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Fusion Neutronics Experiments for Thorium Assemblies

Rong Liu

Abstract

Thorium is a fertile element that can be applied in the conceptual blanket design of a fusion-fission hybrid energy reactor, in which ^{232}Th is mainly used to breed ^{233}U by capture reaction. It is essential to validate ^{232}Th nuclear data by carrying out integral fusion neutronics experiments for macroscopic thorium assemblies. The thorium assemblies with a D-T fusion neutron source consist of a polyethylene shell, depleted uranium shell, and thorium oxide cylinder. The activation of γ-ray off-line method for determining the thorium reaction rates is developed. The ^{232}Th(n, γ), ^{232}Th(n, f), and ^{232}Th(n, 2n) reaction rates in the assemblies are measured by using ThO$_2$ foils and an HPGe γ spectrometer. From ^{232}Th reaction rates, the fuel and neutron breeding properties of thorium under different neutron spectra are obtained and compared. The leakage neutron spectra from the ThO$_2$ cylinders are measured by a liquid scintillation detector. The experimental uncertainties are analyzed. The experiments are simulated by using the MC code with different evaluated data. The ratios of calculation to experimental values are analyzed.

Keywords: neutronics experiment, D-T fusion, thorium assembly, ^{232}Th reaction rate, neutron spectra, MC simulation

1. Introduction

The fusion-fission hybrid energy reactor, consisting of a low-power magnetic confinement fusion assembly and a subcritical blanket, is one of the advanced reactors of applying fusion technology to solve the present energy crisis. Natural thorium contains one isotope ^{232}Th. Thorium is a fertile element that can be applied in the conceptual blanket design of a fusion-fission hybrid reactor [1, 2]. The actual neutron spectrum in the subcritical blanket based on the Th/U fuel cycle is composed of fast and thermal spectra. The ^{232}Th capture cross section at fast neutron is slightly larger than that of ^{238}U, and ^{232}Th is more suitable to breed ^{233}U under fast spectrum. Since ^{232}Th capture cross section for thermal neutron is about 2.7 times larger than that of ^{238}U, the conversion rate in the Th/U fuel cycle is more than that in the U/Pu fuel cycle and the neutron economy of thorium is better. Moreover, the ^{233}U capture cross section for thermal neutron is smaller than that of ^{239}Pu and ^{233}U needs to absorb neutrons many times to produce Pu and long-life Minor Actinides (MA, such as ^{237}Np, ^{241}Am, and ^{242}Cm), whereas Pu and MA produced in the Th/U fuel cycle are one order of magnitude less than those in the U/Pu fuel cycle. Therefore, the Th/U fuel cycle is beneficial to reduce the long-life nuclear waste and prevent nuclear proliferation. The feasibility and reliability of the physical

design for the subcritical blanket based on thorium depend on the accuracy of ^{232}Th nuclear data and calculational tool. It is essential to carry out the fusion neutronics experiments for validating the evaluated ^{232}Th nuclear data and studying the breeding properties.

A small number of fusion neutronics experiments on thorium were carried out, and there exist essential differences between the calculations and experiments [3–5]. The ^{232}Th fission rate with fast neutrons was determined by detecting the gamma rays emitted from ^{140}Ba and ^{140}La, and the calculated-to-experimental ratio was 0.9 based on ENDF/B-IV [4]. The thorium fission reaction rate in a metallic sphere setup was determined by absolute measurement of the gamma-emission from ^{143}Ce, the experimental uncertainty was 5.2%, and the calculation to experiment ratio was 1.17 employing ENDF/B-IV [5].

The integral fusion neutronics benchmark experiments for macroscopic thorium assemblies with a D-T fusion neutron source were carried out at Institute of Nuclear Physics and Chemistry (INPC) [6–17]. The method for measuring integral ^{232}Th reaction rate and its application in an experimental assembly were developed and investigated [6–8]. In this chapter, the progress in the fusion neutronics experiments for thorium assemblies is described. The overview of main results is presented. The thorium assemblies with a D-T fusion neutron source consist of a polyethylene shell, depleted uranium shell, and thorium oxide cylinder. The ^{232}Th reaction rates in the assemblies and leakage neutron spectra are measured separately. The benchmark experiments on fuel and neutron breeding properties derived from the ^{232}Th reaction rates in representative thorium assemblies are carried out and analyzed. The breeding properties are valuable to the breeding ratio in the conceptual design of subcritical blanket based on the Th/U fuel cycle. The experimental results are simulated by using the MC code with different evaluated data. The ratios of calculation to experimental values are analyzed.
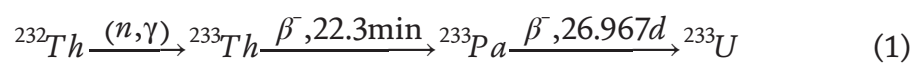

2. Methods

The fusion neutronics experiments contain the measurements of the ^{232}Th(n,γ), ^{232}Th(n, f), and ^{232}Th(n,2n) reaction rates, and the neutron spectra for thorium assemblies with a D-T fusion neutron source.
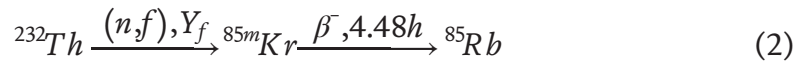
2.1 ^{232}Th reaction rates

The experimental method of activation of γ-ray off-line measurement of ^{232}Th reaction rates is used. The activation γ-rays are measured by using an HPGe γ spectrometer.

The ^{232}Th capture reaction rate (THCR) indicates the fuel breeding, that is, the production rate of fissile ^{233}U (^{233}Pa decay). THCR can be deduced by measuring 311.98 keV γ rays emitted from ^{233}Pa [6, 7]. The reaction process is as follows:

$$^{232}Th \xrightarrow{(n,\gamma)} {}^{233}Th \xrightarrow{\beta^-, 22.3min} {}^{233}Pa \xrightarrow{\beta^-, 26.967d} {}^{233}U \tag{1}$$

The ^{232}Th fission (with threshold of 0.7 MeV) reaction rate (THFR) indicates energy amplification and neutron breeding. The fission fragment yield correction method is used [8]. THCR can be deduced by measuring 151.16 keV γ rays emitted from the decay of ^{85m}Kr from ^{232}Th (n, f) reaction. The reaction process is as follows:

$$^{232}Th \xrightarrow{(n,f), Y_f} {}^{85m}Kr \xrightarrow{\beta^-, 4.48h} {}^{85}Rb \qquad (2)$$

The ^{232}Th(n,2n) ^{231}Th (with threshold of 6.5 MeV) reaction rate (THNR) indicates neutron breeding. THNR is obtained from measuring 84.2 keV γ rays emitted from ^{231}Th [9]. The reaction process is as follows:

$$^{232}Th \xrightarrow{(n,2n)} {}^{231}Th \xrightarrow{\beta^-, 25.52h} {}^{231}Pa \qquad (3)$$
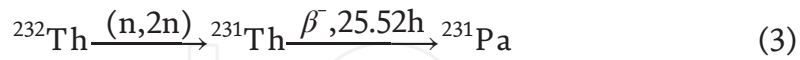
The ^{232}Th reaction rates are deduced from the measured activity and corrections, which include detection efficiency of the HPGe γ spectrometer, cited value of branching ratio, D-T neutron yield during irradiation, self-absorption of gamma rays in the foils, ^{85m}Kr yield only for THFR, etc. The ^{232}Th reaction rates are normalized to one source neutron and one ^{232}Th atom.

