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Study on the method with associated particle for measuring the neutron yield of D–D neutron generator†

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ABSTRACT

A measuring method with associated particles has been developed and tested to monitor the D–D neutron yield at a ZF-300 intense neutron generator in Lanzhou University. The experiment has been carried out in an environment of 236 keV and 0.5 mA of deuteron beam with a thick titanium-filmed target of molybdenum substrate at 135° for proton emission. All correction factors, including anisotropy factors and the yield ratio of neutron and proton, have been calculated, and the uncertainty of calculation result has been discussed.

1. Introduction

In recent years, the neutron generator based on D–D reaction is widely applied due to its potential applications and its advantage of increased safety due to the lack of using radioactive tritium target but just long lifetime target with D ion self-injection effect [1–3]. The present applications of D–D neutron generators have brought about the need to know the absolute neutron source strength (namely the total neutron yield). And a method with associated particles is possibly one of the most accurate ways of the neutron source strength calibration in D–D neutron generators. In the process, the accelerated deuterons bombard the solid-state Ti-targets saturated with deuterium (D–Ti target) in the generator. Then protons are produced by the D(d,p)T reaction channel and neutrons are produced by the D(d,n)^{3}He reaction channel. The associated proton counts from the D(d,n)^{3}He reaction are generally collected to determine the neutron yield for the proton peak from the D(d,p)T reaction as it is easily distinguished from the background spectrum due to its energy of 3 MeV. This puts forward the task of calculating the yield ratio ($Y_{d,n}/Y_{d,p}$) of the neutron to the proton according to the cross-section data of D(d,p)T and D(d,n)^{3}He reactions. However, the D(d,p)T and D(d,n)^{3}He reactions are anisotropic even at lower deuteron energies. Thus, the anisotropic factors (R) also need to be calculated. Usually, the product of $R$and $Y_{d,n}/Y_{d,p}$is regarded as the total correction factors (R_T).

The calculation methods of R_T have been investigated in some previous research works [4–6]. However, the R_T data brought about by the different researchers do not agree with each other. For example, the deviation between Ruby's data [4] and Jordanova's data [5] was about 4.5% for a 150 keV deuteron beam. The precision discrepancies of the reaction across section data used by the different researchers might be the main reason for the disagreement. In this work, the most accurate cross-section data available at present are applied to compute the R_T values in an environment of 20–600 keV deuteron energies and 135° for the proton emission direction. And it forms a measurement system with associated particle detection results at 135°. All the tests were carried out at the ZF-300 intense neutron generator in Lanzhou University.

2. Methods

2.1. Principles

The principle for monitoring D–D neutron yield with associated particles is shown in Fig. 1. A charged particle detector is installed at an angle θ to the incident deuteron direction for measuring the associated proton count. The following equations are applied to calculate the neutron yield. For D–D neutron generator using the

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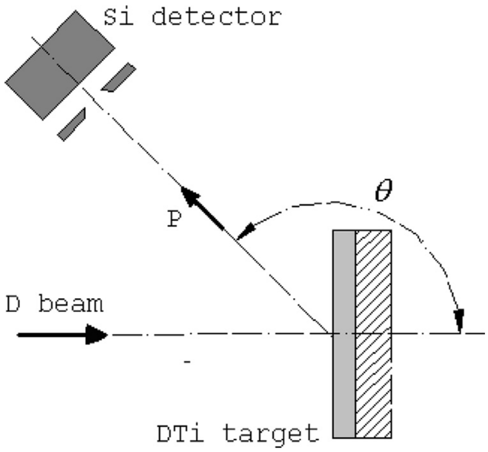

Fig. 1. Principle of associated particle measurement.

thick D–Ti target, the neutron yield (Y_n) is derived from [4,5]

$$Y_n = 4\pi \frac{n_p}{\Omega_p} R_{thick} \left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick} \quad (1)$$

where n_p is the proton count per-second and Ω_p is the solid angle around angle θ; R_{thick} and $(Y_{d,n}/Y_{d,p})$ are the anisotropic factor and the yield ratio, respectively which can be computed by [4,5]

$$R_{thick} = \frac{\int_o^{E_d} \left(\frac{\sigma_{d,p}}{4\pi} / \frac{dE}{dx}\right) dE}{\int_0^{E_d} \left(\frac{d\sigma_{d,p}}{d\omega'} / \frac{dE}{dx}\right) \left(\frac{d\omega'}{d\omega}\right) dE} \quad (2)$$

$$\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick} = \frac{\int_0^{Ed} \left(\frac{\sigma_{d,n}}{4\pi} / \frac{dE}{dx}\right) dE}{\int_0^{Ed} \left(\frac{\sigma_{d,p}}{4\pi} / \frac{dE}{dx}\right) dE} \quad (3)$$

where E_d is the incident deuteron energy, $\sigma_{d,n}$ and $\sigma_{d,p}$ are respectively the integrated cross-section of D(d,n)^{3}He reaction and D(d,p)T reaction in the lab frame (Lab.), $d\sigma_{d,p}/d\omega'$ is the differential cross-section of D(d,p)T reaction at an angle θ_C in the center-mass system (C.M.) to that at the angle θ in the Lab. frame, dE/dx is the stopping power of deuteron in the D–Ti target, and $d\omega'/d\omega$ is the ratio of change of the C.M. solid angle to Lab. solid angle. If the product of R_{thick} and $(Y_{d,n}/Y_{d,p})_{thick}$ is regarded as the total correction factor (R_T), the neutron yield can be derived from

