Simulation Study of Neutron Yield in Self-Target Neutron Tubes

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Abstract

Self-targeting neutron tubes exhibit advantages of high temperature resistance, high stability, and long service life, offering broad application prospects in nuclear well logging. Simulation studies on neutron yield of self-targeting neutron tubes can provide a foundation for their physical design. Based on the TARGET program and utilizing the relationship between integral neutron yields of D-T and T-D reactions under thick-target conditions, an equivalent simulation method for T-D reactions was established, enabling the simulation and calculation of neutron yields for self-targeting neutron tubes. Using this method, the effects of beam parameters and target parameters on neutron yield were calculated and analyzed. The results demonstrate that the neutron yield reaches its maximum when the D-T mixing ratio in the incident beam is 1:1, with any deviation in D proportion decreasing the yield. Parameters including target atomic ratio, beam energy, and single-atom ion fraction in the beam are positively correlated with neutron yield; to enhance neutron yield, these parameters should be maximized within the design constraints of the neutron tube.

Full Text

Simulation Study of Neutron Yield in Neutron Tubes with Drive-in Targets

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Abstract

Neutron tubes with drive-in targets offer significant advantages in high-temperature resistance, stability, and longevity, making them highly promising for nuclear logging applications. Conducting simulation studies on neutron yield from such tubes provides essential guidance for their physical design. This paper establishes an equivalent simulation method for T-D reactions based on the TARGET program by leveraging the relationship between integral neutron yields of D-T and T-D reactions under thick-target conditions, enabling the simulation of neutron yield in drive-in target neutron tubes. Using this method, we calculate and analyze the effects of beam parameters and target parameters on neutron yield. The results demonstrate that neutron yield reaches its maximum when the incident beam contains a 1:1 deuterium-tritium mixture, with any deviation from this ratio reducing yield. Target atom ratio, beam energy, and the proportion of monatomic ions in the beam all exhibit positive correlation with neutron yield. To enhance neutron yield in drive-in target neutron tubes, these parameters should be maximized within the design constraints.

Keywords: Neutron tube with drive-in target; D-T reaction; T-D reaction; Neutron yield

1. Drive-in Target Neutron Tubes

A drive-in target neutron tube is a sealed D-T neutron tube that utilizes a drive-in target. Its working principle involves first injecting deuterium-tritium mixed gas into the tube, which is then ionized by an ion source into deuterium and tritium ions. These ions are extracted and accelerated to bombard a blank target, gradually implanting deuterium and tritium into it. Over time, the target becomes saturated with deuterium and tritium, forming a drive-in target. This approach eliminates the need for pre-hydriding the target, resulting in better stability and longer service life.

During operation, the accelerated D-T mixed ion beam undergoes fusion reactions with deuterium and tritium atoms already present in the target, producing 14 MeV neutrons and a small number of 2.5 MeV neutrons. The beam-target interaction involves four reaction channels: D(d,n)^{3}He, T(d,n)^{4}He, D(t,n)^{4}He, and T(t,2n)^{4}He, abbreviated as D-D, D-T, T-D, and T-T reactions. While D-D reactions produce 2.5 MeV neutrons, both D-T and T-D reactions generate 14 MeV neutrons. According to the ENDF/B-VII.1 deuterium and tritium sub-library [18], the integral cross-sections for these four nuclear reactions vary with incident ion energy as shown in [Figure 1: see original paper]. For D-T neutron tubes used in oil and gas logging applications, which have compact dimensions and limited target voltage, we consider only beam energies below 300 keV. In this energy range, D-D and T-T reaction cross-sections are significantly lower than those of D-T and T-D reactions; therefore, simulation of drive-in target D-T neutron tubes need only consider D-T and T-D reactions.

2. Equivalent Simulation Method for T-D Reactions

For drive-in target neutron tubes, D-T reactions can be simulated directly using the TARGET program, but T-D reactions cannot due to program limitations. To address this, we derive the relationship between D-T and T-D reaction neutron yields under thick-target conditions from their integral formulas, establishing a T-D reaction equivalent simulation method based on the TARGET program.

