Optimization of Experimental System Design for Benchmarking of Large Angle Scattering Reaction Cross Section at 14 MeV Using Two Shadow Bars*)

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At 14 MeV, it is known that the absolute value of large angle scattering cross section is small. The contribution is thus thought to be neglected in the neutronics design of fusion reactor. However, in case that a neutron source can be regarded as a beam like a neutron streaming, large angle scattering cross sections might affect the nuclear design result largely. In fact, in fusion neutronics benchmark experiments using a neutron beam so far, there was a difference observed between experiment and simulation. Also it is known that there are differences in large angle scattering cross sections among nuclear data libraries. Then we have been carrying out preliminary benchmark experiments for verification of large angle scattering reaction cross sections of iron for a few years. The purpose of the present study is to optimize the experimental system design to realize an accurate benchmarking of large angle scattering reaction cross sections. Finally, we reached the optimized experimental system and developed the experimental procedure which was supposed to perform more accurate benchmark experiments for large angle scattering reaction cross sections.

Keywords: nuclear data library, neutron scattering reaction, fusion reactor, shadow bar, fusion neutronics

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1. Introduction

The reaction cross section of iron which is used as the main structural material is important in neutronics design of fusion reactor. However, because the large angle scattering reaction cross section is known to be small among reaction cross sections of iron, it was thought that the contribution in the result of transport calculation was small. On the other hand, it is reported that when the structure becomes as large as the fusion reactor, the activation or exposure dose in the deeper places by like neutron streaming could be affected by the effect of the large angle scattering reaction [1]. As in the previous research, Ohnishi carried out fusion neutronics benchmark experiments of iron using a DT neutron beam and examined the effect of the large angle scattering reaction [2]. The experimental system is shown in Fig. 1.

Collimated beam neutrons were bombarded to the center of the iron assembly. In the assembly, six activation foils ($4 \times 4 \times 0.6\,\mathrm{cm}^3$, niobium and indium) were arranged at positions shown in Fig. 1 to confirm how neutrons are scattered by measuring the radioactivities of them. The C/E value of each activation foil is shown in Fig. 2. The

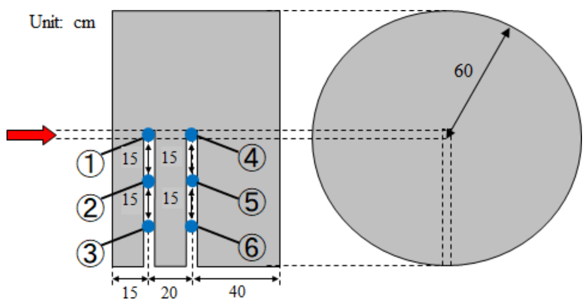

Fig. 1 The experimental system of fusion neutronics benchmark experiment.

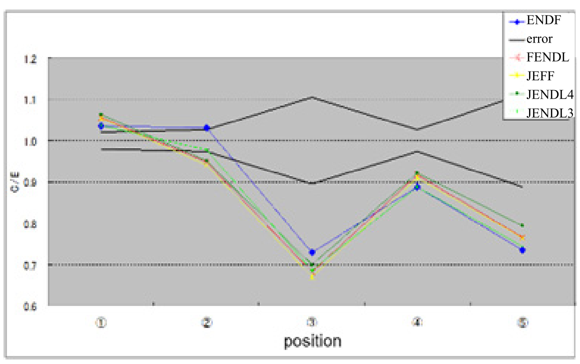

Fig. 2 The result of fusion neutronics benchmark experiment.

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activation foil which was placed in a deep and off-center position, especially foils 3 and 5, shows a disagreement between calculation and experiment. We thought that this disagreement could be due to the uncertainty of large angle scattering reaction cross section.

Neutron elastic scattering reaction cross sections are included in all neutron transport nuclear data libraries. However, it is known that there are differences in large angle scattering cross section among them even in the case of iron as shown in Fig. 3. Under these circumstances, it would be an important task to examine a hypothesis that the differences observed in the previous research by Ohnishi would really be due to the uncertainty of the large angle scattering cross section.

