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Integral experiments on thorium assemblies with D-T neutron source

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Abstract. To validate nuclear data and code in the neutronics design of a hybrid reactor with thorium, integral experiments in two kinds of benchmark thorium assemblies with a D-T fusion neutron source have been performed. The one kind of 1D assemblies consists of polyethylene and depleted uranium shells. The other kind of 2D assemblies consists of three thorium oxide cylinders. The capture reaction rates, fission reaction rates, and (n, 2n) reaction rates in ^{232}Th in the assemblies are measured by ThO_2 foils. The leakage neutron spectra from the ThO_2 cylinders are measured by a liquid scintillation detector. The experimental uncertainties in all the results are analyzed. The measured results are compared to the calculated ones with MCNP code and ENDF/B-VII.0 library data.

1. Introduction

The fusion-fission hybrid energy reactor (FFHER) for energy production, consisting of a low-power magnetic confinement fusion device and a blanket with subcritical fuel region, is one of advanced reactors of applying fusion technologies to solve the present energy crisis [1]. With the development of blanket technology, it is considered that thorium could be put in the blanket and used to breed ^{233}U by ^{232}Th capture reaction. Some conceptual blankets of FFHER based on the Th/U fuel cycle were designed [2]. The accuracy and reliability of evaluated nuclear data of thorium decide the validity of the physical design of the thorium-based blanket directly. Only a small number of integral neutronics experiments determining the ^{232}Th reaction rates are available in the literatures, and furthermore for some cases large differences between calculations and experiments can be observed [3]. In conceptual design stage, it is essential to perform the experiments for validating nuclear data and code [4].

The integral experiments on the thorium assemblies with a D-T neutron source have been performed in INPC [5–9]. In this paper, the progress in the integral experiments on representative assemblies is described. The ^{232}Th reaction rates in the assemblies and leakage neutron spectra are measured, separately. The measured results are compared to ones by using MCNP code with ENDF/B-VII.0 library data.

2. Thorium assemblies

Aiming at researching on the nuclear data of thorium, the ways for establishing the assemblies are that the experiment is feasible for benchmark check and the material and neutron spectra are relevant to the conceptual design. The assemblies are classified as shells based on available materials and thorium oxide (ThO_2) cylinders.

2.1. Polyethylene shell

A polyethylene shell (PE), requiring only the use of standard cross sections H(n,n) and C(n,n) for interpretation of the results, is used for measuring the ^{232}Th reaction rates. The inner radius (IR) and the outer radius (OR) of the PE shell with density of 0.95 g/cm^3 are 80 and 230 mm, respectively. The schematic diagram of the experimental assembly is shown in Fig. 1. Five slices of ThO_2 (concentration>99.95%) foils are put in the radial channel at the 0° direction to the incident D^+ beam. The mass and size of foils are about 4.2 g and φ30 mm×1 mm.

A D-T fusion neutron source is located at the center of the assembly. The energy of D^+ ions is 225 keV and 14-MeV neutrons are produced by D^+ beam bombarding a TiT Target. The yield of the source is about 3×10^{10} neutrons/s. The absolute yield is measured by the associated α particle method [10]. An Au-Si surface barrier semiconductor detector is at 178.2^0 to D^+ beam in drift tube and used to measure the yield with LabVIEW-based auto-timing counter [11].

2.2. Depleted uranium shell

A depleted uranium (DU) shell in which fission nuclides are relevant to the fuel in the blanket [1] is adopted. The IR/OR of the DU (∼99.6% ^{238}U, ∼0.4% ^{235}U) shell is 131 mm/300 mm. The schematic diagram of the experimental assembly is shown in Fig. 2. Six slices of ThO_2 samples are put in the radial channel at a 90° direction to the incident D^+ beam. The ThO_2 sample as a foil is that ThO_2 powder is filled in a plexiglass box with inner diameter of 18 mm and outer diameter of 19 mm. The mass of ThO_2 powder is about 0.45 g and the thickness is about 0.7 mm.

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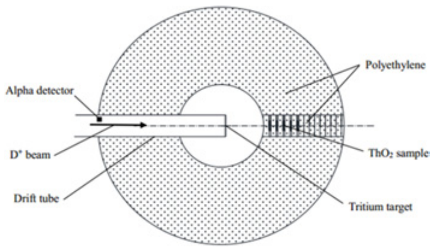

Figure 1. Polyethylene shell assembly.

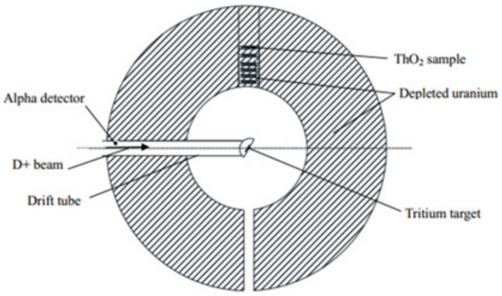

Figure 2. Depleted uranium shell assembly.