2.2 Breeding properties

The breeding ratio in the conceptual design of subcritical blanket is more than one [1]. The experiment on breeding properties of thorium is used to support the design [17]. The breeding properties are relevant to the reaction type, cross section, and neutron spectrum. The breeding properties contain the fuel breeding and neutron breeding. The fuel breeding is derived from the reaction rate ratio of ^{232}Th capture to fission, and neutron breeding from the ^{232}Th(n,2n) and fission reaction rates. The different neutron spectra are constructed by using the macroscopic assemblies in which the material is relevant to that of the conceptual design. The breeding properties under different assemblies are obtained and analyzed from the measured ^{232}Th reaction rates.

2.3 Neutron spectra

The neutron spectra leaking from the ThO$_2$ cylinders of different thickness are measured by the proton recoil method and the liquid scintillator [16]. 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 to 16 MeV.

3. Assemblies

The experimental assemblies are composed of polyethylene shell, depleted uranium shell, and ThO$_2$ cylinder with a D-T fusion neutron source and thorium samples.

3.1 Polyethylene shell

One can assume the elastic scattering cross sections of H and C, which are widely used as standard cross sections [18] to be reliable. The polyethylene (PE) shell is adopted for checking the method of measuring the ^{232}Th reaction rates. The inner radius (IR) and the outer radius (OR) of the PE shell are 80 and 230 mm [11], respectively. Five slices of ThO$_2$ (concentration > 99.95%) foils are put in the radial channel at 0° to the incident D$^+$ beam, as shown in **Figure 1**. The mass and size of foils are about 4.2 g and φ30 × 1 mm, respectively.
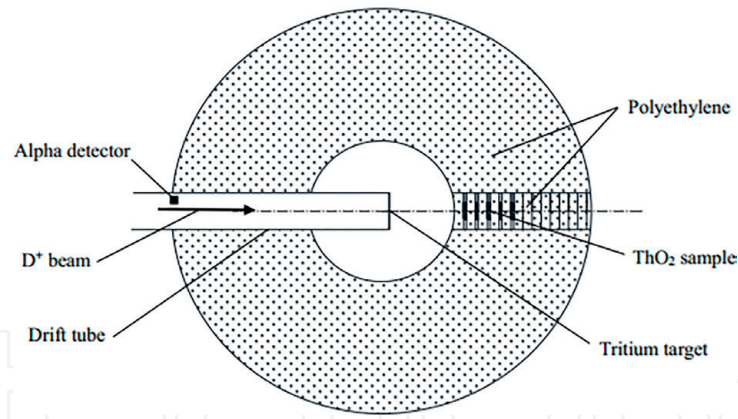
Figure 1.
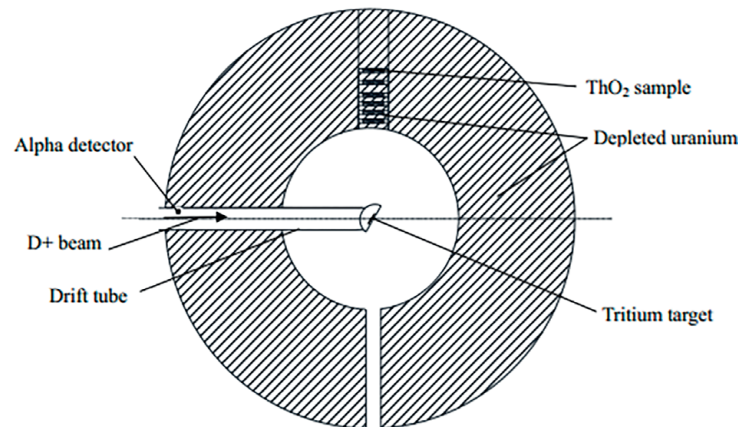*Polyethylene shell assembly.*

Figure 2.
Depleted uranium shell assembly.

A D-T fusion neutron source is located in the center of the shell. The 14 MeV neutrons are produced by a neutron generator at INPC. The energy of D^+ beam bombarding a T-Ti target is 225 keV. An Au-Si surface barrier semiconductor detector is at an angle of 178.2° to the incident D^+ beam in the drift tube and used to measure the absolute yield by counting associated α particles [19, 20]. D-T neutron yield is about 3×10^{10}/s.

3.2 Depleted uranium shell

In the conceptual design of a subcritical blanket based on thorium, the neutrons from the U reaction process are used to maintain the Th/U fuel cycle. The depleted uranium (DU) shell is adopted for studying Th reaction. The IR/OR of the DU shell is 131/300 mm [12]. Six slices of ThO_2 samples are put in the radial channel at 90° to the incident D^+ beam, as shown in **Figure 2**. ThO_2 samples are foils made from ThO_2 powder filling a plexiglass box with IR/OR of 9/9.5 mm. The mass of ThO_2 powder is about 0.45 g, and the thickness is about 0.7 mm. The D-T neutron source is located in the center of the shell.

3.3 ThO₂ cylinders

3.3.1 ThO₂/DU cylinders

The thorium oxide (ThO_2) cylindrical assembly with the thickness of 150 mm is produced and consists of three ThO_2 cylinders with the thickness of 50 mm and the

diameter of 300 mm. The ThO_2 cylinders are made by pressing ThO_2 powder using PEO (CH_2CH_2O) as the binder and their densities are 4.25–5.59 g/cm^3 [9, 10]. The structure of the ThO_2 cylinders as benchmark is simple. To change neutron spectra in ThO_2 cylinders, the latter can be combined with DU cylinders. The combination of two ThO_2 cylinders and one DU cylinders is shown in **Figure 3**. Three slices of the ThO_2 samples are put in axial channel of the assembly. The front surface of the assembly is 113 mm from the center of a tritium target.

3.3.2 ThO_2 powder cylinder

Based on thorium oxide powder, the ThO_2 assembly is produced, as shown in **Figure 4** [13–15]. ThO_2 powder fills a stainless steel/aluminum cylinder container with IR/OR of 93.4/96.2 mm. The height of the ThO_2 cylinder is 168.9 mm and the density 1.5 g/cm^3. Five pieces of ThO_2 foils are put at 0° to the incident D$^+$ beam and fixed using holders consisting of aluminum plate and stainless steel. The mass and size of ThO_2 foils are about 5.0 g and ϕ30 × 1 mm, respectively. The distance between the tritium target center and the front end of the cylinder is 78.8 mm.

