YIELDS AND SPECTRA OF PRODUCTS FROM (d+T) AND (d+D)-REACTIONS ON TiT AND TiD-TARGETS

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Energy spectra and yields of fast neutrons and accompanying charged particles are calculated in a range of angles 0-180^0 by an analytical method for the neutron-generating solid-state TiT and TiD-targets irradiated by accelerated deuterons. The deuteron slowing-down and product yields of (d+T) and (d+D)-reactions were simulated in depth of the target in view of nuclear reaction characteristics, kinematics and contents of the hydrogen isotopes.

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1. INTRODUCTION

The fast neutron sources based on (d+T) and (d+D)-reactions are widely used for the scientific and applied purposes [1, 2, 3]. In neutron generators the accelerated deuterons with $E_d \sim 150$ keV bombard the solid-state Ti-targets saturated with tritium or deuterium. Thus d(T,n)^{4}He and d(D,n)^{3}He-reactions are realized with the yield of quasi-monoenergetic neutrons with $E_n \sim 14$ and ~ 2.5 MeV, accordingly. To carry out the precision experiments it is necessary to know the real neutron spectra and yields from the specified targets, which depend on the energy of deuterons E_d, the output angle θ, and the distribution of hydrogen isotopes in depth of the target. Besides in many such experiments the neutron flux is determined by the yields of accompanying charged particles ^{4}He and ^{3}He [4], having the big angular anisotropy.

It is necessary to note, that calculated and experimental data submitted in [1, 2, 3, 5, 6] are incomplete. They are insufficient to carry out tentative estimations and processing of the experimental data received with neutron generators. Therefore, to supply the necessary data on nuclear reactions with fast neutrons the code was developed on the FORTRAN language by means of which analytical calculations of product spectra and yields of two-partial nuclear reactions proceeding in solid-state targets were performed. The purpose of our work was the calculation of energy spectra and yields of neutrons and accompanying charged particles from (d+T) and (d+D)-reactions proceeding in solid-state TiT and TiD-targets.

2. CALCULATION

Modeling of nuclear reactions of deuterons with hydrogen isotopes in solid-state neutron-generated targets is schematically shown in Fig.1 for a TiT-target. Accelerated deuterons with energy E_d bombard the target which is a thin layer (~1 micron) of Ti hydride on a Cu backing. In process of promotion on depth of the target deuterons are stopped and react with tritium (deuterium in TiD-targets). As a result the neutron and α-particle are ejected from the target in opposite directions. The neutron flux intensity is determined by accompanying charged particles registered under the set angle θ (see Fig.1).

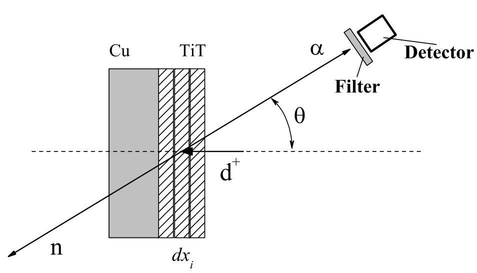

Fig.1. *The modeling scheme*

In calculation the projective deuteron path in a target R_d^{pr} is divided into elementary layers $dx_i << R_d^{pr}$. The losses of deuteron energy dE_d, the average value of energy $\overline{E}_d^i$, the yield $dY_i(\overline{E}_d^i, \theta)$ and the average energy $\overline{E}_{out}^i$ of corresponding particles from the reaction under a corner in relation to the bombarding deuteron are calculated for each layer. The losses of energy for the charged particles $\Delta\overline{E}_{out}^i$ are calculated on thickness of a layer of Ti hydride. Thus, the total

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yield $Y(E_d, \theta)$ and a spectrum $dN(E_d)/dE$ of neutrons and charged particles from neutron-generated TiT and TiD-targets are formed. Thus calculation was performed by a method of an iterative variation of dx_i for obtaining spectra of particles with the set step. The process of registration is modeled for the charged particles (the Si surface barrier detector is usually used), at which the losses of energy of the charged particle ΔE^f_{out} in a protective film (filter) of the detector (see Fig.1) and the energy resolution of the detector are considered.

The energy losses of charged particles on thickness of a target Δx are calculated by:

$$\Delta E = \int_a^b \frac{dE}{dX} dx, \qquad (1)$$

where the energy losses for Ti hydride dE/dX are determined on the basis of ionization losses for Ti and hydrogen isotopes H (T or D) as:

$$\frac{dE}{dX} = \omega_{Ti} \left(\frac{dE}{dX}\right)_{Ti} + \omega_H \left(\frac{dE}{dX}\right)_H, \qquad (2)$$

where ω_{Ti} and ω_H - percentage of Ti and hydrogen isotopes, accordingly.