Under thick-target conditions, the integral neutron yields for D-T reactions ($Y_{D-T}(E)$) and T-D reactions ($Y_{T-D}(E)$) can be calculated using the following formulas [7]:

$$Y_{D-T}(E) = \int_0^E \frac{I_D N_T \sigma_{D-T}(E')}{S_D(E')} dE' \quad (1)$$

$$Y_{T-D}(E) = \int_0^E \frac{I_T N_D \sigma_{T-D}(E')}{S_T(E')} dE' \quad (2)$$

where I_D and I_T represent incident ion intensities for deuterium and tritium, N_D and N_T are the atomic number densities of deuterium or tritium in the target, $\sigma_{D-T}(E')$ and $\sigma_{T-D}(E')$ are the D-T and T-D reaction cross-sections, and $S_D(E')$ and $S_T(E')$ represent the stopping powers of incident ions in the target.

When T^+ and D^+ bombard the target at the same velocity, the integral cross-sections for T-D and D-T reactions are equal. In this case, the relationship between T^+ energy E_T and D^+ energy E_D is:

$$E_T = \frac{m_T}{m_D} E_D \quad (3)$$

Therefore:

$$\sigma_{T-D}(E_T) = \sigma_{D-T}(E_D) \quad (4)$$

According to the Bethe-Bloch formula [19], stopping power depends only on the velocity of incident ions, not their mass. When T^+ and D^+ bombard the target at the same velocity, their stopping powers are equal, giving:

$$S_T(E_T) = S_D(E_D) \quad (5)$$

Substituting equations (3) and (4) into equation (2) yields:

$$Y_{T-D} = 1.5 Y_{D-T} \quad (6)$$

when $N_D = N_T$. Substituting the values of m_T and m_D confirms this relationship.

Based on equation (6), we establish the following equivalent simulation method for T-D reaction neutron yield using the TARGET program: (a) calculate the energy of D^+ ions having the same velocity as the incident T^+ ions; (b) simulate the D-T reaction process for these equivalent D^+ ions incident on the drive-in target using TARGET; (c) multiply the resulting neutron yield by 1.5 to obtain the T-D reaction neutron yield.

To verify equation (6), we performed numerical calculations using equations (1) and (2), with results shown in . In the table, Y_{T-D} represents the neutron yield from a single T^+ ion incident on a drive-in target, while Y_{D-T} is the yield from a single equivalent D^+ ion. For these calculations, the target film thickness was 10 m with a deuterium-tritium-titanium atomic ratio of 0.5:0.5:1. D-T and T-D reaction cross-sections were taken from [Figure 1: see original paper], and stopping powers were calculated using the SRIM program [20]. The results show that the ratio Y_{T-D}/Y_{D-T} varies little with incident T^+ energy, remaining approximately constant at 1.5, consistent with equation (6).

3. Results and Discussion

Using the method described above, we simulated the neutron yield from D-T mixed beams normally incident on drive-in targets and analyzed the relationships between neutron yield and beam parameters and target parameters. In the simulations, titanium was used as the target material with a thickness of 10 m, and deuterium and tritium atoms were uniformly distributed in the target film. Since the D-T mixed beam energy did not exceed 300 keV, giving a maximum ion range of 2.01 m, the thick-target condition was satisfied.

3.1 Effect of Beam Deuterium-Tritium Ratio on Neutron Yield

To investigate how the proportions of deuterium and tritium ions in the incident beam affect neutron yield, we calculated yields for various D^+:T^+ ratios, as shown in [Figure 2: see original paper]. Beam energies of 50 keV and 100 keV were considered, with the target atomic ratio of deuterium:tritium:titanium fixed at 0.5:0.5:1.0. The results show that for both beam energies, neutron yield initially increases then decreases as the D^+ proportion in the mixed beam rises, reaching a maximum when D^+ accounts for 50% of the beam. This occurs because the deuterium-tritium ratio in the beam matches that in the drive-in target.

