CPC(HEP & NP), 2012, **36**(9): 905–908 Chinese Physics C Vol. 36, No. 9, Sep., 2012

Designing of the 14 MeV neutron moderator for BNCT*

CHENG Dao-Wen(程道文)[1;1)] LU Jing-Bin(陆景彬)[2] YANG Dong(杨东)[2]
LIU Yu-Min(刘玉敏)[2] WANG Hui-Dong(王辉东)[2] MA Ke-Yan(马克岩)[2]

[1] School of Basic Sciences, Changchun University of Technology, Changchun 130012, China
[2] College of Physics, Jilin University, Changchun 130021, China

Abstract: In boron neutron capture therapy (BNCT), the ratio of the fast neutron flux to the neutron flux in the tumor (RFNT) must be less than 3%. If a D-T neutron generator is used in BNCT, the 14 MeV neutron moderator must be optimized to reduce the RFNT. Based on the neutron moderation theory and the simulation results, tungsten, lead and diamond were used to moderate the 14 MeV neutrons. Satisfying RFNT of less than 3%, the maximum neutron flux in the tumor was achieved with a three-layer moderator comprised of a 3 cm thick tungsten layer, a 14 cm thick lead layer and a 21 cm thick diamond layer.

Key words: BNCT, D-T neutron generator, three-layer moderator, RFNT

PACS: 28.20.Gd, 28.20.Ka, 29.25.Dz **DOI:** 10.1088/1674-1137/36/9/020

1 Introduction

Boron neutron capture therapy (BNCT) is an effective cancer treatment [1, 2]. Because a high neutron flux is needed, a neutron reactor or a D-T neutron generator can be used as the neutron source in BNCT. Compared with the reactor neutron source, the D-T neutron generator is an optimal neutron source for this technique because of advantages such as removability, low cost, no radioactivity after being turned off and so on [3, 4]. In BNCT, the RFNT must be less than 3% to reduce neutron induced damage and the neutron flux in the tumor (NFT) should exceed 10^9 cm^{-2}s^{-1} to increase therapy efficiency [5–7]. When a D-T neutron generator with a yield of 10^{13} n/s is used as a thermal neutron source in BNCT, the key point is that the 14 MeV neutron moderator must be designed appropriately to reduce the RFNT and increase the NFT. Hydrogen-rich materials are usually used as the neutron moderator, but the Thermal Neutron Absorption Cross Section (TNACS) of hydrogen is too large to make the RFNT less than 3%. This means that the D-T neutron generator cannot be directly used in BNCT, no matter how high the yield of the neutron generator is. In order for it to be used in BNCT, heavy water, lead or graphite was employed to moderate the 14 MeV neutrons. Although their TNACSs are lower, the thermalization efficiencies for 14 MeV neutrons are so low that the yield of the D-T neutron generator must exceed 10^{13} n/s in BNCT [8, 9]. In order to increase the thermalization efficiency, tungsten, lead and diamond were used to moderate the 14 MeV neutrons by the Monte Carlo neutron-photon transport code (MCNP) in this paper.

2 Design of the simulation model

In practical applications, the installation of BNCT is very complicated, but the moderator is usually a cube. If the components and the thicknesses of the cubic moderator and the global moderator are the same, the thermalization efficiencies are almost equal. In this paper, the global moderator was studied to save the simulation time and enhance the calculation precision. The section drawing of the global moderator is shown in Fig. 1.