One of the important characteristics of targets is the relative contents of hydrogen isotopes which is determined by parameter $\eta = \omega_H/\omega_{Ti} = N_H/N_{Ti}$, where N is equal to the number of nuclei of hydrogen isotopes or Ti in 1 cm^3 of Ti hydride. Yields of particles from corresponding reactions are proportional to the value of η. However, the density of Ti hydride depends on η too, that as a whole, leads to nonlinear dependence of $Y(\eta)$. Therefore, calculations of the total energy losses of charged particles in Ti hydride were performed in view of dependence of mass density of hydride on the contents of hydrogen $\rho(\eta)$ [7], and the values of energy losses $(dE/dX)_H$ and $(dE/dX)_{Ti}$ were calculated with the TRIM code[8].

The average energy $\overline{E}^i_{out}$ and the yield $dY_i(\overline{E}^i_d, \theta)$ in a layer dx_i are calculated on the basis of energy dependence of total cross-section $\sigma_{tot}(E_d)$, angular and energy dependence of differential cross-section $d\sigma(E_d, \theta)/d\theta$ and the reaction kinematics. As the reaction yield is proportional to the total deuteron path R^{tot}_d the renormalization was performed for the reaction yields to the factor $k = R^{tot}_d/R^{pr}_d$ [9].

Calculations are performed for one channel (d+T)-reactions and two channels for (d+D)-reactions:

$$\begin{aligned} &d(T,n)^4He,\ Q = 17.59\,MeV,\\ &d(D,n)^3He, Q = 3.269\,MeV,\\ &d(D,p)T, \quad Q = 4.033\,MeV. \end{aligned} \qquad (3)$$

The total reaction cross-section is equal to [10]:

$$\sigma_{tot}(E) = \frac{S(E)}{E} \exp\left(-\frac{B}{\sqrt{E}}\right), \qquad (4)$$

where E - the deuteron energy in the center-of-mass system (CMS).

Astrophysical factor $S(E)$ is approximated by:

$$S(E) = S_0 \frac{1 + a(E - E_0) + b(E - E_0)^2}{1 + c(E - E_0)^2}, \qquad (5)$$

Where constants S_0, E_0, a, d, c are taken from [10].

In a range of accelerated deuteron energy $E_d = 0 - 200\,keV$ the yield of (d+T)-reactions in CSM is isotropic [11], and the angular dependence of (d+D)-reaction cross-section in CSM is approximated by:

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(90^0)(1 + A\cos^2\theta + B\cos^4\theta), \qquad (6)$$

where parameters A and B are the deuteron energy function E_d, the values of which are taken from [12].

Registration of the charged particles by the corresponding detector (see Fig.1), is modeled by performing the operation of convolution of the initial spectrum of particles dN/dE with function of the energy resolution of the detector $g(E - E)$:

$$\left(\frac{dN(E)}{dE}\right) = \int_{E1}^{E2} \frac{dN(E)}{dE} g(E - E) dE. \qquad (7)$$

In our calculations the resolution function was in form of Gaussian function:

$$g(E - E) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(E - E)^2}{2\sigma^2}\right). \qquad (8)$$

3. RESULTS

Calculations of spectra and yields of particles from the (d+T) and (d+D)-reactions were performed for a constant form of distribution of hydrogen isotopes in Ti hydride with the typical parameter $\eta = 1$ for TiT and TiD-targets, and additionally for TiT-target with the depleted surface layer of tritium. Dependencies of the absolute yields of (d+T) and (d+D)-reactions on the accelerated deuteron energy, normalized on 1 μA of the deuteron current, are shown in Fig.2. Yields of (d+D)-reactions were multiplied by the factor 100. Our results are well agreed with [2].