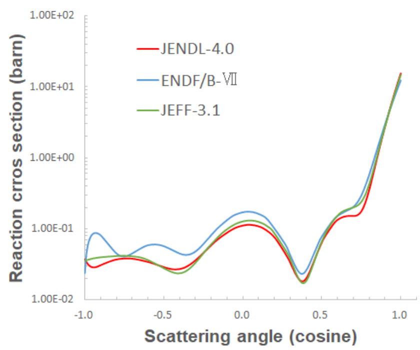

Fig. 3 Angular distribution of neutron elastic scattering of 56 Fe [3–6].

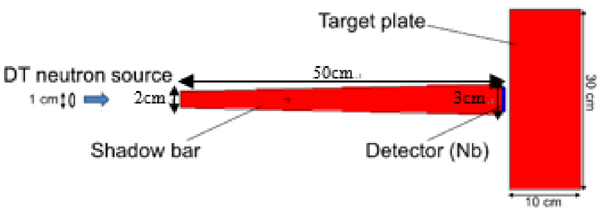

Fig. 4 Schematic experimental arrangement in previous study [6].

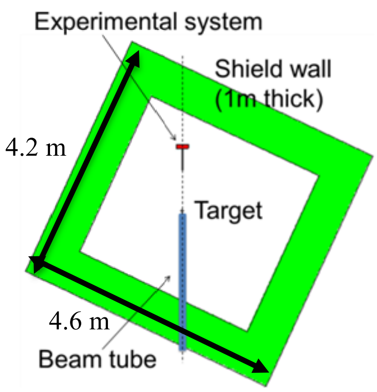

Fig. 5 Experimental arrangement in the heavy irradiation room in OKTAVIAN, Osaka University.

Then we have been carrying out preliminary numerical experiments for verification of large angle scattering reaction cross sections of iron for a few years and optimized an experimental system numerically assuming an isotropic neutron source and a shadow bar with MCNP-5[7]. The experimental system is shown in Fig. 4. Using this experimental system, we can suppress the contribution of neutrons other than large angle scattered neutrons to be less than 2%. We verified theoretically that we can carry out an accurate benchmark experiment.

This experimental system was designed assuming it was in an ideal surrounding where the wall is far enough from the experimental system. However, the heavy irradiation room in OKTAVIAN, Osaka University where we will carry out our experiment is relatively small as shown in Fig. 5 ($4.2 \times 4.6 \times 4.2\,\mathrm{m}^3$). We thus have to consider the room-return neutrons because the wall of heavy irradiation room is near to the experimental system. The aim of the present study is to design an optimized experimental system and develop an experimental procedure using two shadow bars to benchmark the large angle scattering cross section even in a finite irradiation room.

2. Experimental System Design Procedure

According to the discussion in Chap. 1, we designed the experimental system in order to extract the contribution of large angle scattering reaction especially for iron. In the simulation, MCNP-5 was used as a calculation code and JENDL-4.0, ENDF/B-VII and JEFF-3.1 were used as nuclear data libraries. As a result of physical considerations, the basic experimental arrangement was decided as shown in Fig. 6. S1 is a shadow bar which we used in our previous study. However, the contribution of room-return neutrons was too large to determine the contribution of large angle scattered neutrons accurately. Then we designed a shadow bar S2 to be used with S1 to remove the contribution of room-return neutrons and to extract that of large angle scattering.

In this experiment, the two shadow bars play an important role to suppress direct incidence of 14 MeV DT neutrons. In addition, shadow bar S1 measures all the con-

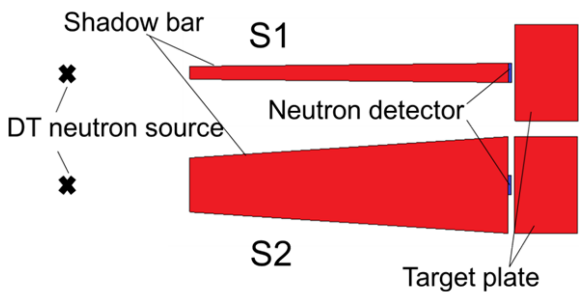

Fig. 6 Present schematic experimental arrangement.