Received 23 December 2011
* Supported by National Natural Science Foundation of China (10105003)
1) E-mail: chengdaowen@mail.ccut.edu.cn

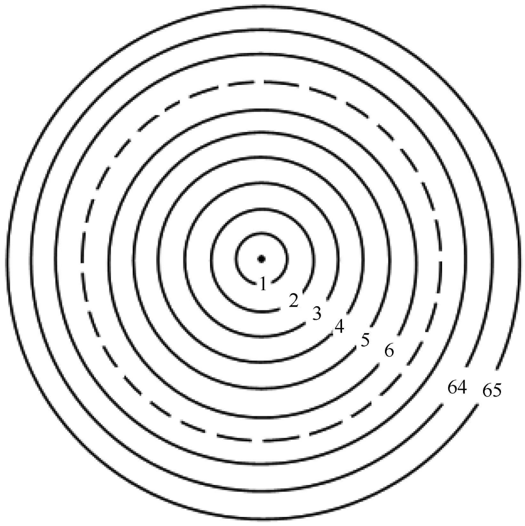

Fig. 1. Section drawing of the simulation model.

The concentric circles shown in Fig. 1 are concentric spherical surfaces. The D-T neutron generator, regarded as a point source, is located at the center of the sphere. The minimum radius is 1 cm, and the distance between the adjacent spherical surfaces is 1 cm. The maximum radius is 65 cm, which is large enough to find the optimal moderator for thermalizing 14 MeV neutrons. The reasons for this design are as follows:

(1) In a D-T neutron generator, the target is so small that it can be regarded as a point. Therefore, the D-T neutron generator can be regarded as a point source.

(2) The simulation time was markedly reduced and the calculation precision was significantly enhanced by the spherical symmetry. In order to search the optimal moderator, many kinds of models were simulated by the MCNP code and this took a long time. Because of the spherical symmetry, the simulation time could be greatly reduced. Moreover, the average neutron flux of the special spherical surface could be calculated by the F2 tally, which gives the neutron flux averaged over a surface. In the MCNP, the precision obtained by the F2 tally is considerably higher than that from the F5 tally, which gives the neutron flux at a point.

(3) The multilayer moderator could be obtained by filling different materials between different spherical surfaces. For example, a three-layer moderator, composed of a 5 cm thick tungsten layer, a 7 cm thick lead layer and an 18 cm thick diamond, is needed. It can be designed by filling tungsten in the 5 cm radius sphere, filling lead between two spherical surfaces with radii of 5 cm and 12 cm, and filling diamond between two spherical surfaces with radii of 12 cm and 30 cm. If the depth of the tumor is supposed to be 1 cm, the material which resembles the person's flesh will be filled between two spherical surfaces with radii of 30 cm and 32 cm. Then, we can calculate the average neutron flux of the spherical surface with a radius of 31 cm.

3 Single-layer moderator

The energy of the neutron is usually reduced by the collision, especially elastic collision with the atomic nucleus. After an elastic collision, the average energy loss of a neutron is:

$$\overline{\Delta E} = \frac{2A}{(A+1)^2} E_0, \tag{1}$$

where, E_0 is the initial energy of the neutron, and A is the mass-number of the nuclear. The smaller A is, the higher the moderating ability is. In this paper, diamond, heavy water, water and polythene were used to moderate the 14 MeV neutrons. Although graphite is also often used as a neutron moderator, it wasn't studied in this paper because it has a lower density than diamond. Because the large diamond is too expensive to be used as a moderator, small artificial diamond particles (abbreviated as diamond) whose density is supposed to be 3.2 g/cm^3 were studied in this paper. The change of RFNT with the thickness of the moderator is shown in Fig. 2.

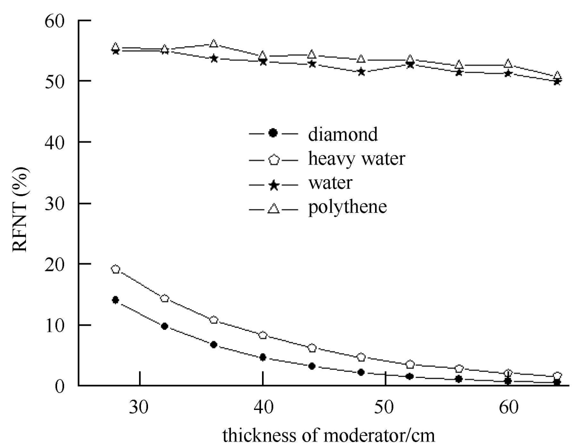

Fig. 2. RFNT changed with the thickness of the moderator.