3.4 Neutron spectra in three assemblies

The neutron spectra in PE, DU, and ThO_2 assemblies are simulated by using the MCNP4B code [21] with ENDF/B-VII.0 [22], in which the S (α, β) thermal scattering model in PE is considered. The angular dependences of the source neutron
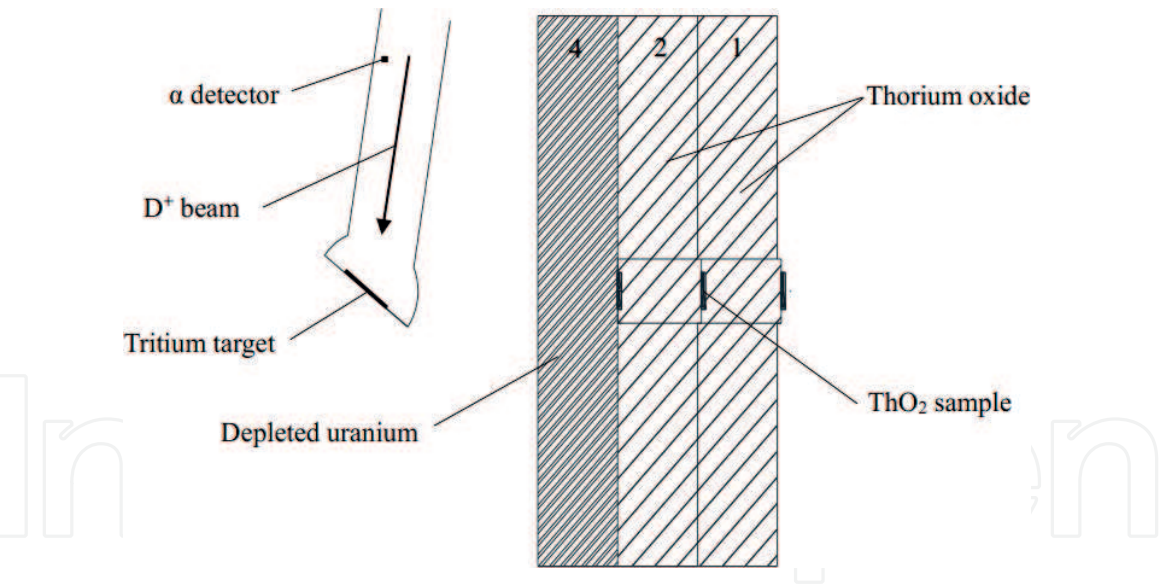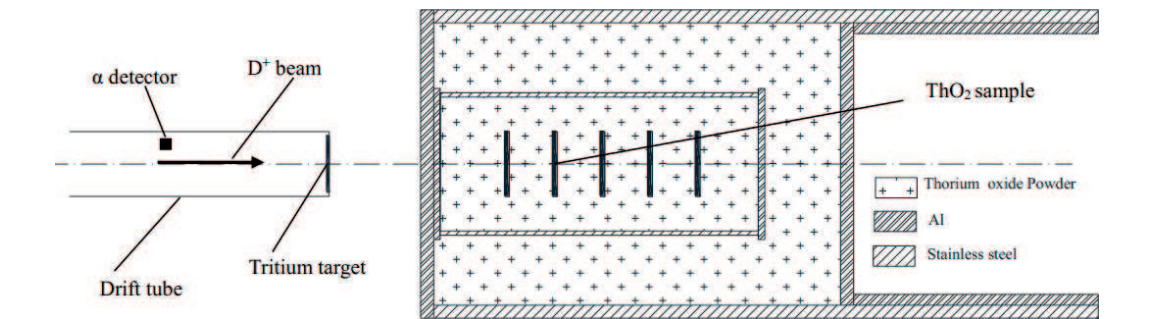

Figure 3.
ThO_2/DU assembly.

Figure 4.
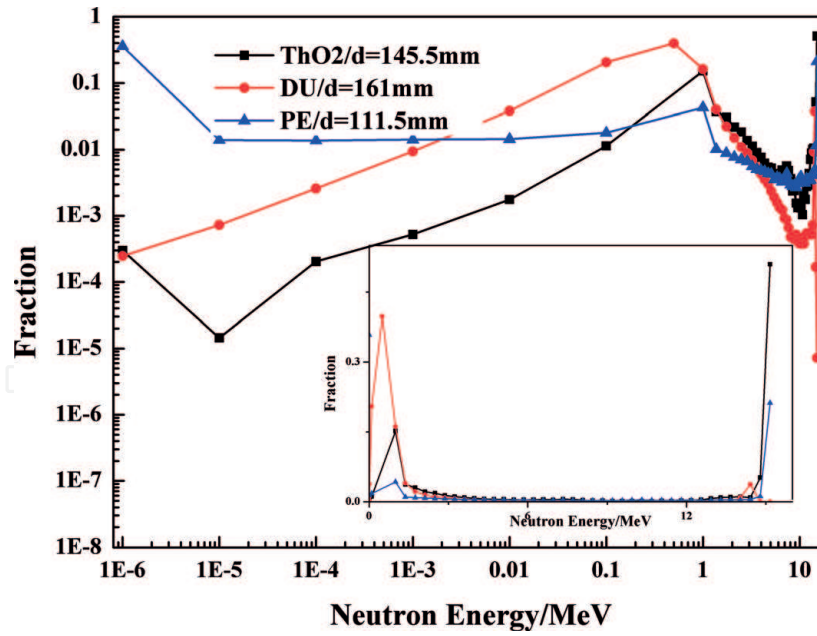*ThO_2 powder cylindrical assembly.*

Figure 5.
Neutron spectra at foils in three assemblies.

energy and intensity are calculated by "DROSG-2000" code [23]. The neutron spectra at foils with different distances *d* to the neutron source in three assemblies are relatively compared, as shown in **Figure 5**. The ordinate is a normalized neutron fraction, that is, the proportion of the neutron number in each energy segment to the one in the whole energy range [11, 13]. The results show that the differences of the fractions are very obvious, especially in the low-energy region.

4. Results

4.1 ^{232}Th reaction rates in PE shell

The PE shell assembly for measuring ^{232}Th reaction rates is shown in **Figure 1**. THCR is deduced from measuring 311.98 keV γ rays emitted from ^{233}Pa (its half-life is 26.967 days, it is obtained from ^{233}Th decay). THFR is deduced from measuring 151.16 keV γ rays emitted from ^{85m}Kr decay (its half-life is 4.48 hour), which is one of the fragments of ^{232}Th(n,f) reaction, and using the fragment yield correction method. THNR is deduced from measuring 84.2 keV γ rays emitted from ^{231}Th (its half-life is 25.52 hour).

The experimental uncertainty of THCR is 3.1%, including neutron yield 2.5%, γ-ray detection efficiency 1.0% (HPGe-GEM 60P), self-absorption 1.0%, characteristic gamma branch ratio 1.0%, ^{232}Th nucleus number 0.5%, and counting statistics 0.3–0.6%.

The experimental uncertainty of THFR is 5.3%, including neutron yield 2.5%, γ-ray detection efficiency 1.0%, self-absorption 1.0%, average fission yield of ^{85m}Kr 4.3%, characteristic gamma branch ratio 0.7%, ^{232}Th nucleus number 0.5%, and counting statistics 0.8–1.0%.

The experimental uncertainty of THNR is 6.8%, including neutron yield 2.5%, γ-ray detection efficiency 1.0%, self-absorption 1.0%, characteristic gamma branch ratio 6.1%, ^{232}Th nucleus number 0.5%, and counting statistics 0.5–0.6%.

