Chinese Physics C Vol. 37, No. 5 (2013) 056202

Measurement of tritium production rate distribution for a fusion-fission hybrid conceptual reactor *

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Abstract: A fusion-fission hybrid conceptual reactor is established. It consists of a DT neutron source and a spherical shell of depleted uranium and hydrogen lithium. The tritium production rate (TPR) distribution in the conceptual reactor was measured by DT neutrons using two sets of lithium glass detectors with different thicknesses in the hole in the vertical direction with respect to the D^+ beam of the Cockcroft-Walton neutron generator in direct current mode. The measured TPR distribution is compared with the calculated results obtained by the three-dimensional Monte Carlo code MCNP5 and the ENDF/B-Ⅵ data file. The discrepancy between the measured and calculated values can be attributed to the neutron data library of the hydrogen lithium lack $S(\alpha, \beta)$ thermal scattering model, so we show that a special database of low-energy and thermal neutrons should be established in the physics design of fusion-fission hybrid reactors.

Key words: fusion-fission hybrid conceptual reactor, TPR, DT neutron source, MCNP

PACS: 28.20.-v, 28.41.Ak, 28.52.Av **DOI:** 10.1088/1674-1137/37/5/056202

1 Introduction

Compared with fossil energy, which produces carbon dioxide and sulfur emissions, nuclear energy is a clean energy. Nuclear energy includes fission energy and fusion energy. The fuel for the former is uranium or thorium, and for the latter deuterium and tritium. The fission energy currently in use is a thermal neutron reactor with uranium as the fuel, which can only make use of 1%–2% of the uranium resources. There are still some technical difficulties in the production of fusion energy by deuterium burning, and tritium resources used for the burning of deuterium and tritium are extremely limited, as are the lithium resources for tritium production [1]. Using the sub-critical reactor of a fusion driven fission system with the natural uranium and thorium that are abound in nature as fuel [2], and reducing the demand for tritium and fissile resources, have become the potential direction. The basic idea is to use magnetic confinement fusion as a fusion neutron source and the interaction (mainly fission reaction) between neutrons produced in fusion and natural uranium (thorium) will amplify the energy. Tritium is produced by the reaction between the neutrons leaking from the fission blanket and the tritium-producing blanket for self-sustaining tritium in the fusion reaction.

The core-driven hybrid reactor where magnetic confinement fusion is used is still in the conceptual design stage. For this reason, experimental data for neutronics are required in the physics design of the hybrid reactor to verify the neutron transport methods and the reliability of the evaluation database involved. The tritium production rate, as one of the important parameters for a neutronics integral experiment, can not only be used in the verification of programs and databases, but is also related to self-sustaining tritium in the running of subcritical reactor. Thus, it is one of the key links in a successful design of subcritical reactors. A large number of experiments [3–9] on the tritium production rate associated with nuclide benchmarking or simulation devices have been carried out to verify a variety of programs and evaluation databases. Consequently, a fusion-fission hybrid conceptual reactor with a spherical shell of depleted uranium and lithium hydride was set up at the Institute of Nuclear Physics and Chemistry to verify the design programs and databases for the hybrid reactor (developed on the core basis of MCNP5 [10] and the ENDF/B-Ⅵ evaluation database). Depleted uranium is used to simulate the energy amplification blanket, lithium hydride to simulate the tritium-producing blanket and a DT neutron in the accelerator in the center of the sphere to simulate the fusion neutron source. The tritium pro-

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Received 26 July 2012
∗ Supported by Chinese Special Project for ITER (2010GB111002)

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duction rate distribution of the DT neutron within the lithium hydride blanket is measured and compared with the value calculated from simulation using two sets of lithium glass detectors with different thicknesses to verify the calculation methods used in the theoretical design and the credibility of the evaluation database.