$$Y_n = 4\pi \frac{n_p}{\Omega_p} R_T \quad (4)$$

2.2. Calculation of R_T values

In order to compute R_T for the thick TiD target, the thick target was divided into many thin layers to make the results more accurate. According to Eqs. (2) and (3), R_{thick} and $(Y_{d,n}/Y_{d,p})_{thick}$ can be approximately calculated by the following equations:

$$R_{thick} = \frac{\sum_i \left(\frac{\sigma_{d,p}(E_i)}{4\pi} / \frac{dE}{dx}(E_i)\right) \Delta E_i}{\sum_i \left(\frac{d\sigma_{d,p}}{d\omega'}(E_i,\theta_C) / \frac{dE}{dx}(E_i)\right) \left(\frac{d\omega'}{d\omega}(E_i,\theta)\right) \Delta E_i} \quad (5)$$

$$\left(\frac{Y_{d,n}}{Y_{d,p}}\right) = \frac{\sum_i \left(\frac{\sigma_{d,n}(E_i)}{4\pi} / \frac{dE}{dx}(E_i)\right) \cdot \Delta E_i}{\sum_i \left(\frac{\sigma_{d,p}}{4\pi}(E_i) / \frac{dE}{dx}(E_i)\right) \cdot \Delta E_i} \quad (6)$$

where i is the index of the layers, E_i is the deuteron energy impinging in the ith layer, and ΔE_i is the energy loss of deuteron ion in the ith layer. If $E_0 = E_d$ and $\Delta E_0 = 0$, E_i and ΔE_i are computed by the following equations:

$$E_i = E_{i-1} - \Delta E_{i-1} \quad (7)$$

$$\Delta E_{i-1} = \frac{dE}{dx}(E_{i-1}) \Delta x_{i-1} \quad (8)$$

Here Δx_{i-1} is the thickness of the $(i-1)$th layer. $\frac{d\omega'}{d\omega}(E_i,\theta)$ is computed by [4]

$$\frac{d\omega'}{d\omega}(E_i,\theta) = \frac{J\left\{\cos\theta + \left[((J^2+L)/J^2) - \sin^2\theta\right]^{1/2}\right\}^2}{\left(E'_{ip}\right)^{1/2}\left[((J^2+L)/J^2) - \sin^2\theta\right]^{1/2}} \quad (9)$$

$$J = \frac{(m_1 m_3 E_i)^{1/2}}{m_3 + m_4} \quad (10)$$

$$L = \frac{m_4(Q + E_i) - m_1 E_i}{m_3 + m_4} \quad (11)$$

where subscripts 1, 2, 3 and 4 are used to distinguish, respectively, the mass of the incident deuteron, the deuteron in the D–Ti target, proton and triton. Q is the Q-value of D(d,p)T reaction (4.033 MeV). E'_{ip} is the proton energy in C.M. system, which is derived from [7]

$$E'_{ip} = E_{ip}\left(\frac{\sin\theta}{\sin\theta_C}\right)^2 \quad (12)$$

$$\theta_C = \theta + \sin^{-1}(\gamma \sin\theta) \quad (13)$$

$$\gamma = \left(\frac{E_i}{3(E_i + 2Q)}\right)^{1/2} \quad (14)$$

where E_{ip} is the proton energy at the angle θ in Lab. frame, and it can be computed by following equation [8]:

$$E_{ip} = \left(0.35402 E_i^{1/2} \cos\theta + \frac{(2.0382 E_i \cos^2\theta + 48.92325 + 4.03062 E_i)^{1/2}}{4.02276}\right)^2 \quad (15)$$

In the calculation process of R_T, the total cross-section data ($\sigma_{d,p}$ and $\sigma_{d,n}$) were taken from ENDF/B-VI [9]. The differential cross-section data ($d\sigma_{d,p}/d\omega'$) in C.M. system were from Refs. [10,11]. The stopping powers (dE/dx) of deuteron in the D–Ti target were computed by using the SRIM-2003 code [12].

With the code achieved based on above mentioned data, R_T values at the 135° detector at deuteron energies from 20 to 600 keV has been calculated. The computed R_T values as a function of deuteron energy are presented in Fig. 2. A comparison has been made between our results and earlier calculations by Ruby [4] and Jordanova [5]. It is clear that our results are coincident with Jordanova's data in the energy range of 50–150 keV. However, R_T values of this work deviate significantly from Ruby's in the energy range of 50–300 keV. Maximal relative deviation is about 5%. This deviation we think is due to Ruby's application of earlier cross-section data.

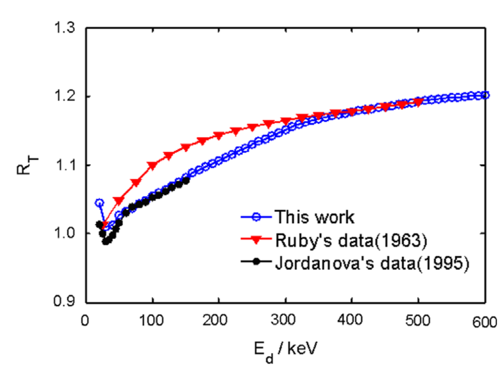

Fig. 2. R_T values vs. deuteron energy.