tributions of neutrons except direct incidence. It means it also includes contribution of large angle scattered neutrons. On the other hand, S2 suppresses all the neutrons from the neutron source in order to measure only the contribution of room-return neutrons. The thickness of an iron target plate is set to be thin (as thin as 2 mean free path) so that neutrons scattered to forward directions can mostly go through the target plate. The large angle scattered neutrons in the plate are incident to a niobium foil, which is placed just behind the shadow bar, in order to count large angle scattered neutrons. The induced radioactivity is measured by a Ge detector.

2.1 Details of the experimental system

We assume the DT neutron source to be an isotropic disk neutron source (1 cm in diameter). This specification is fixed to simulate the specification of the intense 14 MeV neutron source facility, OKTAVIAN in Osaka University where we plan to carry out practical benchmark experiments.

The dimensions of the iron target plate are 15 cm in diameter and 10 cm in thickness. By making the target plate thin, i.e., around 2 mean free path, we can reduce the number of scattering reaction inside the target plate and make the contribution of the large angle scattering reaction relatively dominant.

The thickness of the niobium foil is 5 mm-thick and 3 cm in diameter. The reason why we chose niobium is that the energy threshold of ^{93}Nb(n,2n)^{92m}Nb reaction is as high as 9 MeV and also the reaction cross section is enough high as 0.464 barn. Therefore, the niobium foil can count only large angle scattered neutrons of around 13.5 MeV, having no sensitivity to neutrons moderated in the shadow bar.

The shadow bar material is iron because the macroscopic cross section at 14 MeV is large to attenuate the 14 MeV neutrons. The shadow bars are circular truncated cones and the dimensions of the shadow bar S1 are 50 cm in length, 2 cm in top diameter and 3 cm in bottom diameter and those of S2 are 50 cm in length, 8.3 cm in top diameter and 15 cm in bottom diameter. These dimensions are optimized by parameter survey calculations by MCNP-5.

The distance between the DT neutron source and the upper base of the shadow bar is also optimized as 55 cm. This distance depends on the shape of the shadow bar.

3. Simulation Result

We carried out four numerical experiments with MCNP-5 using S1 and S2. Practically, for each shadow bar, two experiments were performed with and without the target plate. The track length tally (F4) was used to calculate the reaction rate of Nb foil.

In the design, we considered six paths of neutrons to the Nb foil in order to extract the contribution of large angle scattered neutrons. The separation is shown in Fig. 7.

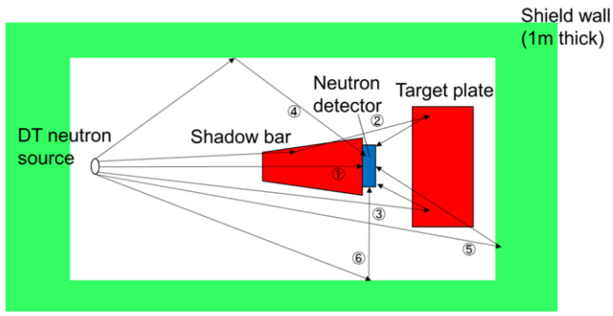

Fig. 7 Separation of the paths of neutrons.

Table 1 Reaction rate in each simulations using JENDL-4.0 (unit: 10^{-9} reaction/source neutron).

	S1it	S2it	S1nt	S2nt	S1it - S2it - (S1nt - S2nt)
①	0.02	0.12	0.01	0.12	0.01
②	0.10	0.01	0	0	0.09
③	4.04	0	0	0	4.04
④	1.01	0.57	1.02	0.56	-0.02
⑤	1.05	1.06	2.98	2.97	-0.02
⑥	0.75	0.23	0.81	0.23	-0.06
sum	6.97	1.99	4.82	3.88	4.04

Neutron No.1 only passes through the shadow bar, No.2 passes the shadow bar and reflect in the target plate, No.3 reflects only in the target plate, No.4 reflects in the wall and reach the Nb foil via the shadow bar, No.5 reflects in the wall and reach the Nb foil via the target plate and No.6 reflects only in the wall. The large angle scattered neutrons are neutron No.3 and we finally determine the contribution of neutron No.3 by the four experiments.