The results from Fig. 2 are as follows:

(1) Neither polythene nor water, composed of carbon, hydrogen and oxygen, can be used as a neutron moderator in BNCT. The TNACSs of carbon, hydrogen and oxygen are about 3 mb, 0.19 b and 0.1 mb, respectively. In water and polythene, the number densities of hydrogen atoms are high, which

can reduce the fast neutron flux. But the TNACS of hydrogen is large, which will reduce the thermal neutron flux. So, it is difficult to estimate the relationship between the RFNT and the number density of hydrogen atoms. Based on the simulations, we find that when the thickness of polythene or water is 60 cm, the RFNT is still more than 50%. If they are used as the moderators in BNCT, the RFNT is hardly less than 3%.

(2) Heavy water and diamond can be used as a moderator in BNCT. They are made of deuterium, oxygen and carbon. The TNACS of deuterium is about 0.0005 b. Although the moderator abilities of heavy water and diamond are low, their TNACSs are small, which can increase the thermal neutron flux and reduce the RFNT. If the thickness of heavy water or diamond is more than 60 cm, the RFNT is less than 3%.

(3) The RFNT of diamond is the smallest if the moderators have the same thicknesses. So, diamond was used to moderate the 14 MeV neutrons in this paper.

If the neutron flux is normalized to one source neutron in the simulation, the maximum NFT (abbreviated as MNFT), moderated by diamond, was 1.007×10^{-4} $cm^{-2}\cdot s^{-1}$ at the RFNT which is less than 3%.

4 Double-layer moderator

If the 14 MeV neutrons are inelastic scattered by the heavy metal, the energies of the neutrons are often lower than 3 MeV and the peak value of the neutron spectrum is about 2 MeV. If a double-layer moderator composed of heavy metal and diamond is used to moderate the 14 MeV neutrons, the NFT can be greatly increased under the condition of RFNT which is less than 3%. Uranium and lead are often used to first moderate the 14 MeV neutrons. In this paper, uranium wasn't studied because of its high price and large TNACS.

Tungsten is a very heavy metal, whose ability to moderate the 14 MeV neutrons is very strong. The (n, 2n) cross-sections of lead and tungsten are both about 2 b, which can increase the neutron flux. In this study, lead or tungsten was first used to moderate the 14 MeV neutrons, and then diamond. Taking the double-layer moderator composed of tungsten and diamond as an example, the simulation process is as follows:

(1) The radius of tungsten (R_W) was increased from 1 cm to 24 cm in steps of 1 cm;

(2) The radius of diamond (R_D) was increased from (R_W +1) cm to 63 cm at each R_W, and then this model was simulated by the MCNP code;

(3) Fixing the R_W, R_D was changed to get the MNFT (maximum value of the NFT at each R_W) under the condition of RFNT which is less than 3%. The MNFT could be considered as the NFT of tungsten with R_W (cm) thickness.

The change of NFT with the thickness of lead or tungsten is shown in Fig. 3.

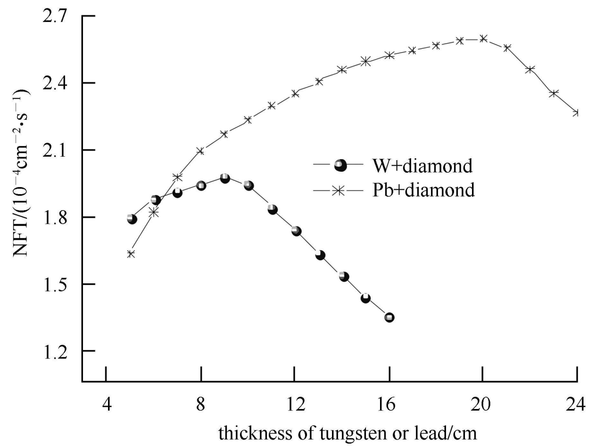

Fig. 3. NFT changed with the thickness of lead or tungsten.