2 The experimental setup

A fusion-fission hybrid conceptual reactor is shown in Fig. 1. The inner layers are two depleted uranium hemispherical shells with a diameter of 8.0–26.2 cm and density of 18.8 g/cm^3. The isotopic abundance is: ^{238}U 99.579%, ^{235}U 0.4154%, ^{234}U 0.00236%, and ^{236}U 0.003087%. The total amount of other impurity elements is below 0.1%. The outer layer of the lithium hydride spherical shell consists of four hemispherical shells with a diameter of 26.2–46.4 cm and 46.6–60.0 cm. The average density of the spherical shell is 0.746 g/cm^3. The elemental composition of the spherical shell is ^{7}LiH 90.3%, ^{6}LiH 8.7%, and other impurities 1%. The impurity elements are O, C, Cl, Si, K, Na Ca, Al, Mn, Fe, Ni, Cr, Cu, Mg, etc. There is a target chamber channel (half and half in two hemispheres) with a diameter of 35 mm on the combination surface of the upper and lower hemisphere shells.

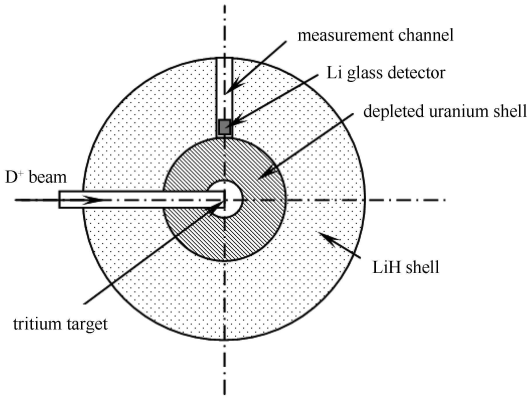

Fig. 1. A cross-sectional view of the fusion-fission hybrid conceptual reactor.

The fusion-fission hybrid conceptual reactor is placed on a movable bracket with the center of the sphere coinciding with the tritium target. The neutron source is the DC DT neutrons generated by the Cockcroft-Walton neutron generator (Institute of Nuclear Physics & Chemistry). The average energy of the D$^+$ ions is 134 keV, and the neutron energy at 0° angle is 14.89 MeV. The air cooling of the target surface is accomplished using a stainless-steel single-tube target chamber and air compressor. The active target area is Φ12 mm and the neutron yield is about 5×10^7/s. The associated particle method is implemented for neutron source monitoring and the angle between the Au-Si surface barrier detector and the D$^+$ beam is 178°.

3 Experimental measurement

The so-called tritium production rate distribution refers to the probability of the unit ^{6}Li nuclei to produce tritium in a particular position of the lithium hydride shell when the DT neutron source at the center of the conceptual reactor emits a neutron in the fusion-fission hybrid conceptual reactor. The probability of tritium production is given as follows when the lithium glass detector is utilized for measurement:

$$P_{\mathrm{T}}=\frac{N_{\mathrm{T}}}{N_{\mathrm{n}}\cdot N_{^6\mathrm{Li}}}, \tag{1}$$

where N_{n} is the number of source neutrons emitted from the center of the sphere detected by the associated particle method; $N_{^6\mathrm{Li}}$ is the number of ^{6}Li nucleons within the sensitive region of the lithium glass detector, inferred from the mass of the sensitive region and the mass percentage content of ^{6}Li; and N_{T} is the peak area count of tritium on the pulse height spectrum measured by detectors.

Two sets of lithium glass detectors with a size of ϕ2 mm×12 mm and ϕ12.7 mm×1 mm are used in the measurement channel positioned at 90° with respect to the D$^+$ beam to measure the tritium production rate distribution of the conceptual reactor. A clean tritium pulse spectrum can be obtained by subtracting the pulse height spectrum measured by the ^{7}Li detector from that by the ^{6}Li detector. Starting from the outer layer of the depleted uranium shell (13.1 cm from the center of the sphere), the measurement points are placed about every 1 cm. Then the measurement points are moved backwards and the channel is filled with LiH of ϕ 34 mm×10 mm. The measurement points total is 16.

4 Data analysis and discussion

4.1 The computational model

The program based on the evaluation database of MCNP and ENDF/B-Ⅵ is adopted in the design of the subcritical reactor. A simulation calculation of the tritium production rate from the DT neutron in the fusion-fission conceptual reactor is conducted using the three-dimensional Monte Carlo program MCNP5 and the evaluation database of ENDF/B-Ⅵ to verify the design program and database for the hybrid reactor. The computational model is consistent with the conceptual reactor (except the simplified experimental hall), consisting of isotopic composition, geometric dimensions, neutron source distribution, the channels of the target chamber, detectors, etc. The TARGET program [11] (PTB laboratory, Germany) is used to simulate the interaction between the deuterium particles and the tritium target, and to obtain the intensity, angle and energy distribution of the source neutron, as shown in Fig. 2. The calculated neutron distribution is taken as the input of MCNP5 to obtain the tritium production rate distribution in the conceptual reactor.

