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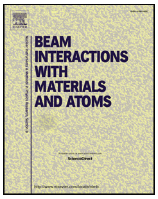

Yield measurement and Monte Carlo correction of CPDG neutron generator

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ABSTRACT

It is useful to obtain the exact neutron yield and distribution of a portable neutron generator. In this paper, the neutron yield of a K400 accelerator D-D neutron source under conditions of 160 kV and 25 uA is $1.69 \times 10^6 \pm 4.1 \times 10^4$ n/s, which is calibrated using the associated proton method. A long counter consisting of a ^{3}He counter surrounded by a paraffin cylinder was used as secondary standard after efficiency calibration using a K400 accelerator. The Monte Carlo method is then used to evaluate the distribution change of emitted neutrons from each surface of the CPDG caused by its structural materials. Energy spectrum distortion and angle distribution distortion of emitted neutrons are studied. Simulation results show that the proportion of the forward neutron is reduced and the proportion of the lateral neutron is increased. The number of neutron transporting into the counter has been reduced by 28.1%, 28.4%, 29.8%, 29.0%, 28.7%, and 28.0% for acceleration voltages of 90 kV, 100 kV, 110 kV, 120 kV, 130 kV, and 160 kV, respectively. In addition, the respective yield correction factors caused by structural materials are 1.36, 1.38, 1.38, 1.34, 1.37, and 1.39. The neutron yield of the CPDG is 1.28×10^6 and 1.75×10^6 before and after Monte Carlo correction when working at conditions of 130 kV and 600 μA. The total uncertainty of this result is approximately 6%.

1. Introduction

D-D and D-T neutron beams play an important role in basic scientific research and industrial applications. They can be used in prospecting [1], radiography [2,3], activation analysis [4], and many other fields. Miniaturization of a device is easy because a small target can supply a high-flux neutron beam, with the advantage of low cost and easy operation. Using nonradioactive deuterium as the target, a D-D neutron generator has higher security compared with a D-T neutron generator that uses radioactive tritium as the target.

Obtaining the exact neutron yield of a device is very important. Counting neutrons using neutron counters or activation detectors is often used to measure neutron yield [5,6]. However, associated proton counting is preferred [7], because the efficiency of a proton detector is more accurately defined at a given geometry, and the proton peak can be easily distinguished from the background due to its high energy, which makes this method have a higher accuracy than others. Unfortunately, for a portable D-D neutron generator, whose neutron tub is fixed around structural materials, using a calibrated long counter as a secondary standard may be the best method to measure its neutron yield, because the generated protons are not possible to fetch out for detection. However, the position distribution, direction distribution, and energy distribution of emitted neutrons have changed because of interactions in the structural materials, making the neutron yield obtained by a secondary standard inconsistent with the generated yield. Therefore, it is necessary to correct the result by a certain method.

CPDG, a portable D-D neutron generator developed by Northeast Normal University, China, is used for neutron backscattering detection of land mines. In this paper, the exact neutron yield of a K400 accelerator neutron source is obtained first using associated proton method, and a long counter is calibrated using the K400 as a secondary standard by which to measure the yield of CPDG. A Monte Carlo method is then used to study the effect of structural materials on the distribution change of neutrons, especially the count change of the long counter, which is then used to correct the original yield of the CPDG.

2. Theory and experimental setup

2.1. Associated-particle theory and measurement system

$$D + D \rightarrow {}^3\text{He} + n + 3.27\ \text{MeV}, \tag{1a}$$

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$$\mathrm{D} + \mathrm{D} \rightarrow p + {}^{3}\mathrm{H} + 4.03\ \mathrm{MeV}. \tag{1b}$$

In a D-D neutron generator, an accelerated deuterium ion beam bombards the D-Ti target, and two kinds of nuclear reactions take place: the neutron channel reaction in Eq. (1a) and the proton channel reaction in Eq. (1b). The cross-section ratio of the two reactions is related to the energy of incident deuterium ion. By counting the protons that recoil into a well-defined solid angle, the neutron flux at a certain angle and the total neutron yield can be determined; this is associated proton method:

$$\varphi_n(\theta, E_d) = A_F(\theta, E_d)\cdot\frac{n_p}{\Delta\Omega_p} = \frac{(d\omega/d\omega')_p(E_d, \theta_p)}{(d\omega/d\omega')_n(E_d, \theta_n)}\cdot\frac{\sigma_n(E_d)}{\sigma_p(E_d)}\cdot\frac{h_n(E_d, \theta_n')}{h_p(E_d, \theta_p')}\cdot\frac{n_p}{\Delta\Omega_p}, \tag{2}$$

$$\varphi_n(E_d) = \int_0^{\pi} A_F(\theta, E_d)\cdot\frac{n_p}{\Delta\Omega_p}d\theta = F(E_d)\cdot\frac{n_p}{\Delta\Omega_p}. \tag{3}$$