From Fig. 3, we can obtain:

(1) When the thickness of the heavy metal is less than 7 cm, the NFT with tungsten is slightly higher than that of lead. Because the density of tungsten is much higher than lead, the moderating ability of tungsten is stronger than that of lead.

(2) When the thickness of the heavy metal is more than 7 cm, the NFT with lead is much higher than tungsten. The moderating ability of tungsten is stronger than lead, but its TNACS (11 b) is much larger than lead (0.1 b). With the increase of the thermal neutron flux, the NFT moderated by tungsten and diamond becomes lower than that moderated by lead and diamond.

Under the condition of RFNT which is less than 3%, the MNFT, moderated by the double-layer moderator composed of lead and diamond, is 2.590×10^{-4} $cm^{-2}\cdot s^{-1}$.

5 Three-layer moderator

Considering the stronger moderating ability of tungsten and the smaller TNACS of lead, a moderator composed of three layers was designed, and the 14 MeV neutrons were first moderated by tungsten, then by lead and at last by diamond. The simulation process is as follows:

(1) The R_W was increased from 1 cm to 7 cm in steps of 1 cm;

(2) The radius of lead (R_{Pb}) was increased from (R_W +1) cm to 20 cm at each R_W;

(3) The R_D was increased from (R_{Pb} +1) cm to 63 cm at each R_{Pb}, and then this model was simulated by the MCNP code;

(4) Fixing the R_W, R_{Pb} and R_D were changed to get the MNFT at the RFNT which is less than 3%.

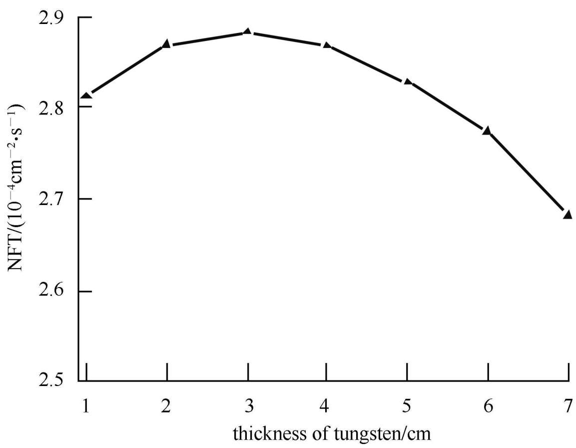

Fig. 4. NFT changed with the thickness of tungsten.

The MNFT could be considered as the NFT of tungsten with R_W (cm) thickness. The NFT changed with the thickness of tungsten is shown in Fig. 4.

Keeping the RFNT less than 3%, the MNFT, moderated by the three-layer moderator composed of a 3-cm-thick tungsten layer, a 14 cm thick lead layer and a 21 cm thick diamond layer, was 2.882×10^{-4} cm^{-2}·s^{-1}.

6 Conclusions

Hydrogen-rich materials are usually used to moderate the neutrons. However, they cannot be used in BNCT because the TNACS of hydrogen is too large to make the RFNT less than 3%. Under the RFNT conditions of less than 3%, the MNFTs moderated by a single-layer moderator, a double-layer moderator and a three-layer moderator were 1.007×10^{-4} cm^{-2}·s^{-1}, 2.590×10^{-4} cm^{-2}·s^{-1} and 2.882×10^{-4} cm^{-2}·s^{-1}, respectively. A three-layer moderator was composed of a 3 cm thick tungsten layer, a 14 cm-thick lead layer and a 21 cm thick diamond layer. If it is used to moderate the 14 MeV neutrons in BNCT, the yield of the D-T neutron generator only needs to be 3.470×10^{12} n/s.

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