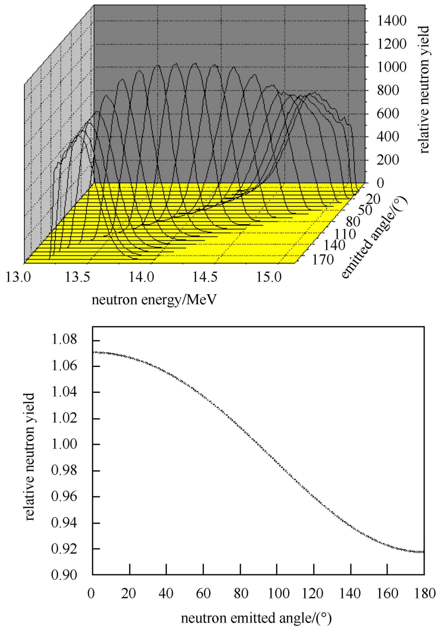

Fig. 2. Intensity, angle and energy distribution of the source neutron.

4.2 Analysis of the tritium production rate

The calculated values of the tritium production rate distribution and the values measured by two lithium-glass detectors with different thicknesses in the conceptual reactor are shown in Fig. 3. It can be seen from the figure that the tritium production rates increase at first and then decrease with increasing distance to the core. The rise near the depleted uranium is due to the quick slowing of the lower-energy neutrons leaking from depleted uranium through elastic scattering on hydrogen. The lower the neutron energy, the higher the cross section of the lithium-6 nucleus ^{6}Li (n, T) ^{4}He will be, which results in an upward trend of tritium production rate distribution. As the reaction between the low-energy neutrons and lithium-6 nuclei is exhausted with increasing distance, the energy continues to decline with the reaction between the high-energy neutron and hydrogen nuclei, but the increase in distance leads to a reduction in the number of neutrons. Thus, a downward trend is shown in the tritium production rate distribution. Moreover, the tritium production rate reduces accordingly with the thickness increase in the detectors for either experimental data or simulated data. The tritium production rate with the thick detector is 90% that with the thin detector, except the last three points in Fig. 4. This illustrates that there is a more intense neutron self-shielding effect in the lithium-glass detector of high abundance. Finally, the calculated values for both detectors are 22% smaller than the experimental values (the ratios shown in Fig. 5) on average.

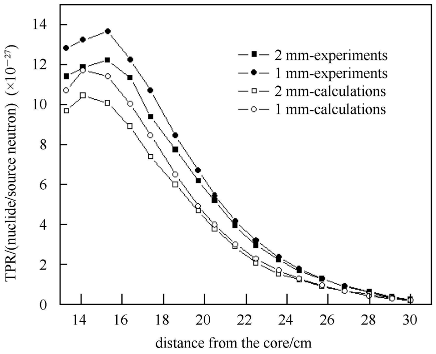

Fig. 3. The tritium production rate distribution in the lithium hydride shell.

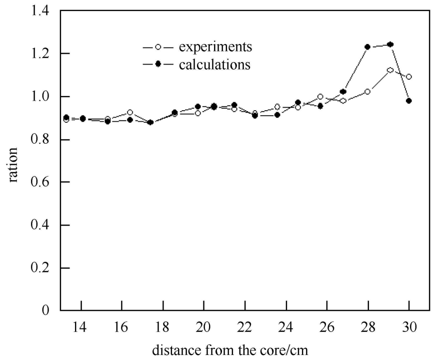

Fig. 4. The ratios of TPR distribution for detectors with different thicknesses.