The experiment is simulated by using the MCNP code with evaluated nuclear data from different libraries, including ENDF/B-VII.0, ENDF/B-VII.1 [24] and JENDL-4.0 [25]. The model is completely consistent with the structure of the

assembly; it takes into account the target chamber and experimental hall. The calculated statistical uncertainty is less than 1%. The ranges of C/E with ENDF/B-VII.0 are 0.96–1.02 for THCR, 0.95–0.97 for THFR, and 0.89–0.91 for THNR. The results show that the experiment and calculation for THCR and THFR are well consistent within the range of experimental uncertainties, respectively. It is shown that the γ-ray off-line method is feasible for determining the ^{232}Th reaction rates.

The distributions of ^{232}Th reaction rates obtained from the experiments and calculations with ENDF/B-VII.0 are shown in **Figure 6**. The reaction rate ratio of ^{232}Th capture to fission gives fissile production rate in unit of fuel burn-up [12]. The relative ratios measured are about 10.76–20.17 with the increase of radius in PE shell.

The ratios of calculation to experimental values (C/E) are analyzed. The C/E ratios of ^{232}Th reaction rates are shown in **Figure 7**, and the ^{232}Th(n,f) reaction results for different evaluated nuclear data are shown in Ref. [11]. The calculations with ENDF/B-VII.0 and ENDF/B-VII.1 for THNR underestimate the experimental values. Meanwhile, large differences still exist in the ^{232}Th(n,2n)^{231}Th cross sections among different evaluated data [26]. Fractions with different energies in the PE shell are calculated by using ENDF/B-VII.0, and neutrons of energy more than 6.5 MeV account for 33–48% in the whole energy range, as shown in **Figure 5**. Since the neutron spectra in the PE shell are reliable, it is suggested that ^{232}Th(n,2n) reaction cross sections should be studied further.

4.2 ^{232}Th reaction rates in DU shell

The DU shell assembly for measuring ^{232}Th reaction rates is shown in **Figure 2**. The ^{232}Th reaction rates are measured by the same method as described above.

The experimental uncertainties are 3.1% for THCR, 5.3–5.5% for THFR [6, 8], and 6.8% for THNR in DU shell.

The experiment is simulated using the MCNP code with different evaluated data, including ENDF/B-VII.0, ENDF/B-VII.1, JENDL-4.0, and CENDL-3.1 [27]. The distributions of ^{232}Th reaction rates from the experiments and calculations with ENDF/B-VII.0 are shown in **Figure 8**. The ranges of C/E ratios with ENDF/B-VII.0
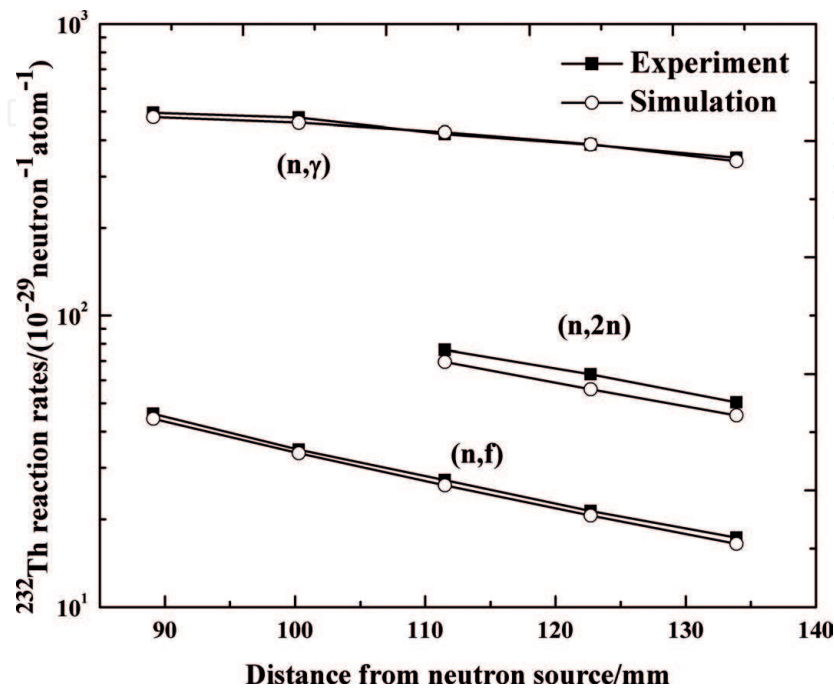

Figure 6.
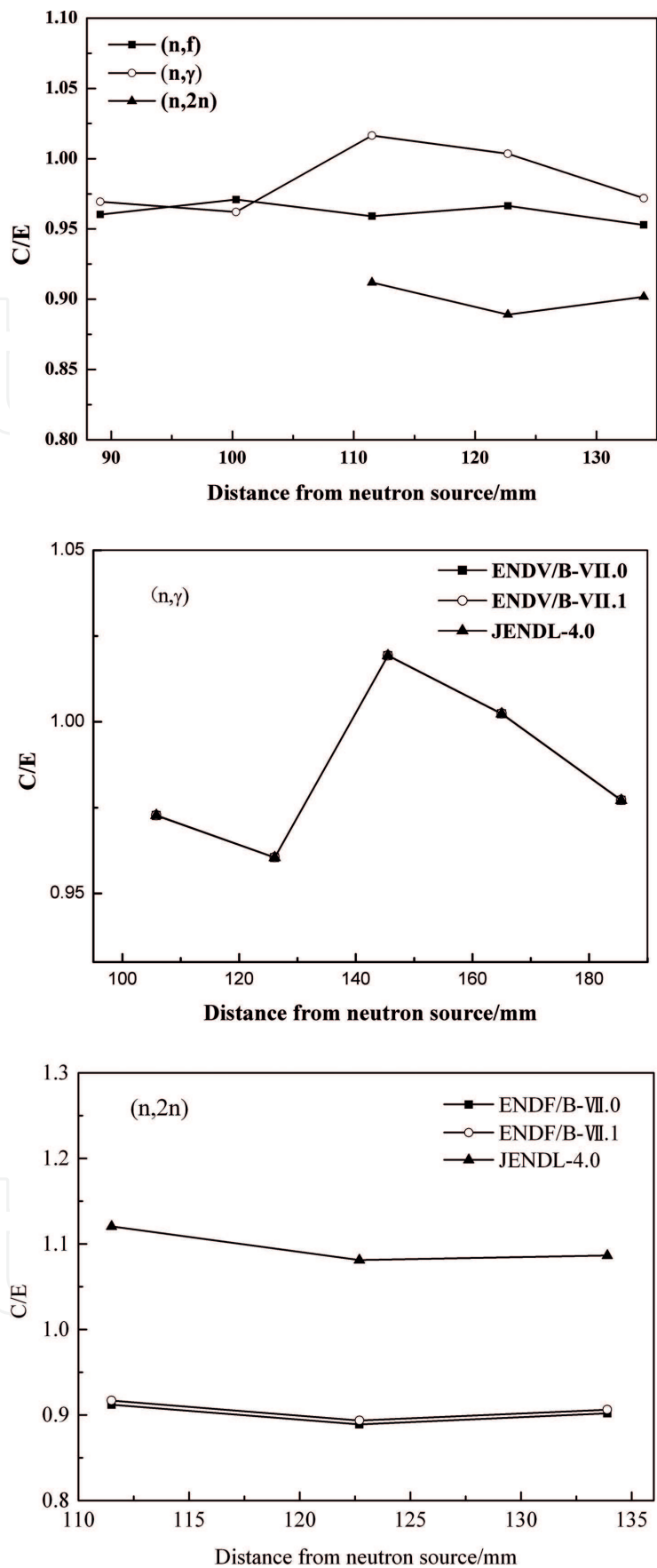*^{232}Th reaction rates in PE shell.*

