Simulation of D-D Neutron Yeild Based on Geant 4

Chenyang Dong[a], Changying Yuan, Bo Li, Haobo Xu, Huiyi Lyu[b]

School of National Defense Science and Technology, Southwest University of Science and Technology, Mianyang 621010, China.

[a]54146803@qq.com, [b]huiyilv@163.com

Abstract

With the increasing demand for neutron generation in experimental research and industrial applications, accelerator-based neutron sources have achieved great development. The D-D neutron generator has the advantages of compact structure, high cost performance, high neutron intensity, and the capacity to generate neutron beams approaching a single energy in a wide energy range. Geant4 program is used to simulate and calculate the neutron energy spectrum, yield and angular distribution of the accelerator neutron generator under construction in Southwest University of Science and Technology under different incident energies. It can be seen from the simulation results that the neutron yield increases with the energy of deuterium ions within the incident energy range of deuterium ions in this study. The angular distribution of neutrons tends to be 0° and 180°. According to the analysis on the neutron energy spectrum, it is discovered that the neutron energy is distributed in a certain range. Hence, the produced neutron beams are with a quasi-single energy. The simulation results provide a reference for the index of the accelerator neutron generator and how to optimize it.

Keywords

Geant 4; Neutron Generator; Neutron Yield; Angular Distribution; Neutron Energy Spectrum.

1. Introduction

The accelerator neutron source can be widely used in various aspects such as nuclear data measurement, radiation damage research of fusion reactor materials, semiconductor anti-nuclear reinforcement, radiation breeding, activation analysis, and cancer treatment.Operating this type of neutron generator and the usual supervision and maintenance burden is very small, because it does not contain radioactive materials, and will not produce radiation when closed [1-5]. 1 cm^3 of metal titanium can absorb up to 9.2×10^{22} hydrogen atoms, which is the elemental metal material with the highest hydrogen absorption density found so far [6], The incident deuterium ions will interact with the deuterium atoms in the deuterium titanium target under the acceleration of the accelerator:

$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n \tag{1}$$

$$^{2}H + {}^{2}H \rightarrow {}^{3}H + p \tag{2}$$

The probability of reaction (1) and (2) occurring when the deuterium ion energy is lower than 2 MeV is almost equal. The Q value of the D-D reaction is approximately equal to 3.27 MeV, of which approximately 2.45 MeV is carried away by neutrons. Under the lower deuterium ion beam energy, the D-D reaction has a higher reaction cross section. Under the lower accelerator energy condition, a higher neutron yield can be achieved, and it can be miniaturized and has broad application value.

This article focuses on the evaluation of the accelerator neutron generator under construction at Southwest University of Science and Technology. The main indicators for evaluating the neutron source include: neutron energy spectrum, neutron yield, and neutron angle distribution.

2. Program introduction

The Geant4 program can be used to simulate the physical process of particle transport in matter. The cross-sectional data used in the program is taken from the database evaluated by ENDF/B-VIII for a few elements (^{1,2,3}H, ^{3,4}He, ^{6,7}Li, ^{10,11}B, ^{7,9}Be, ^{12,13}C,^{14,15}N, ^{16,17,18}O, ^{19}F, ^{232}Th, ^{233,235,238}U, ^{239}Pu) data. The cross-section used in the D-D reaction simulated in this paper is taken from the ENDF/B-VIII database. Since there are only a few of these isotopes, most of the isotope data uses the TENDL database of the TALYS nuclear model (TALYS is an open source software package for simulating nuclear reactions). TENDL contains the evaluation of seven incident particles, including: Deuteron, Triton, ^{3}He, Neutron, Proton, Alpha and Gamma [7]. Applicable to all isotopes with a lifespan of more than 1 second: Z = 1^{1}H to Z = 115^{291}Mc (about 2800 isotopes), with a maximum energy of 200 MeV, with covariance. The Geant4 program determines the path and state of the particle and records the feedback by tracking the physical process (collision, reaction, absorption, etc.) that occurs when the particle passes through the medium.