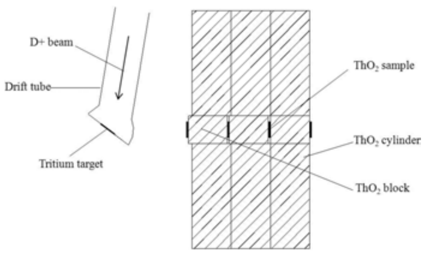

Figure 3. ThO_2 cylindrical assembly.

2.3. ThO_2 cylinders

The ThO_2 benchmark assembly with the thickness of 150 mm is established and consists of three ThO_2 cylinders with the thickness of 50 mm and the diameter of 300 mm. The density and ingredient of these cylinders are described in Ref. [7]. The schematic diagram of ThO_2 cylindrical assembly is shown in Fig. 3. The front surface of the assembly is 113 mm from the center of a target. Four slices of the ThO_2 sample as described above are put in axial channel of the assembly.

3. Results

3.1. ^{232}Th reaction rates in polyethylene shell

The neutron induced reactions of ^{232}Th investigated are ^{232}Th(n, γ), ^{232}Th(n,f) and ^{232}Th(n,2n). The ^{232}Th reaction rates are obtained by using foil activation technique and an HPGe γ spectrometer, and normalized to one source neutron and one ^{232}Th atom, as shown in Fig. 1.

The fertile nuclide ^{232}Th(n,γ)^{233}Th capture reaction rate (THCR) indicates breeding of fissile fuel ^{233}U. THCR by measuring 311.98 keV γ rays emitted from ^{233}Pa (half-life 26.967 d, from ^{233}Th decay), i.e., the production rate of ^{233}U (^{233}Pa decay), can be deduced [5,6].

The ^{232}Th(n,f) (threshold 0.7 MeV) fission reaction rate (THFR) indicates energy amplification and neutron multiplication. THFR is obtained by using the fragment yield correction method. To estimate total fission rate, 151.16 keV γ rays emitted from ^{85m}Kr decay (half-life 4.48 hr) which is one of the fragments of ^{232}Th(n,f) reaction are measured [7].

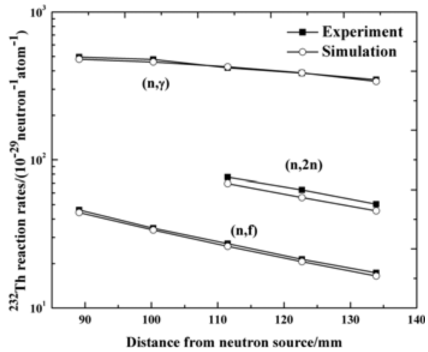

Figure 4. ^{232}Th reaction rates in PE shell.

The ^{232}Th(n,2n)^{231}Th (threshold 6.5 MeV) reaction rate (THNR) indicates neutron multiplication. THNR is obtained by measuring 84.2 keV γ rays emitted from ^{231}Th (half-life 25.52 hr) [8].

The ^{232}Th reaction rates are deduced from the measured activity by performing the appropriate corrections, which include fluctuations of the neutron flux during irradiation, detection efficiency, self-absorption of gamma ray in the foils, counting statistics and cited value of branching ratio. The experimental uncertainties are 3.0% for THCR, 5.3% for THFR and 6.8% for THNR.

THCR, THFR and THNR are calculated by using MCNP code with ENDF/B-VII.0 library data. The model is completely consistent with the structure and ingredient of the assembly contained the target chamber and experimental hall. The angular dependences of the source neutron energy and intensity are calculated by "DROSG-2000" code [12]. The S (α, β) thermal scattering model in PE is considered. The calculated statistical uncertainty is less than 1%. The ratio range and average values of calculation to experiment (C/E) are 0.96 $\sim$ 1.02 and 0.99 for THCR, 0.98$\sim$1.0 and 0.99 for THFR, and 0.89 $\sim$ 0.91 and 0.90 for THNR. The results state that both for THCR and THFR is well consistent within the range of experimental uncertainties, and calculations for THNR underestimate about 10%. It is showed that the γ-ray off-line method is feasible for determining the ^{232}Th reaction rates. The distributions of ^{232}Th reaction rates by the experiments and calculations are shown in Fig. 4.

The reaction rate ratio of ^{232}Th capture to fission gives fissile production rate in unit of fuel burn-up [9]. The relative ratios measured are about 10.76–20.17 with the increase of radius in PE shell.