Table 1 shows an example of calculation summary in case of using JENDL-4.0. Suffix “it” and “nt” means experiments with and without the target plate, respectively. The numbers No.1~6 correspond to the separated path of neutrons shown in Fig. 7.

The contribution of large angle scattered neutrons (No.3) is included in the foil of S1it. However, other contributions are also contained in S1it. The other contributions can be compensated because the contributions are contained in other three foils. As a result, the contribution of large angle scattered neutrons (No.3) can finally be deduced by the four Nb reaction rates with the equation; (S1it) - (S2it) - ((S1nt) - (S2nt)). By this calculation, other contributions still remain, but these are small enough compared to that of large angle scattered neutrons as shown in Table 1. Therefore, if we carry out these four experiments, we can determine the contribution of large angle scattered neutrons by a simple calculation of the four reaction rates of Nb foil.

Next we show a calculation summary in case of using ENDF/B-VII and JEFF-3.1 in Tables 2 and 3, respectively. By these results, the contribution of large angle scattered neutrons (No.3) was 4.04×10-9, 6.26×10-9 and 3.85×10-9

Table 2 Reaction rate in each simulations using ENDF/B-VII (unit: 10^{-9} reaction/source neutron).

	S1it	S2it	S1nt	S2nt	S1it - S2it - (S1nt - S2nt)
①	0.01	0.09	0.01	0.09	0.00
②	0.23	0.03	0	0	0.20
③	6.26	0	0	0	6.26
④	0.98	0.62	1.03	0.62	-0.05
⑤	1.06	1.11	2.95	2.97	-0.03
⑥	0.74	0.24	0.80	0.23	-0.07
sum	9.28	2.09	4.79	3.91	6.31

Table 3 Reaction rate in each simulations using JEFF-3.1 (unit: 10^{-9} reaction/source neutron).

	S1it	S2it	S1nt	S2nt	S1it - S2it - (S1nt - S2nt)
①	0.01	0.10	0.02	0.10	-0.01
②	0.12	0.02	0	0	0.10
③	3.85	0	0	0	3.85
④	1.03	0.64	1.03	0.66	0.02
⑤	1.08	1.09	2.97	2.98	0.00
⑥	0.74	0.24	0.81	0.25	-0.06
sum	6.83	2.09	4.83	3.99	3.90

Table 4 Reaction rate in each experiment compared with the result of numerical experiment (unit: 10^{-9}reaction/source neutron).

	S1it	S2it	S1nt	S2nt	S1it - S2it - (S1nt - S2nt)
Experiment	8.31	1.68	6.92	3.83	3.54
JENDL-4.0	6.97	1.99	4.82	3.88	4.04
ENDF/B-Ⅶ	9.28	2.09	4.79	3.91	6.31
JEFF-3.1	6.83	2.09	4.83	3.99	3.90

(reaction/source) for JENDL-4.0, ENDF/B-VII and JEFF-3.1, respectively. The result indicates that a significant difference exists between ENDF/B-VII and others. We think we can make clear the cause of the difference by this measuring technique.

4. Experimental Result

We carried out four preliminary experiments, S1it, S1nt, S2it, S2nt at OKTAVIAN, Osaka University. Table 4 shows the experimental result compared with the results of numerical experiment using JENDL-4.0, ENDF/B-VII and JEFF-3.1.

There is a significant difference between ENDF/B-VII and others. However experiment S1nt does not have good agreement with the calculation result. We are going to carry out more accurate additional experiments.

5. Conclusion

We finally designed and optimized the experimental system and procedure for benchmarking of large angle scattering reaction cross section. In case of iron, the numerical results indicate that a significant difference exists between ENDF/B-VII and others. We think we can make clear the cause of the difference by this measuring technique.

We will carry out additional experiments to perform more accurate nuclear data benchmarking. Thereafter, we will find a way to feedback the result to the nuclear data libraries.

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