The neutron fluence in the unit solid angle at an angle of θ, the angle to the accelerated deuterium beam direction, can be calculated by formula 2. θ_p is the angle between the proton detector and the incident deuterium beam, and $\Delta\Omega_p$ is the solid angle of the detector to the target. $\sigma_n(E_d)$ and $\sigma_p(E_d)$ are cross-sections of neutron channel and proton channel at deuterium energy of E_d, respectively. $(d\omega/d\omega')_p(E_d, \theta_p)$ and $(d\omega/d\omega')_n(E_d, \theta_n)$ are the rates of change of the laboratory solid angle to the center-of-mass solid angle for proton and neutron, respectively. $h_p(E_d, \theta_p')$ and $h_n(E_d, \theta_n')$ are the angle distribution correction factors for a proton and neutron, respectively. A_F is called the anisotropy factor. A numerical method is used to calculated the neutron angle distribution at some energy of the incident deuterium beam. The energy of the deuterium beam decreases before the nuclear action takes place, so the average energy $\overline{E_d}$ calculated using Eq. (4) is used in the numerical calculation. Data used in the numerical calculation are from [8], and the distributions are shown in Fig. 1. It is obvious that the neutron angle distribution is different for incident deuterium beams with different energies. The forward effect increases as the energy increases, so the proportion of neutrons that are transported into the counter detector is different at different accelerating voltages, even without consideration of structural materials. The neutron yield of the target can be obtained by the integral of θ from 0 to π, as shown in Eq. (3):

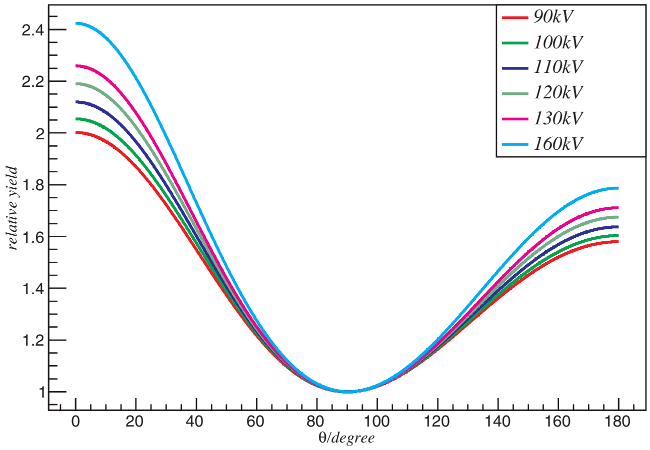

Fig. 1. Angle distribution of neutrons generated by incident deuterium with energies of 90 keV (red), 100 keV (green), 110 keV (black), 120 keV (yellow), 130 keV (pink), and 160 keV (aqua). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\overline{E_d} = \frac{\int_0^{E_0}\frac{\sigma_d(E_d)}{\frac{dE}{dX}(E_d)}E_d\,dE_d}{\int_0^{E_0}\frac{\sigma_d(E_d)}{\frac{dE}{dX}(E_d)}dE_d}. \tag{4}$$

A D-Ti target with a diameter of 12 mm is used in the K400 accelerator. The substrate is 0.8-mm-thick oxygen-free Cu with a diameter of 28 mm. The target is hemispherical and placed in a stainless-steel target chamber. The water-cooling method is used for the target, whose surface is 45° to the incident deuterium beam. A Au-Si surface barrier detector with an effective diameter of 4 mm is used for proton detection, and it is placed at 178° to the incident deuterium beam. The feasibility of measuring at this angle has been verified, and the uncertainty has been measured [9]. The detector has a window of 2 μm Al. In front of the detector is a Cu-foil collimating grating with a thickness of 100 μm. The electronics measurement system consists of a charge-sensitive preamplifier, 500 V high-voltage module, main amplifier, and multichannel buffer 927.

2.2. Secondary standard and experiment system

A long counter is a neutron detector that has almost constant(or slowly changed) efficiency for neutrons from 0.025 MeV to 14 MeV. Its neutron-detection efficiency is high. The long counter used in the measurement system consists a ^{3}He counter (Houston DOTE-1213) surrounded by a paraffin cylinder. The efficiency of this long counter is calibrated by the K400 accelerator, whose neutron yield is measured exactly using the associated proton method, and this long counter is then used as a secondary standard. The count rate of this long counter is n_{He0}, and φ_0 is the K400 accelerator's neutron yield. The count rate changes to n_{He1} when the neutron yield changes to φ_1. Then, φ_1 can be calculated by Eq. (5). F_{He} is the long counter efficiency factor reflecting the effect of the long counter's efficiency. F_{cor} is a correction factor reflecting the effect of changed conditions on the long counter. If the measurement conditions remain unchanged, the value of F_{cor} is 1:

$$\varphi_1 = F_{cor}\cdot\frac{\varphi_0}{n_{He0}}\cdot n_{He1} = F_{cor}\cdot F_{He}\cdot n_{He1}. \tag{5}$$

The layout of primary equipment while calibrating the long counter using the K400 accelerator is shown in Fig. 2(a). The target chamber is parallel to the ground surface, and the center of the target is at a height of $H = 149$ cm. The long counter, whose center axis is parallel to the deuterium beam direction, is located in front of the target on the ground, and the distance from the front surface center of the paraffin to the center of the target is $d = 206.5$ cm. The positions of the long counter and working state of the neutron counter are fixed after efficiency calibration. The CPDG neutron generator is placed at certain position so that its target's center coincides with the K400 accelerator's target center, and the direction of the deuterium beam remains unchanged. Fig. 2(b) is a photograph of the K400 and our neutron generator CPDG.

2.3. Monte Carlo simulation setup

Neutrons generated in the portable generator interact with various structural materials. Some transport out without any reaction, some transport out after scattering, and some are absorbed during transportation. Then, the energy spectrum and angle distribution of the emitted neutrons are different from those of the original neutrons, and the number that transport into the counter is different from that without structural materials. The Monte Carlo simulation toolkit Geant4 [10,11] was used to study this effect. Fig. 3(a) shows the generator's detailed size. Fig. 3(b) shows the model used in this simulation, whose size is the same as that shown in Fig. 3(a), and whose structure has been reasonably simplified from that of the CPDG. Materials used and their specific components are shown in Table 1.