Figure 7.
C/E ratio of ^{232}Th reaction rates in PE shell.

are 0.97–1.04 for THCR and 0.95–1.02 for THFR [8, 12], respectively. The results show that calculations and experiments are well consistent within the range of experimental uncertainties. The ratio of ^{232}Th capture to fission is about 6.71–12.23 with the increase of radius in DU shell.
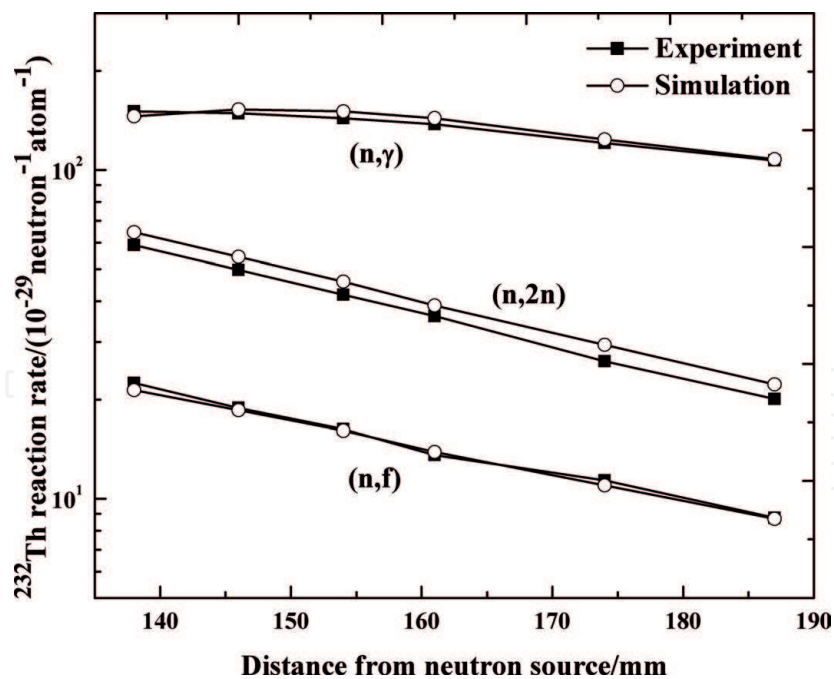
Figure 8.
^{232}Th reaction rates in DU shell.

The C/E ratios of ^{232}Th reaction rates with different evaluated data are shown in **Figure 9**. The calculations for THNR overestimate the experiments. Meanwhile, large differences still exist in C/E of THNR. The range of C/E with ENDF/B-VII.0 is 1.07–1.12. Fractions with different energies in DU shell are calculated by using ENDF/B-VII.0, and neutrons of energy more than 6.5 MeV account for 4–9% in the whole energy range, as shown in **Figure 5**. Since U(n,f) cross sections are standard in the wide energy range, it is suggested that U inelastic cross sections and ^{232}Th(n,2n) reaction cross sections should be studied further.

4.3 ^{232}Th reaction rates in ThO$_2$ cylinders

4.3.1 ^{232}Th fission and (n,2n) reaction rates in ThO$_2$ cylinder

The ThO$_2$ assembly for measuring ^{232}Th reaction rates in three ThO$_2$ cylinders with the thickness of 150 mm (without DU cylinder) is shown in **Figure 3**. The ^{232}Th fission and (n,2n) reaction rates are measured by the same method as described above.

The experimental uncertainties are 5.3–5.5% for THFR and 7.1% for THNR [9, 10]. The ^{232}Th reaction rates are calculated by using MCNP code with ENDF/B-VII.0. The ranges of C/E are 0.77–0.91 for THFR, and 0.92–1.0 [12] for THNR, respectively. The results show that the calculations generally underestimate the experiments for THFR. The PEO influence on THFR is described below. The distributions of ^{232}Th reaction rates by the experiments and calculations are shown in **Figure 10**.