3.2. ^{232}Th reaction rates in depleted uranium shell

The ^{232}Th reaction rates in DU shell are measured by the same method as described above and shown in Fig. 2. The experimental uncertainties are 3.1% for THCR, 5.3% $\sim$ 5.5% for THFR [8,9] and 6.8% for THNR. The ^{232}Th reaction rates are calculated by using MCNP code with ENDF/B-VII.0 library data. The range and average values of C/E are 0.97 $\sim$ 1.04 and 1.02 for THCR, 0.95 $\sim$ 1.02 and 0.98 for THFR [7,9], and 1.07 $\sim$ 1.12 and 1.10 for THNR, respectively. The results state that the calculations and experiments are well consistent within the range of

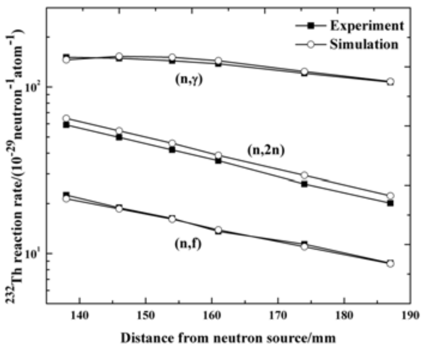

Figure 5. ^{232}Th reaction rates in depleted uranium shell.

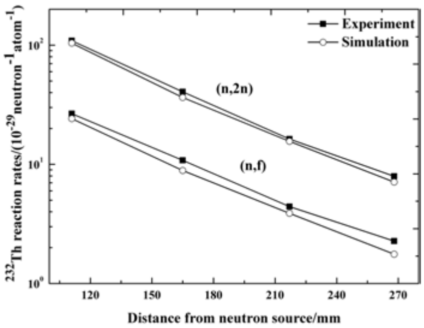

Figure 6. ^{232}Th reaction rates in ThO_2 cylinder.

experimental uncertainties, except overestimating about 10% for THNR. The ratio of ^{232}Th capture to fission are about 6.71 ∼ 12.23 with the increase of radius in DU shell. The ^{232}Th reaction rates by the experiments and calculations are shown in Fig. 5.

3.3. Integral experiment in ThO_2 cylinders

3.3.1. ^{232}Th reaction rates

The ^{232}Th(n,f) and ^{232}Th(n,2n) reaction rates in the ThO_2 cylinder are measured by the same method as described above and shown in Fig. 3. The experimental uncertainties are 5.3% ∼ 5.5% for THFR and 7.1% for THNR [8]. The ^{232}Th reaction rates are calculated by using MCNP code with ENDF/B-VII.0 library data. The range and average values of C/E are 0.77 ∼ 0.91 and 0.85 for THFR, and 0.92 ∼ 1.0 and 0.96 for THNR [9], respectively. The results state that the calculations generally underestimate the experiments for THFR. The ^{232}Th reaction rates by the experiments and calculations are shown in Fig. 6.

3.3.2. Leakage neutron spectra

The neutron spectra leaking from the ThO_2 cylinders are measured by the proton recoil method [4]. A 50.8 mm diameter and 50.8 mm length BC501A liquid scintillator coupled to a 50.8 mm diameter 9807B photomultiplier of is used to measure recoil proton spectrum. The n-γ pulse shape discrimination is based on the cross-zero method. The spectra are resolved by using iterative method, and their range is from 0.5 MeV to 16 MeV. The detector is arranged in shielding room and at a 0^0 direction to incident D^+ ion beam. The front surface of the assembly is 220 mm from the center of a target. The distance is 10.75 m from the detector to the neutron source. The

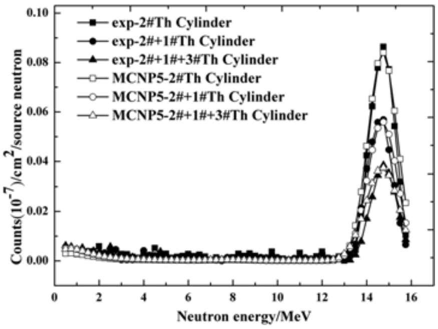

Figure 7. Leakage neutron spectra from ThO_2 cylinders.

affect of background neutrons is negligible. The spectra from the three assemblies with thicknesses of 50, 100 and 150 mm are measured, respectively, as shown in Fig. 3. The results are normalized to one source neutron and unit area. The experimental uncertainties are 9.7% for 0.5–1 MeV, 6.7% for 1–3 MeV and 6.3% for 3–16 MeV. The spectra are calculated by using MCNP code with ENDF/B-VII.0 library data. The results state that the experiments and calculations are generally consistent within the range of experimental uncertainties, and the spectra (<5 MeV) should be analyzed further, as shown in Fig. 7.

4. Conclusions

To validate nuclear data and code in the neutronics design of blanket with thorium in FFHER, the integral experiments in the thorium assemblies with a D-T neutron source have been performed. The spherical assemblies based on available DU and PE shell, and the ThO_2 cylinders are established. The distributions of ^{232}Th capture, fission and (n,2n) reaction rates in the assemblies are measured, respectively. The leakage neutron spectra from ThO_2 cylinders are measured. The experiments are compared to the calculations by using MCNP code with ENDF/B-VII.0 library data. The results state that the activation approach developed can work well for the experiments, and the ^{232}Th reaction rates are relevant to neutron spectra in assemblies. It is suggested that the integral experiments in a thorium assembly should be conducted further, and relevant cross section of ^{232}Th should be measured at CSNS white neutron source [13] in the future.

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