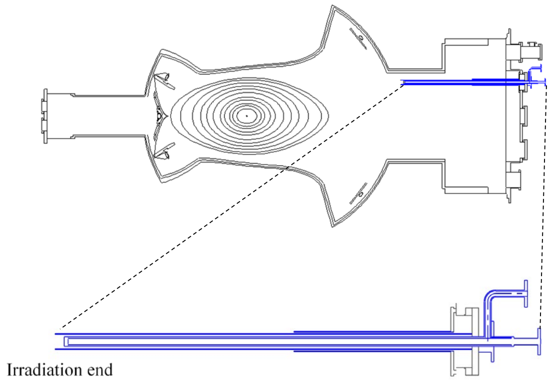

Fig. 1 The irradiation end of neutron activation system at poloidal cross section of 8-O port. The oval shape of the center shows the plasma.

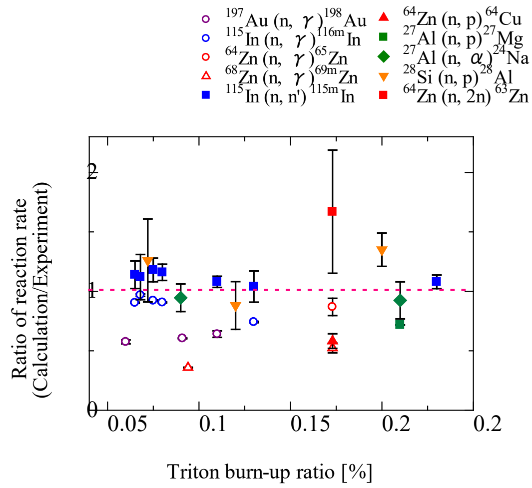

Fig. 2 The ratio of the simulation result using MCNP6 to the experimental results of the reaction rate.

3.2 Unfolding and uncertainty

Unfolding with SAND-II [8] was carried out using the result of the reaction rate and the data of cross section. As the amount of DT neutron varies in each shot, this effect should be considered in the unfolding process. As shown in Figure 3, in the reaction having the threshold neutron energy between 2.45 MeV and 14 MeV of DT neutron such as ^{28}Si (n, p) ^{28}Al reaction, the reaction rate greatly depends on the triton burn-up because this energy range of neutron is only caused by DT neutron. Thus, the reaction rates of these reactions were normalized with the triton burn-up ratio of 0.1 % in this study. In the cases of other reactions, the averaged reaction rates were used because the reaction rate is hardly affected by DT neutrons, and the yield of DT neutron is quite smaller than that of DD neutron. The reaction rates per the number of target nuclei and the amount of neutron generation are shown in Table 2. In this table the triton burn-up ratio is normalized to be 0.1%.

For the estimation of the neutron energy spectrum by SAND-II code, the neutron energy spectrum simulated by MCNP 6 was used as the initial guess spectra. Figure 4 shows the neutron spectra estimated by MCNP6 code and by the unfolding with SAND-II. The neutron energy spectra were roughly in agreement within an order. It was confirmed that the simulation result is was smaller than the experimental result at 10^{-2} MeV or lower region. This represents the same tendency as the result showed in the figure 2. In addition, it can be seen that the unfolding result changed greatly around 2.45 MeV peak.

Table 2. Reaction rate when the triton burn-up ratio is normalized to be 0.1%.

Reactions	Reaction rates [/s]	Uncertainty [%]
^{197}Au (n, γ)^{198}Au	1.29×10^{-5}	0.63
^{115}In (n, γ)^{116m}In	5.22×10^{-6}	0.17
^{64}Zn (n, γ)^{65}Zn	9.88×10^{-8}	8.34
^{68}Zn (n, γ)^{69m}Zn	1.52×10^{-8}	2.15
^{115}In (n, n')^{115m}In	1.76×10^{-7}	2.58
^{64}Zn (n, p)^{64}Cu	1.66×10^{-8}	10.5
^{27}Al (n, p)^{27}Mg	7.49×10^{-11}	3.83
^{27}Al (n, α)^{24}Na	2.29×10^{-11}	1.79
^{28}Si (n, p)^{28}Al	7.62×10^{-11}	9.01
^{64}Zn (n, 2n)^{63}Zn	2.73×10^{-11}	31.0