In equation (1), the beam deuterium-tritium ratio affects neutron yield by modifying $I_D N_T$. Letting the total mixed beam intensity be I_0 and the total atomic number density of deuterium and tritium in the target be N_0, we have $I_D = aI_0$, $I_T = (1-a)I_0$, $N_D = aN_0$, and $N_T = (1-a)N_0$, where a represents the deuterium proportion. If only the beam ratio changes while I_0 and N_0 remain constant, then $I_D N_T = a(1-a)I_0 N_0$. According to equation (7), when $a = 0.5$

(i.e., D^+ accounts for 50% of the mixed beam), $I_D N_T$ reaches its maximum value, corresponding to the maximum D-T reaction neutron yield. Similarly, when D^+ accounts for 50% of the mixed beam, $I_T N_D$ also reaches its maximum, corresponding to the maximum T-D reaction neutron yield. This agrees with the calculated results in [Figure 2: see original paper].

3.2 Effect of Target Atom Ratio and Beam Energy on Neutron Yield

The target atom ratio is defined as the ratio of deuterium and tritium atomic number density to titanium atomic density in the drive-in target, denoted as (D+T)/Ti. To study its effect on neutron yield, we calculated neutron yield as a function of beam energy for various target atom ratios, as shown in [Figure 3: see original paper]. In these calculations, the D^+:T^+ ratio in the beam was fixed at 1:1, and target atom ratios of 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 were considered.

The results indicate that neutron yield versus beam energy follows an approximately S-shaped curve, monotonically increasing with the steepest growth in the middle segment. According to equations (1) and (2), neutron yield is the integral of $\frac{I_D N_T \sigma_{D-T}(E')}{S_D(E')}$ and $\frac{I_T N_D \sigma_{T-D}(E')}{S_T(E')}$. Since the integrand is always positive, neutron yield increases with beam energy. The growth rate, represented by the curve' s slope, depends on the magnitude of the integrand. As shown in [Figure 1: see original paper], D-T and T-D reaction cross-sections increase then decrease with beam energy, peaking around 100-200 keV, which corresponds to the middle segment of the curve where the slope is greatest.

The results also show that neutron yield increases with target atom ratio, following an approximately linear relationship. Since the titanium atomic density in the drive-in target is constant, increasing the target atom ratio effectively increases N_D and N_T while also increasing the total atomic density in the target, which modifies the stopping power. From equations (1) and (2), while the stopping power change is a secondary effect, the neutron yield is theoretically approximately proportional to the target atom ratio.

To further compare the contributions of D-T and T-D reactions to total neutron yield, we calculated individual yields for both reactions at target atom ratios of 0.4, 0.8, and 1.2, as shown in [Figure 4: see original paper]. For beam energies below 200 keV, D-T yield exceeds T-D yield; above 200 keV, T-D yield surpasses D-T yield. This behavior correlates with the integral cross-sections of the two reactions. According to the cross-section data in [Figure 1: see original paper], when beam energy E is below 135 keV, $\sigma_{D-T}(E) > \sigma_{T-D}(E)$. From equations (1) and (2), neutron yield is the integral of the cross-section divided by stopping power. Disregarding secondary factors like stopping power, when E is below 135 keV, both D-T yield and its growth rate exceed those of T-D yield. When E is between 135 keV and 200 keV, the growth rate of D-T yield becomes lower than that of T-D yield, allowing T-D yield to begin catching up. Above 200 keV, T-D yield overtakes D-T yield.