The measured results are self-consistent, as indicated in Fig. 5, and there are no systematic errors in the measurement. But there is considerable discrepancy between the experimental and simulated values, which may come from a certain portion of the thermal neutrons (the neutron spectra in the lithium hydride shell calculated by MCNP5 are shown in Fig. 6; the neutron portion below 4 eV of the 14 cm, 21 cm and 22 cm locations are 2.17%, 5.37% and 4.27%, respectively). This is a result of multiple elastic scattering of neutrons moderated by depleted uranium due to a large number of hydrogen nuclei in a large lithium hydride shell, and these neutrons should have been treated in the same way as the thermal neutron $S(\alpha, \beta)$ mode (the MCNP thermal neutron $S(\alpha, \beta)$ mode includes chemical binding and crystalline effects that become important as the neutron energy becomes sufficiently low). However, the databases of the $S(\alpha, \beta)$ mode are only available for light and heavy water, beryllium metal, beryllium oxide, benzene, graphite, polyethylene, zirconium, and hydrogen in zirconium hydride but for lithium hydride at present [10]. So the thermal neutron $S(\alpha,\ \beta)$ mode was substituted by the free gas mode (the free gas thermal treatment effectively applies to elastic scattering only) in the calculation. For example, a special database with the $S(\alpha,\ \beta)$ mode was developed for some of the materials during the design of the fission reactors as well as the thermonuclear fusion reactor [12]. The thermal neutron $S(\alpha,\ \beta)$ mode has to be considered in the calculation of the multi-sphere spectrometer response with large-volume polyethylene ball [13]. As a result, the reliability of the design can be ensured only by developing special databases similar to those used in fission reactors and fusion reactors when designing the subcritical reactor.

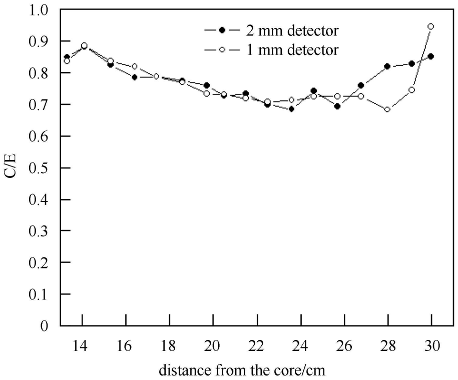

Fig. 5. The TPR distribution ratios of calculated to experimental values.

5 Uncertainty analysis

The uncertainty associated with tritium production rate distribution includes the following respects: neutron source monitoring about 2.3%; sample composition 2.5%; position uncertainty caused by blocking 3.0%; content of lithium nuclide in the detector 2.2%; and deduction of γ rays background 2.0%. The total uncertainty is initially assessed as 5.4%. The uncertainty associated with the simulation calculation is mainly from the uncertainty caused by statistics and the database; the statistical error contributes to about 2% uncertainty. About a 22% contribution is made by the discrepancy between the experimental results and the calculated results, which is probably caused by an inappropriate scattering database of hydrogen nuclei in lithium hydride for the thermal neutron. In future work, a special cross-section database will be established.

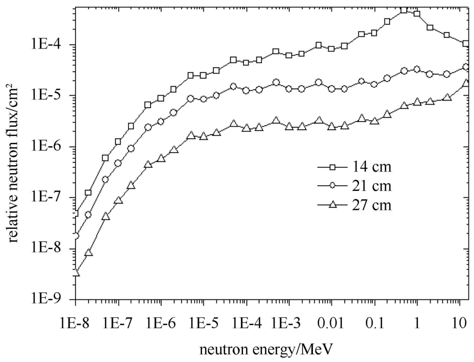

Fig. 6. The neutron spectra of three different locations in the lithium hydride shell calculated by MCNP5.

6 Conclusions

The tritium production rate distribution in a conceptual reactor was measured and comparatively analyzed with the results of simulation calculation using the Cockcroft-Walton neutron generator to generate a DT neutron and two sets of lithium glass detectors with different thicknesses to measure the tritium production rate distribution. The results indicate that the calculated value is about 22% smaller than the experimental value, which is mainly due to the presence of plentiful low-energy neutrons or even thermal neutrons in the conceptual reactor. In the simulation of this project, there is no appropriate neutron database for processing the $S(\alpha,\ \beta)$ scattering model. A special database needs to be established before the physics design of the subcritical reactor, in particular a database for the thermal neutron that is similar to that used in the fission and fusion reactors to ensure the reliability of the design.

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