The Geant4 version used in the simulation is 10.06, and the database version is G4TENDL1.3.2. The physical processes used in this article include: elastic collisions and inelastic collisions of hadrons, elastic and inelastic collisions of ions, ionization, decay, etc. The environmental variables involved include: Deuteron, Alpha, ^{3}He, Trition, Proton.

3. Beam and target parameters

In the Geant4 program, the physical model constructed is shown in Fig 1. The world is a 3.2 cm×3.2 cm×3.2 cm cube with the body center at the origin of the coordinates. The surface of the deuterium-titanium target is perpendicular to the z-axis direction, and the center coincides with the origin of the coordinate. The deuterium ion beam is perpendicular to the deuterium-titanium target along the z-axis from (0, 0, -1 cm). The beam spot diameter of the deuterium ion source is 8 mm, the number of incident deuterium ions per unit time is 2×10^{10}, and the deuterium ions are uniformly distributed on the beam cross section. The deuterium titanium target has a diameter of 3 cm, a thickness of 4.5 μm, and a density of 3.79 g/cm^3. The mass fraction of deuterium element is 3.26%, the mass fraction of titanium element is 96.74%, and the atomic ratio of deuterium-titanium is 1.6:1. Both the deuterium ion beam and the deuterium titanium target are in an ideal state and do not contain other impurity ions and atoms.

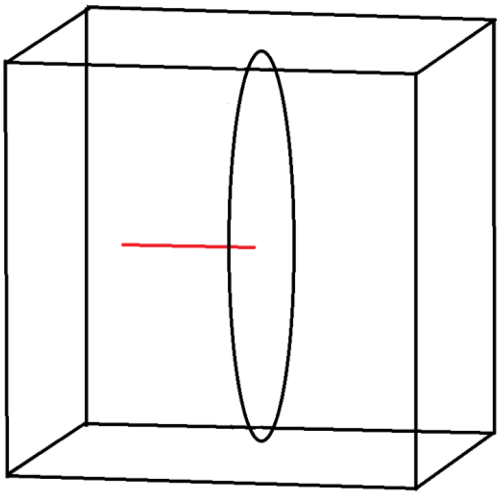

Fig. 1 Geometric model

4. Simulation results and analysis

Use the Geant4 program to simulate the D-D reaction of the incident deuterium ion beam with energy between 300-600 keV,and D-D reactions are observed every 20 keV.Since the upper limit of the number of incident ions each time is 2×10^9, taking into account the running time of the program and in order to reduce the error, each energy is run 10 times, and the results of each run are different. Finally, the results of the 10 runs are calculated with.

Fig. 2 shows the neutron yield of incident deuterium ion energy at 300-600 keV. The neutron yield is determined by the D-D reaction cross section. Within 1 MeV energy in the low energy region, the total cross section of the D-D reaction increases with the energy of the incident deuterium ion beam. While increasing, the output also increases monotonously. In addition to increasing the incident deuterium ion energy to increase neutron production, the yield can also be increased by increasing the deuterium-titanium atom ratio of the deuterium-titanium target and increasing the probability of the D-D reaction. By the microscopic expression of current intensity

$$I = neSv \tag{3}$$

In formula (3), *n* represents the number of deuterium ions per unit volume; *e* is the electric quantity of a single charge; *S* is the cross-sectional area of the conductor, that is, the cross-sectional area of the beam; *v* is the directional movement rate of deuterium ions, and is affected by the energy influences. It can be seen from the current microscopic expression that the number of incident ions simulated in this paper is only 2×10^{10}. In practice, the current of deuterium ion beams commonly used is as strong as 0.5 mA, and the number of deuterium ions emitted per unit time is about 7.3×10^{14}. The amount will also be greatly improved.

