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Neutron Yields, Energy Spectrum and Angular Distribution of D(d, n)^{3}He Reaction in a Thick Target Neutron Source

YAO Zeen[1], DU Hongxin[1], TAN Xinjian, ZHANG Yu[1],
Tooru Kobayashi[2], Gerard Bengua[2]

(1. *School of Nuclear Science and Technology, Lanzhou University, Lanzhou* 730000, *China*;
2. *Research Reactor Institute, Kyoto University, Osaka* 590-0494, *Japan*)

Abstract: A mathematical model and a program are developed to calculate neutron yields, energy spectrum and angular distribution of D(d, n)^{3}He reaction in a thick deuterium-titanium (TiD_x) target as incident deuteron energy lower than 1.0 MeV. D(d, n)^{3}He reaction cross section from nuclear data tables and stopping power derived with SRIM-2003 code are adopted in the calculatoin of neutron production of an accelerator-based D(d, n)^{3}He reaction neutron source. Integrated neutron yields, neutron energy spectrums and angular distribution are obtained.

Key words: D(d, n)^{3}He reaction; thick TiDx target; neutron yields; neutron energy spectrum; neutron angular distribution

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0 Introduction

Accelerator-based D(d, n)^{3}He (D-D) and T(d, n)^{4}He (D-T) fusion reaction neutron sources are widely used in many fields including basic nuclear data measurements, irradiation effect researches of fusion reactor materials and electronic materials, neutron activation analysis, and neutron cancer therapy[1]. Although neutron yield from D-T reaction is approximately two orders of magnitude larger than that from D-D reaction, applications of D-T neutron generator are restricted due to cost and safety concerns regarding tritium and short target lifetime. In recent years, compact neutron generators based on D-D reaction are widely investigated due to advantage of long target lifetime and manageability. For instance, a compact coaxial D-D neutron generator with neutron yield of 1.2×10^{12} n• s^{-1} for boron neutron capture therapy (BNCT) was successfully developed at Lawrence Berkeley National Laboratory (LBNL)[2] and Torino University[3]. A project on intensity neutron generator based on D-D and D-T fusion reactions is in progress at Lanzhou University[4]. It is expected to generate D-D neutron output higher than 1×10^{11} n• s^{-1}. Characteristics of D-D neutron source with thick target are studied for accurate design of beam shaping assembly (BSA) in various applications.

In previous investigations concerning beam shaping assembly (BSA) D-D neutron source was generally assumed generating isotropically 2.45 MeV mono-energetic neutrons[3,5]. In fact, D-D neutron source produce in a thick target has distinct angular distribution and intrinsic neutron energy spectrum. For accurate design of BSA, an improved D-D neutron source model based on neutron energy spectrum

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Biography: Yao Zeen (1966-), male, Gansu Province, professor, PhD, engaged in neutron physics and neutron technology application and angular distribution is required. Moreover, neutron energy spectrum and angular distribution are important for basic nuclear data measurements (such as in neutron integrate experiments).

Though experimeutal measurement is straight forward, neutron energy spectrums in all directions and neutron angular distributions are an arduous work. Neutron energy spectrums in some special emission directions from a D-D reaction neutron source are measured in laboratories. In this study, a mathematical model and a program computing yields, energy spectrum and angular distribution of neutrons generated by D-D reaction in a thick deuterium-titanium (TiD_x) target are developed. Neutron spectrum in any emission direction is simulated. Integrated and differential neutron yields, neutron energy spectrums and angular distribution are presented.

1 Methods

In a D-D neutron source with a thick target, integrated and differential neutron yields $Y(E_{dI})$ and $\frac{dY}{d\Omega}(\theta, E_{dI})$ are derived as

$$Y(E_{dI}) = \int_{E_{dI}}^{0} I_0 N_d \sigma(E_d) \frac{1}{S(E_d)} dE_d, \tag{1}$$

$$\frac{dY}{d\Omega}(\theta, E_{dI}) = \int_{E_{dI}}^{0} I_0 N_d \sigma(\theta, E_d) \frac{1}{S(E_d)} dE_d, \tag{2}$$

where θ is the neutron emission angle, E_{dI} the incident deuteron energy, I_0 the intensity of incident deuteron ion beam, N_d the atomic density of deuterium in target. $\sigma(E_d)$ and $\sigma(\theta, E_d)$ are integrated and differential cross sections of the D(d, n)^{3}He reaction, respectively. E_d is deuteron energy in the target. $S(E_d)$ is stopping power of deuteron in the target. Energy of neutron produced is computed with the following Q-value equation[6]

$$E_n(\theta, E_d) = \left\{ \frac{\sqrt{2E_d}}{4}\cos\theta + \left[\left(\frac{1}{4} + \frac{1}{8}\cos^2\theta\right)E_d + \frac{3}{4}Q\right]^{\frac{1}{2}} \right\}^2, \tag{3}$$

where Q is the Q-value of D(d, n)^{3}He reaction.