3.3 Effect of Beam Ion Composition on Neutron Yield

In practical operation, the mixed beam composition includes not only monatomic ions (D^+, T^+) but also diatomic ions (${D_2}^+$, DT^+, ${T_2}^+$). Triatomic ions contribute negligibly to neutron yield due to their low proportion and velocity [7], so we neglect them for simplicity. Assuming a 1:1 D:T ratio in the beam, monatomic ions consist of 50% D^+ and 50% T^+, while diatomic ions comprise 25% ${D_2}^+$, 50% DT^+, and 25% ${T_2}^+$, as listed in .

Table 2. Beam Ion Composition

Ion type	Composition of ions	Reaction type	Treatment method
Monatomic ion	50% D^+, 50% T^+	D-T, T-D	Direct simulation
Diatomic ion	25% ${D_2}^+$, 50% DT^+, 25% ${T_2}^+$	D-T, T-D	Equivalent to multiple monatomic ions*

*In the table, E_0 represents beam energy. The method for equivalencing diatomic ions to monatomic ions follows reference [7].

To simulate diatomic ions, we adopt the equivalent treatment method from reference [7], converting diatomic ions into several monatomic ions while preserving total energy and velocity, as shown in . [Figure 5: see original paper] presents simulation results for neutron yield at various monatomic ion proportions (100%, 80%, 60%, 40%, 20%, 0%) in the beam. In these calculations, the target film thickness was 10 m (thick-target condition) with a target atom ratio (D+T)/Ti of 1.0. The results show that neutron yield increases monotonically with beam energy for all ion compositions, with higher monatomic ion proportions yielding greater neutron output. However, as beam energy approaches 300 keV, the differences between various monatomic ion proportions diminish because the contributions from monatomic and diatomic ions change relative to each other with increasing energy.

To compare contributions from different ion components, we calculated individual neutron yields from each component at a monatomic ion proportion of 50%, as shown in [Figure 6: see original paper]. Below 280 keV, monatomic ions dominate the yield. Below 200 keV, D^+ contribution exceeds that of T^+, while above 200 keV, T^+ contribution surpasses D^+, as D^+ contribution corresponds to D-T reactions and T^+ contribution corresponds to T-D reactions. For diatomic ions, the combined contribution from ${D_2}^+$ and ${T_2}^+$ is comparable to that from DT^+.

Conclusion

This study establishes an equivalent simulation method for T-D reaction neutron yield based on the theoretical relationship between T-D and D-T reaction yields, solving the Monte Carlo simulation challenge for drive-in target neutron tubes. Using this method, we analyze the effects of beam parameters and target parameters on neutron yield. First, we examine how the D-T mixing ratio in the incident beam affects yield. Neutron yield increases then decreases as the deuterium ion proportion rises, peaking at a 1:1 D-T mixing ratio. TARGET simulation results confirm this theoretical analysis. Second, we investigate target atom ratio and beam energy effects. Simulation results show that neutron yield is approximately proportional to target atom ratio and follows an S-shaped curve with beam energy, with rapid growth in the 100-200 keV range. At lower beam energies, D-T reaction yield exceeds T-D reaction yield, but above 200 keV, T-D reaction yield becomes dominant. Finally, we analyze beam ion composition effects. The beam contains monatomic ions (D^+, T^+) and diatomic ions (${D_2}^+$, DT^+). Below 300 keV, individual monatomic ions produce greater yield than individual diatomic ions, so higher monatomic ion proportions yield greater overall neutron output.

This simulation study provides valuable guidance for the physical design of drive-in target neutron tubes. To enhance neutron yield, designers should employ a 1:1 D-T mixed beam incident on the drive-in target while maximizing target atom ratio, beam energy, and monatomic ion proportion within the tube' s design constraints.

Author Contributions

Tao Ying-Long was responsible for theoretical derivation, calculations, data analysis, and manuscript writing. Liang Can-Jun proposed the research topic, reviewed the manuscript, and provided guidance. Chang Bo ensured manuscript quality, verified formula derivations, and edited the text. Hao Li-Juan reviewed the manuscript and provided guidance.

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Note: Figure translations are in progress. See original paper for figures.