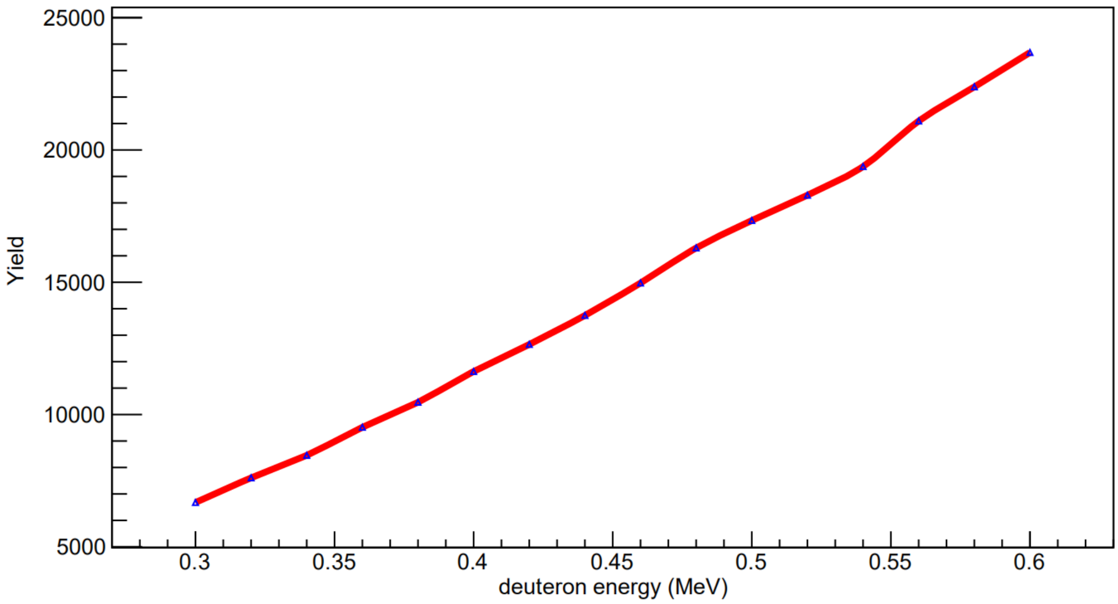

Fig.2 Neutron yield with incident deuterium ion energy in the range of 300-600 keV

Fig. 3 shows the angular distribution of neutrons at different energies. Unsmooth angular distribution curve is the random error caused by fewer counts, which can be eliminated by increasing the number of simulations. The neutron energy should be [8]:

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

In formula (4), E_n is the neutron energy, E_d is the incident deuterium ion energy, θ is the neutron exit angle, and Q is the Q value of the reaction.

E_n is a function of E_d and θ, so when the incident energy E_d is determined, a single-energy neutron beam can be obtained in the determined θ direction. The energy of the neutrons emitted in the 0° direction is the largest, and the energy gradually decreases with the increase of the exit angle, and the energy reaches the lowest at 180°.

According to the simulation results, the lower the incident deuterium ion energy, the smaller the difference between the number of neutrons in the 0° and 180° directions. With the increase of incident deuterium ion energy, the neutron distribution tends to 0° and 180° directions more and more. The accelerator neutron source is determined by the incident particle direction, taking the incident direction as the axis, where the sub-angular distribution is axisymmetric, that is, the angular distribution is axisymmetric from 0° to 180° and from 0° to -180°.