4.3.2 ^{232}Th fission rates in ThO$_2$/DU cylinders

Experimental and simulative studies of THFR are carried out on three sets of ThO$_2$/DU cylinder assemblies to validate the evaluated thorium fission cross section and code [9, 10]. The size of each ThO$_2$ cylinder and DU cylinder is φ300 × 50 mm. The ThO$_2$ cylinders with PEO contents of 7.28, 1.1, and 0.55% are named as number 1, number 2, and number 3, respectively. The DU cylinder is named as number 4. Three sets of cylinder assemblies are combined with different cylinders, and named as "3 + 2 + 1," "4 + 2 + 1" (as shown in **Figure 3**) and "3 + 4 + 2 + 1" assembly, respectively.
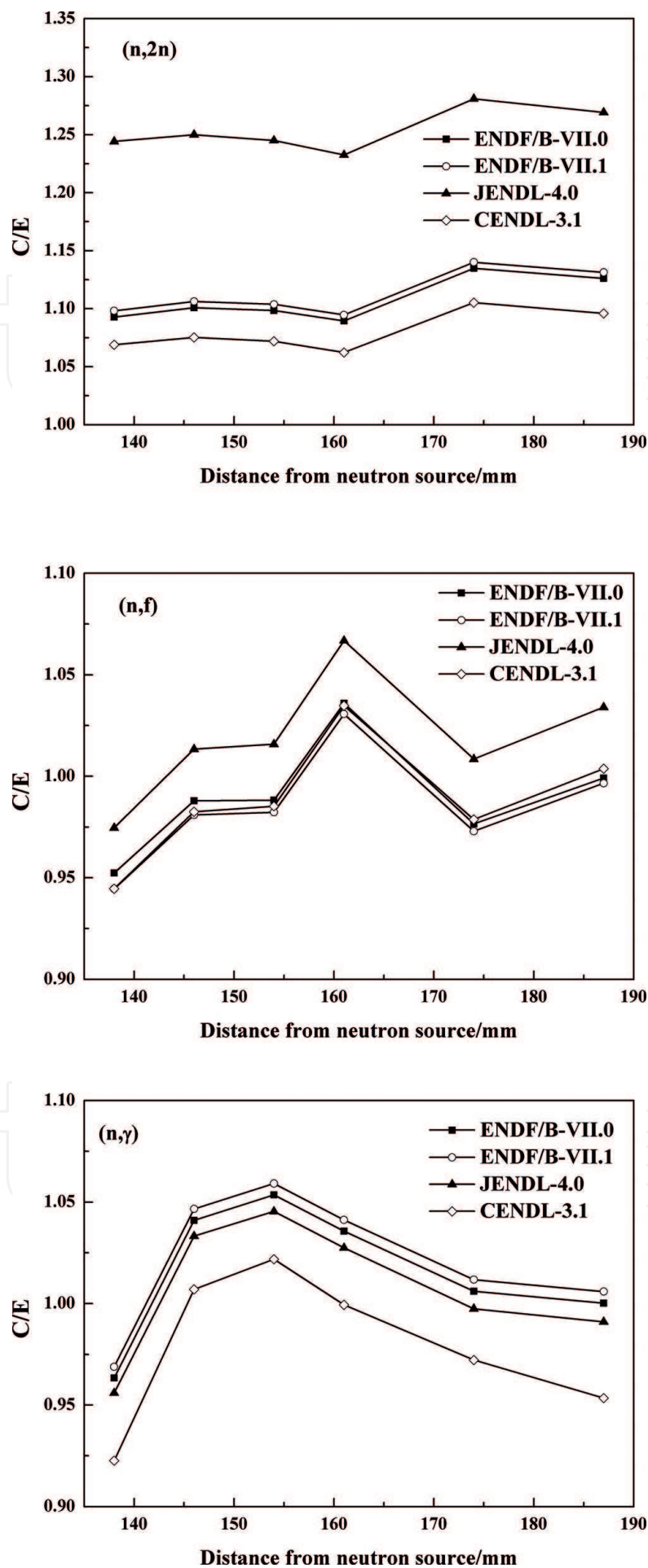
Figure 9.
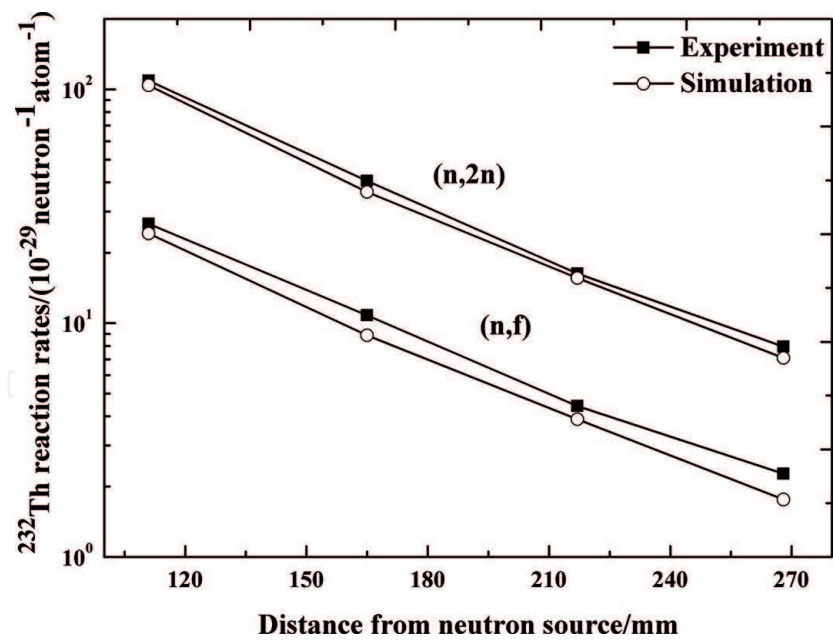*C/E ratio of ^{232}Th reaction rates in the DU shell.*

Figure 10.
^{232}Th reaction rates in ThO$_2$ cylinder.

THFR in the axial direction of the assemblies is obtained by using the activation method as described above, with experimental uncertainties about 5.6–5.9%.

THFRs are calculated by using MCNP code with ENDF/B-VII.0 and ENDF/B-VII.1. The calculations are 5–21% smaller than experimental ones, while the calculations with ENDF/B-VII.0 show better agreement with experimental ones. C/E distributions in the three assemblies are presented in **Figure 11**. The influence of the PEO in the ThO$_2$ cylinders is also evaluated by MCNP simulation employing ENDF/B-VII.0. The results show that the PEO influence on THFR under the measured level is negligible.

In order to gain more experimental results, it is necessary to design a new integral experiment employing thorium transport medium in which the ingredient is single and precisely known, and to determine THFR based on more kinds of fission
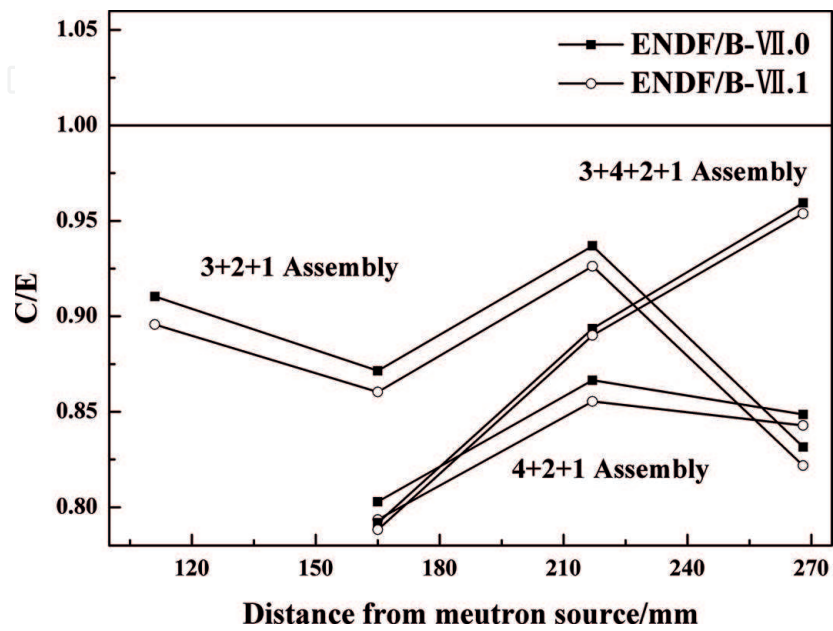

Figure 11.
C/E distribution in the three sets of assemblies.

products, as described below. The stage results could provide reference for the evaluation of neutron-induced thorium fission cross section, and the conceptual design margin of the subcritical blanket.

4.3.3 ^{232}Th reaction rates in ThO$_2$ powder cylinder

The ThO$_2$ power cylinder assembly for measuring ^{232}Th reaction rates is shown in **Figure 4**. The ^{232}Th reaction rates are measured by the same method as described above.

The experimental uncertainties are 3.1% for THCR, 5.5% for THFR, and 7.0% for THNR in the ThO$_2$ powder cylinder.

The experiment is simulated by using the MCNP code with different evaluated data [10, 11]. The C/E ratio of ^{232}Th reaction rates with ENDF/B-VII.0 are shown in **Figure 12**. The ranges of C/E ratio are 0.96–0.98 for THCR, 0.96–0.99 for THFR, and 0.74–0.76 for THNR. The results show that calculations and experiments for THCR and THFR are well consistent within the range of experimental uncertainties. The distributions of ^{232}Th reaction rates in the experiments and calculations are shown in [13–15].

The calculations for THNR underestimate the experiments. Fractions with different energies in ThO$_2$ powder cylinder are calculated by using ENDF/B-VII.0, and neutrons of energy more than 6.5 MeV account for 62–72% in the whole energy range, which is the largest among the assemblies, as shown in **Figure 5**. The suggestion described above is that ^{232}Th(n,2n) reaction cross sections should be studied further.