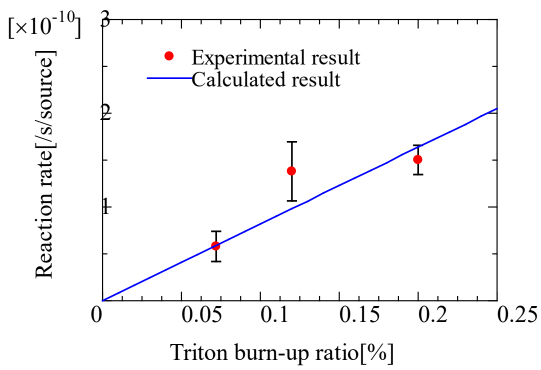

Fig. 3 Relationship between Triton burn-up ratio and reaction rate for the ^{28}Si (n, p) ^{28}Al reaction

The unfolding process using SAND-II does not directly provide the result of uncertainty. Therefore, we estimated how much the uncertainty of the reaction rate obtained from the experiment influences the unfolding result. First, the data of reaction rate was randomly generated with the Gaussian distribution whose average value is the reaction rate for each activation reaction. Then, the unfolding was performed. After this operation was repeated 1000 times, we confirmed how extent the values fluctuated in each energy bin. The relative standard deviation of the variation of the unfolding result is shown in Figure 5. Up to the energy range of 2.45 MeV generated by DD reaction, the relative standard deviation was less than 20%, which is relatively small. On the other hand, the relative standard deviation of the energy range above 2.45 MeV was over 50% and it is considerably large. Although the uncertain component is large in the range of several MeV fast neutrons due to small amount of DT neutron, reliable results could be obtained up to the energy range of 2.45 MeV.

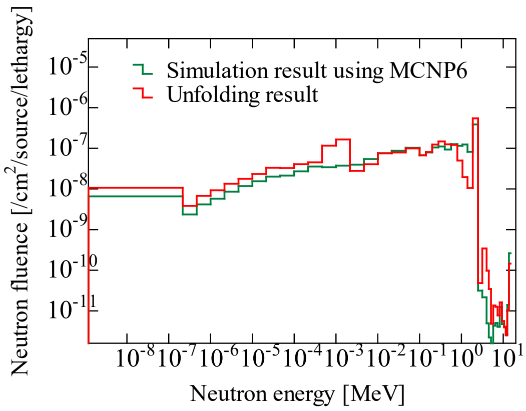

Fig. 5 Unfolded neutron spectrum with SAND-II and calculated spectrum with MCNP6

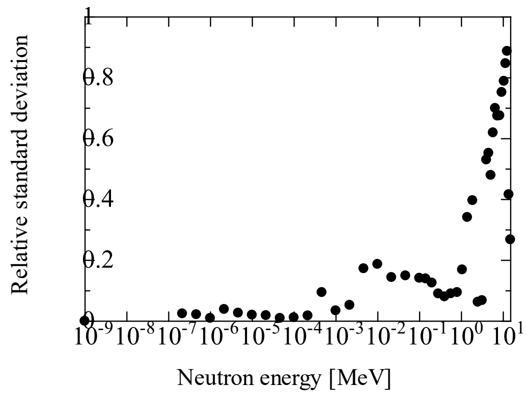

Fig. 4 The relative standard deviation of the variation of the unfolding result in each energy bin

4. Conclusion

A multi-foil activation method was applied to NIFS deuterium experiments in the vacuum vessel of the LHD to experimentally obtain the neutron spectrum. Compared with the simulation result by MCNP 6 that has been conventionally used, the experimental result was generally consistent within the range of an order. In detail, the simulation result was smaller than the experimental result at 10^{-2} MeV or lower region. On the other hand, it was roughly match in the energy range of fast neutrons. In addition, neutrons due to secondary DT reaction could also be confirmed by using activation foil with the reaction threshold energy, but the amount of neutron generated by DT reactions was much smaller than neutron by DD reaction. Therefore, it was difficult to obtain sufficient γ-ray counts and the uncertain component became large. Although it was found that the uncertainty of the unfolding result was large in the high-energy range, the neutron energy spectrum could be obtained in widely energy range.

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