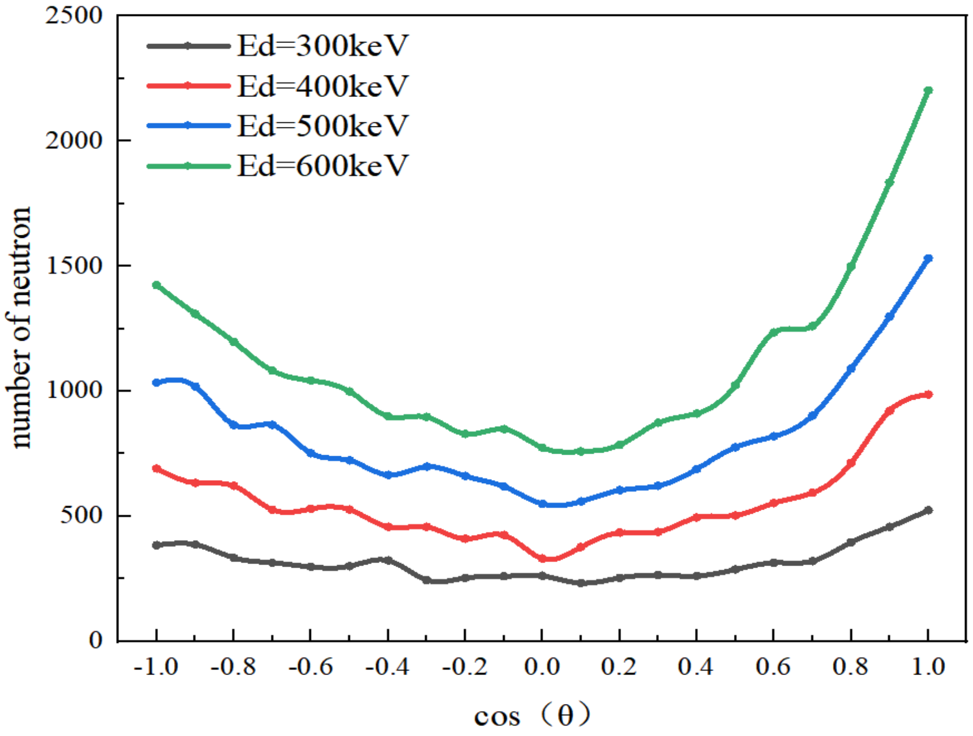

Fig. 3 Neutron angular distribution under different incident deuterium ion energies

The neutron energy spectrum when the incident energy is 300-600 keV is shown in Fig. 4. It can be seen that the energy of most neutrons is between 2-3.5 MeV, and a very small number of neutrons are distributed between 0-2 MeV. The number of neutrons near 2.5MeV is the largest. With the increase of incident deuterium ion energy, the number and energy distribution of neutrons with energy around 2.5 MeV gradually increase. The neutron source is single-valued only in some limited neutron energy intervals. The single-energy neutron energy range of the D-D neutron generator is 1.65-7.75 MeV. The maximum energy of neutrons can be increased by increasing the energy of the incident deuterium ion beam.

From the neutron energy formula, the neutron energy at the 0° angle is the highest, and the yield is the largest. The number of neutrons at the highest energy in the energy spectrum in Figure 4 is not the most. This is because the incident deuterium ion energy will be affected in the target. Loss, resulting in the neutron beam emitted from the same angle containing multiple different energies, the same neutrons emitted from the 0° angle, including the neutron with the highest energy, and other neutrons with lower energy than the highest energy. Neutrons emitted from other angles also contain these energies, so the number of neutrons at the highest energies in the neutron energy spectrum is not the largest.

In the actual process of generating neutrons through nuclear reactions, it is impossible to obtain absolutely monochromatic neutrons. The energy of neutrons always has a certain distribution. The half-width of the neutron energy spectrum is an important indicator to measure the monochromaticity of neutrons.