4.3.4 ^{232}Th fission rate based on ^{135}I in ThO$_2$ powder cylinder

The ThO$_2$ power cylinder assembly for developing the activation method of measuring THFR is shown in **Figure 4**. THFR in the axial direction of the cylinder is determined by measuring the 1260.409 keV gamma emitted from ^{232}Th fission product ^{135}I, with experimental uncertainties of 6.2% [14]. The experiment is simulated by using the MCNP code with ENDF/B-VII.0, ENDF/B-VII.1, JENDL-4.0, and CENDL-3.1. The calculations and experiments are in good agreement within experimental uncertainties. The activation method to determine THFR is developed
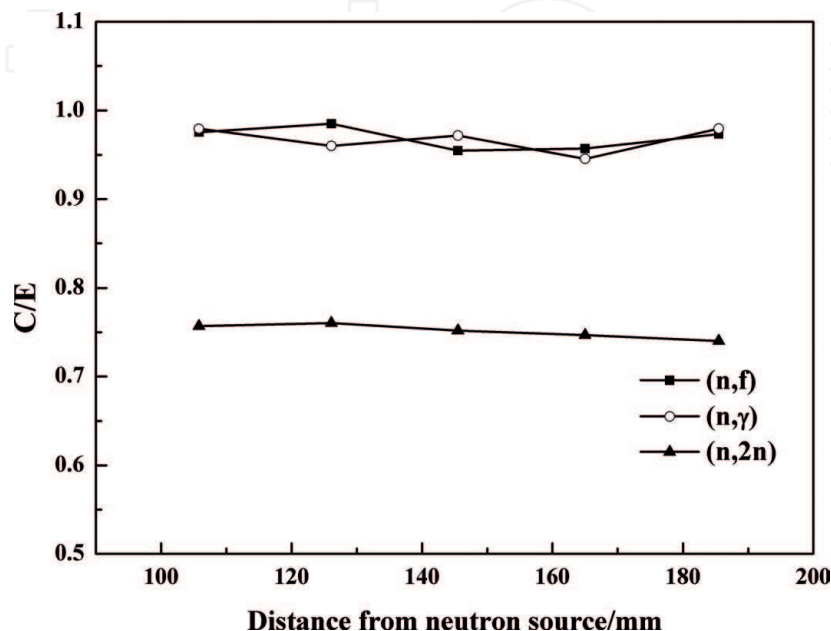

Figure 12.
C/E ratio of ^{232}Th reaction rates in ThO$_2$ powder cylinder.

and the data obtained in this work could provide reference for the validation of thorium fission parameters. The C/E ratio of ^{232}Th fission rates based on different evaluated data is presented in the [14].

4.4 Breeding properties

4.4.1 Fuel breeding

The primary conversion rate is one of the important parameters in the conceptual design of subcritical blanket. The relative reaction rate ratio of ^{232}Th capture to fission as the fissile production rate indicates fuel breeding in the fuel burn-up unit [12]. The ratios of ^{232}Th capture to fission measured in PE shell, DU shell, and ThO$_2$ powder cylinder are obtained.

The ratios are about 10.76–20.17 with the increase in radius of the PE shell. It is demonstrated that the fuel breeding efficiency under the neutron spectra in the PE shell is quite high.

The ratios are about 6.71–12.23 with the increase in radius of the DU shell. It is demonstrated that the fuel breeding efficiency under the neutron spectra in DU shell is high.

The ratios are only about 0.11–0.19 with the increase in radius of the ThO$_2$ powder cylinder. It is demonstrated that the fuel breeding efficiency under the neutron spectra in ThO$_2$ powder cylinder is low.

The results show that the ratios are relevant to neutron spectra in the assemblies. The ratios in the three assemblies are compared and shown in **Figure 13**.

4.4.2 Neutron breeding

The bred neutrons from ^{232}Th(n,2n) and ^{232}Th(n,f) react with thorium or relevant nuclides to maintain the Th/U fuel cycle. THNRs in three assemblies, that is, under different neutron spectra, are compared and shown in **Figure 14**. The results show that the ^{232}Th(n,2n) reaction rates are relevant to the fraction of high-energy neutrons in the assemblies as described above, and the decreasing trend of THNR with the increase in distance to the neutron source are similar for three assemblies.
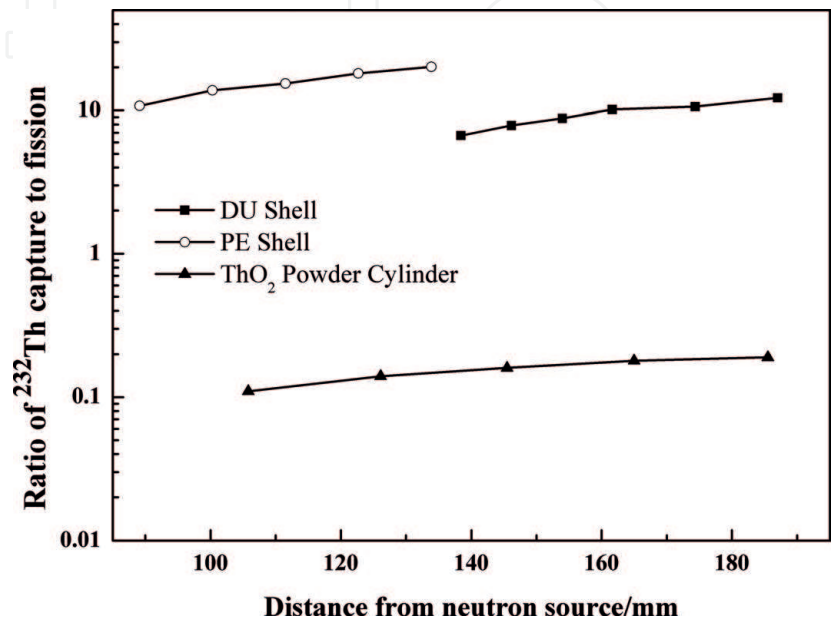