In order to calculate neutron yields, a thick target is divided into thin layers. Integrated neutron yield(ΔY_j) and differential neutron yield $\left(\frac{dY_j}{d\Omega}\right)$ in each layer are given by

$$\Delta Y_j(E_{d,j}) = I_0 N_d \sigma(E_{d,j}) \frac{1}{S(E_{d,j})} \cdot \Delta E_{d,j}, \tag{4}$$

$$\frac{dY_j}{d\Omega}(\theta, E_{d,j}) = I_0 N_d \sigma(\theta, E_{d,j}) \frac{1}{S(E_{d,j})} \cdot \Delta E_{d,j}, \tag{5}$$

respectively. Where j is index of the layer, $E_{d,j}$ the deuteron energy impinging in the j-th layer, $\Delta E_{d,j}$ the energy loss of deuteron ion in the j-th layer. Total integrated neutron yields of a thick target are obtained as

$$Y(E_{dI}) = \sum_j \Delta Y_j(E_{d,j}). \tag{6}$$

In the j-th layer $E_{d,j}$ may be approximated as deuteron ion energy before penetrating through. If

$E_{d,0} = E_{dI}$ and $\Delta E_{d,0} = 0$, $E_{d,j}$ and $\Delta E_{d,j}$ are computed by

$$E_{d,j} = E_{d,j-1} - \Delta E_{d,j-1}, \tag{7}$$

$$\Delta E_{d,j-1} = S(E_{d,j-1}) \cdot \Delta x_{j-1}. \tag{8}$$

Δx_{j-1} is thickness of the $(j-1)$-th layer. Energy of neutrons produced in the j-th layer $E_{n,j}$ is related to deuteron energy $E_{d,j}$ and neutron emission angle θ as in Eq. (3).

Differential yields and energies of neutrons produced in each layer are computed with Eqs. (3), (5), (7), (8). The calculation procedure terminates as $E_{d,j} \leqslant 0$. $dY_j/d\Omega$ is obtained as a function of $E_{n,j}$ and θ. Total differential neutron yield in each emission direction (neutron angular distribution) is computed as

$$\frac{dY}{d\Omega}(\theta) = \sum_j \frac{dY_j}{d\Omega}(\theta, E_{d,j}). \tag{9}$$

And neutron angular yield is obtained.

If $E_{n,j}(\theta)$ and $E_{n,j+1}(\theta)$ are energy of neutron produced in the j-th layer and $(j+1)$-th layer, energy difference of neutron is

$$\Delta E_{n,j}(\theta) = | E_{n,j}(\theta) - E_{n,j+1}(\theta) |. \tag{10}$$

Then, energy spectrum parameter in $\Delta E_{n,j}(\theta)$ energy interval is given by

$$\frac{dY_j}{d\Omega dE_n}(\theta, E_{n,j}) = \frac{\frac{dY_j}{d\Omega}(\theta, E_{d,j})}{\Delta E_{n,j}}, \tag{11}$$

where $dY_{n,j}/d\Omega$ is total differential neutron yield in $\Delta E_{n,j}(\theta)$ energy interval.

2 Result and discussion

Neutron production with a thick TiD_x target is studied. It is assumed that the atomic ratio of deuterium to titanium in the TiD_x target is 1.0, 1.5 or 2.0 and homogenous in the target[7,8]. The number of incident deuteron in the target is constant within a deuteron mean path. Integrated and differential cross sections of D(d, n)^{3}He reaction are recommended by Liskien et al.[9] The stopping power is calculated with SRIM-2003 code[10]. A program is developed to compute yields, energy spectrum and angular distribution of neutrons generated by D(d, n)^{3}He reaction in a thick TiD_x target with incident deuteron energies ≤1.0 MeV.

Figure 1 shows integrated neutron yields of a thick TiDx target with atomic ratio of deuterium to titanium of 1.0, 1.5 and 2.0. Examples on neutron energy spectrum with 150 keV, 400 keV and 1000 keV incident deuteron are shown in Figs. 2(a), (b) and (c), respectively. Figure 2 provides neutron spectrums from 0° to 180° with 5° intervals for a thick TiD with atomic ratio of deuterium to titanium of 1.5. Neutron angular distribution of a D-D neutron source is shown in Fig. 3.