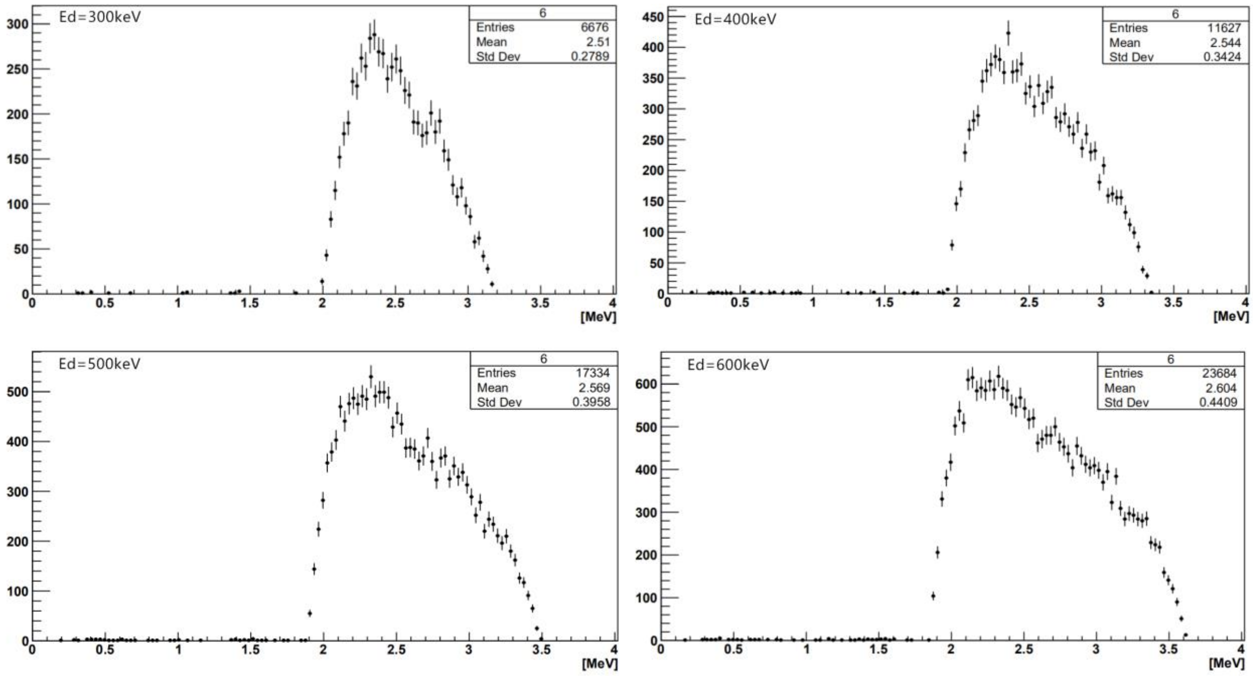

Fig. 4 Neutron energy spectrum of incident deuterium ion energy in the range of 300-600 keV

5. Conclusion

In this paper, the Geant4 program is used to simulate the D-D reaction at different energies, and the neutron energy spectrum, yield and angular distribution of the D-D neutron generator at different energies are analyzed and studied. The research results show that the increase of incident deuterium ion energy increases the energy range of neutrons, and the yield increases. The neutron distribution tends to 0° and 180° directions. When the definite neutron exit angle θ is determined, single neutrons can be obtained. Energy neutron beam, on the contrary, the neutron exit angle θ can also be obtained according to the required neutron energy. The simulations in this article are all under ideal conditions. In practice, the deuterium ion source will contain impurity ions, especially metal ions [9]. These impurity ions will reduce the yield of neutrons. The ion source can be analyzed by beam analysis to reduce impurities.

In addition, it is also found in the simulation that when the number of incident deuterium ions is large enough, a small part of the incident deuterium ions will undergo a nuclear reaction with the ^{3}H generated in reaction (2):

$$^{3}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.58\ \mathrm{MeV} \tag{5}$$

Reaction (5) is an exothermic reaction, releasing 17.58 MeV of energy, among which the energy of releasing neutrons is about 14 MeV. However, the number is very small and the contribution of reaction (5) to the neutron yield can be ignored. The 14 MeV single-energy neutrons produced in reaction (5) can be used in the research of advanced nuclear energy technology represented by fusion reactors and accelerator-driven subcritical systems, the application of nuclear technology represented by neutron cancer treatment, and basic research in national defense and military industry [10].

The results of these simulations can provide a more realistic reference for the indicators of the accelerator neutron generator under construction at Southwest University of Science and Technology and how to optimize them, and enable us to better understand the complex physical processes involved. The result can also be applied to researchs on neutron beam application and neutron activation analysis.

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