Figure 13.
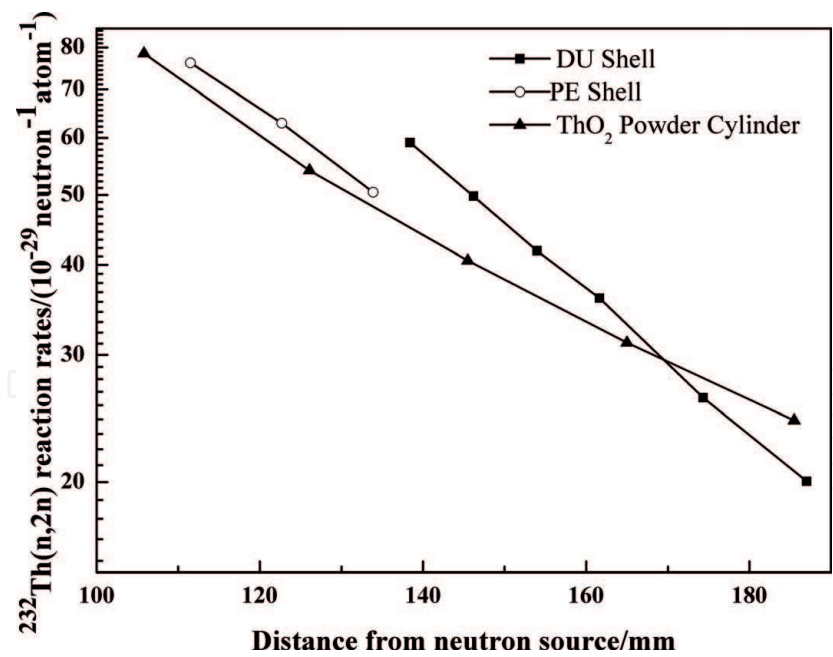*Ratios of ^{232}Th capture to fission in the three assemblies.*
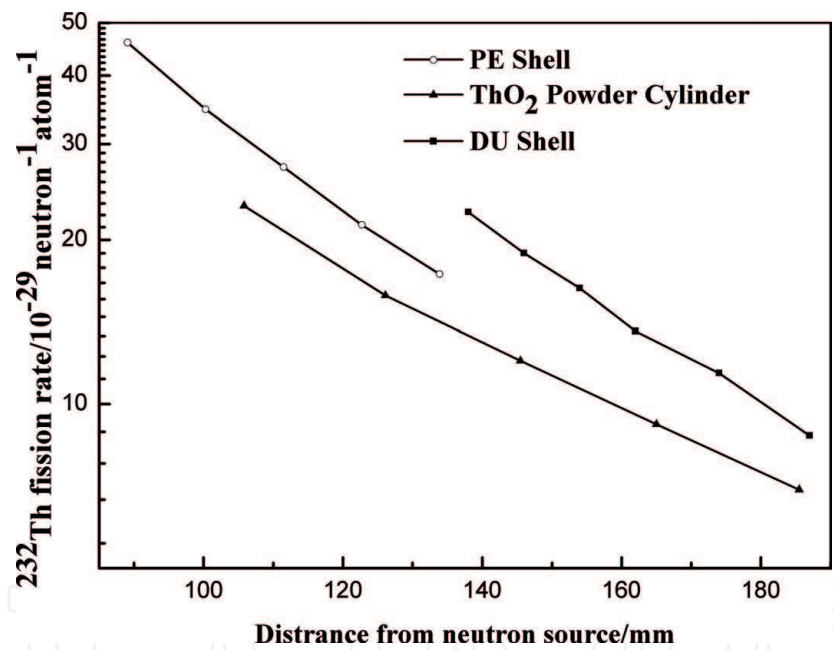
Figure 14.
THNRs in the three assemblies.

Figure 15.
THFRs in the three assemblies.

Since ^{230}Th half-life (7.54×10^4 years) is very long, measurement of ^{232}Th(n,3n) ^{230}Th (with threshold of 11.6 MeV) reaction rate by the activation method is very difficult. The ^{232}Th(n,4n) reaction has high threshold 19 MeV and is not involved in this work.

The prompt neutron and delayed neutron yields from ^{232}Th(n,f) reaction are about 3.7 and 0.0265 per fission at 14.1 MeV [28], respectively. THFRs in three assemblies, that is, under different neutron spectra, are compared and shown in **Figure 15**. From **Figures 14** and **15**, THNRs are higher than THFRs in the three assemblies.

4.5 Leakage neutron spectra

Three assemblies consist of the ThO$_2$ cylinders with thicknesses of 50, 100, and 150 mm (without DU cylinder), respectively, as shown in **Figure 3**. The front
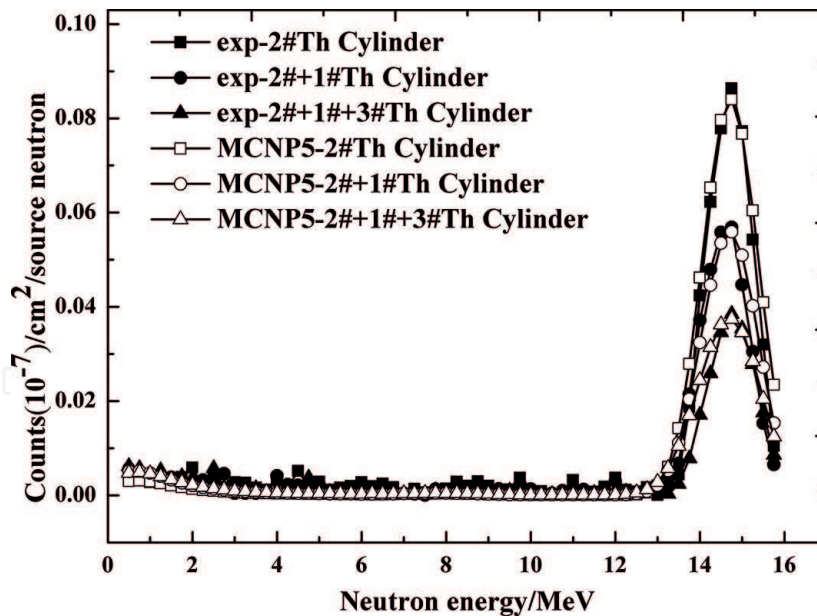
Figure 16.
Leakage neutron spectra from ThO₂ cylinders.

surface of the assembly is 0.22 m from the center of a T-Ti target. The leakage neutron spectra are measured by using a 50.8 mm diameter and 50.8 mm length BC501A liquid scintillator coupled to a 50.8 mm diameter 9807B photomultiplier [16]. The distance from the detector to the neutron source is 10.75 m. The detector is at a 0° to the incident D⁺ beam and arranged in shielding room. The influence of background neutrons is negligible.

The leakage neutron spectra from the three assemblies are measured. The spectra 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 experiments are calculated by using MCNP code with ENDF/B-VII.0. The results show 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 **Figure 16**.

5. Conclusions

To validate ^{232}Th nuclear data, the fusion neutronics experiments for the three kinds of thorium assemblies with a D-T neutron source have been carried out. The two spherical assemblies based on the DU and PE shells, and the cylindrical assemblies based on ThO₂ have been designed and established. The assembly materials are referable to the conceptual design of subcritical blanket of a hybrid reactor. The ^{232}Th(n,γ), ^{232}Th(n,f), and ^{232}Th(n,2n) reaction rates in the assemblies are measured by the foil activation technique. The results show that the developed activation approach can work well for the experiments, and the ^{232}Th reaction rates are relevant to neutron spectra in assemblies. The reaction rate ratios of ^{232}Th capture to fission are obtained. The fuel and neutron breeding properties under different neutron spectra are compared and analyzed. The leakage neutron spectra from ThO₂ cylinders are measured. The experimental results are compared to the numerical results calculated by using the MCNP code with different evaluated data. The results show that the experiments are benefit to validate Th nuclear data and support the conceptual design of subcritical blanket with thorium in a hybrid reactor. Furthermore, it should be beneficial to measure relevant ^{232}Th excitation curve at white neutron source of China Spallation Neutron Source (CSNS) [29] for verifying ^{232}Th nuclear data.

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