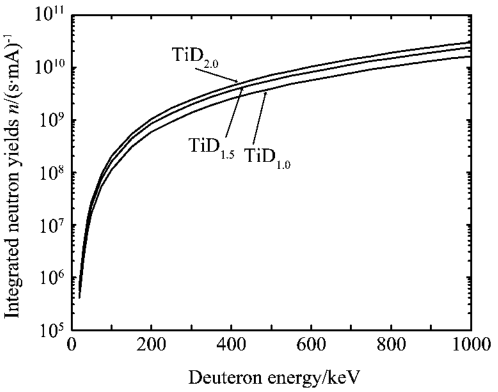

Fig. 1 Integrated neutron yields of D-D neutron source with thick TiD_x target

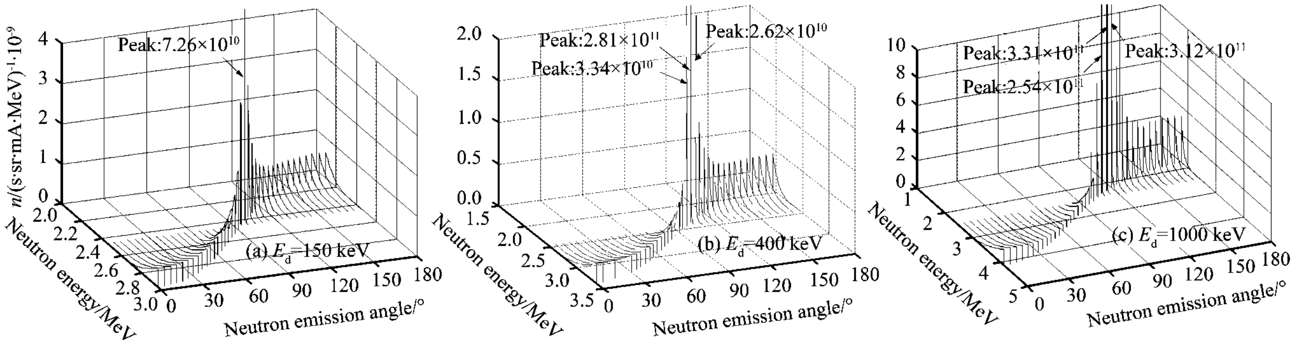

Fig. 2 Neutron energy spectrum of a D-D neutron source TiD$_{1.5}$ thick target at incident deuteron energies 150 keV, 400 keV, 1 000 keV

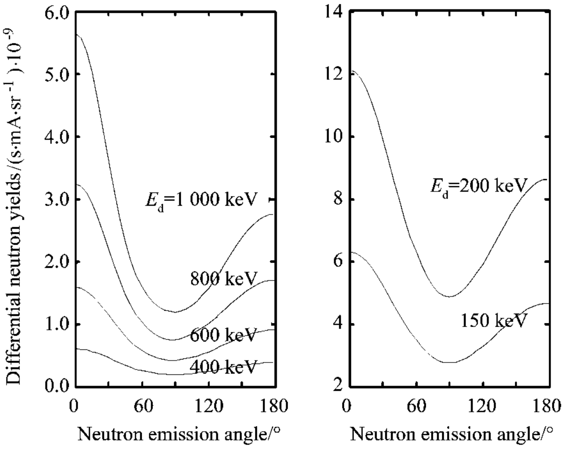

Fig. 3 Neutron angular distributions of a D-D neutron source with TiD$_{1.5}$ thick target

Deviation of calculation depends on thin target approximate method, cross section and stopping power data. Errors produced by thin target approximate method is small as thickness of layer is thin enough. Error of recommended cross section data are averagely lower than 5%. Uncertainty of calculated neutron yields mainly results from stopping power of deuteron in TiD$_x$ target. In the investigation, stopping power calculated by SRIM-2003 are used because experimental and recommended data of stopping power of deuteron in TiD$_x$ target are not enough. It was found that stopping power by SRIM-2003 is averagely about 18.8keV/micron larger than experimental result by Malbrough et al[11]. If Malbrough's results of the stopping power are regarded as a benchmark, yields obtained by stopping power calculated with SRIM-2003 are on the low side. Relative deviation of neutron yields is about 15%. Relative deviations of neutron energy spectrum and angular distribution are less than 15% because they are relative distribution of differential neutron yields.

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厚靶 D(d, n)^{3}He 反应加速器中子源的产额、能谱和角分布

姚泽恩[1], 杜洪新[1], 谭新建[1], 张 宇[1], Tooru Kobayashi[2], Gerard Bengua[2]

(1. 兰州大学核科学与技术学院, 甘肃 兰州 730000; 2. 日本京都大学反应堆研究所, 大阪 590-0494)

[摘 要] 给出一种计算氘钛厚靶 D(d, n)^{3}He 反应加速器中子源的产额、能谱和角分布的方法, 并发展了一个计算机模拟程序, 程序能够计算氘束流能量小于 1.0 MeV 的中子源的产额、能谱和角分布. 计算时使用推荐的 D(d, n)^{3}He 反应截面数据和来自 SRIM-2003 程序的氘在氘钛靶中的阻止本领数据. 给出一些典型计算结果, 包括中子积分产额、中子能谱和角分布.

[关键词] D(d, n)^{3}He 反应; TiD*x* 厚靶; 中子产额; 中子能谱; 中子角分布

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