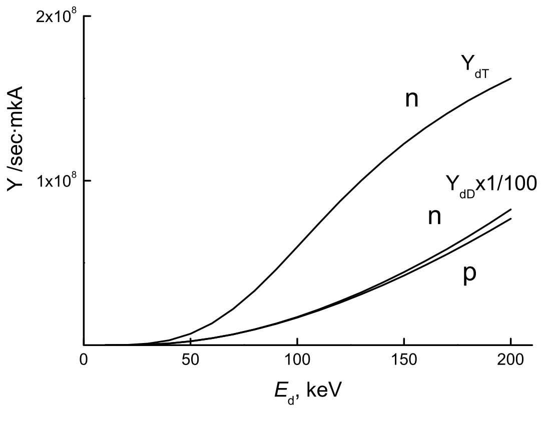

Fig.2. *Absolute yields of (d+T) and (d+D)-reactions*

The typical energy of accelerated deuterons in neutron generators is $E_d = 150\,keV$, therefore the further calculations are performed for this one. The results of calculations of relative angular dependencies for yields of particles from (d+T) and (d+D)-reactions, normalized on the reaction yields at $\theta = 90^0$, are shown in Fig.3 and Fig.4, accordingly.

There is anisotropy of yields in the laboratory system of coordinates (LSK) because of reaction kinematics in spite of the fact that yields of the d(T,n)^{4}He reactions are isotropic in the center-of-mass system. As it is shown in Fig.3 the neutron yield anisotropy in LSK is insignificant and does not exceed 5% for $\theta = 0^0$ and 180^0. The yield anisotropy is essentially greater for α-particles. Those dependencies of yields are important, as neutron fluxes in generators are most precisely determined by intensities of the accompanying charged particles which are registered, as a rule, under the back angles. As it is shown in Fig.3 and Fig.4 for correct definition of neutron fluxes under the set angle θ it is necessary to consider anisotropy of yields of neutrons and the charged particles.

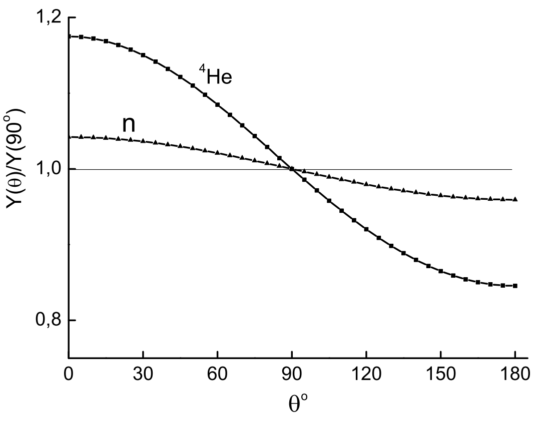

Fig.3. *Relative yields of the (d+T)-reactions*

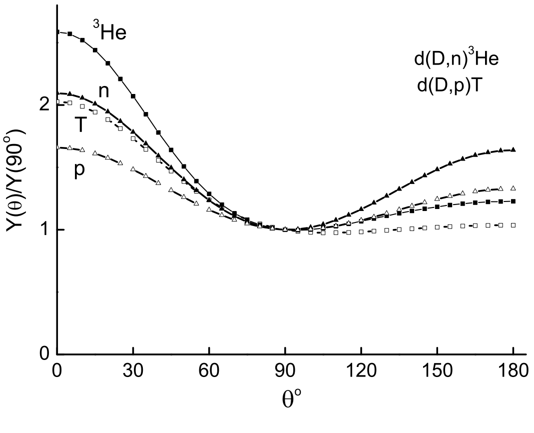

Fig.4. *Relative yields of the (d+D)-reactions*

The neutron spectra of (d+T) and (d+D)-reactions in a range of angles $\theta = 0 - 180^0$ are shown in Fig.5 and Fig.6. Calculations are carried out for neutrons radiated in a solid angle of $4.4\Delta 10^{-3}$ steradian, time is 100 s, the deuteron current is $I_d = 1\mu A$. As it is shown in Fig.5 and Fig.6 the best monochromaticity of neutrons is reached at angles $\theta \sim 90^0$.

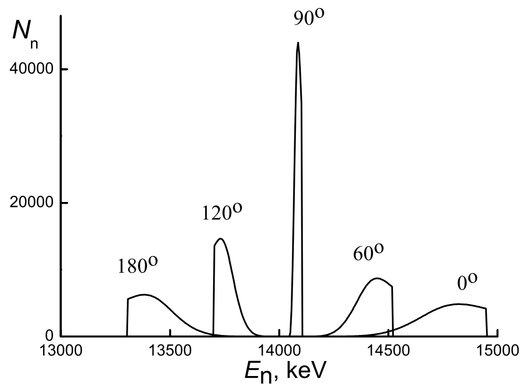

Fig.5. *Neutron spectra from the (d+T)-reactions*

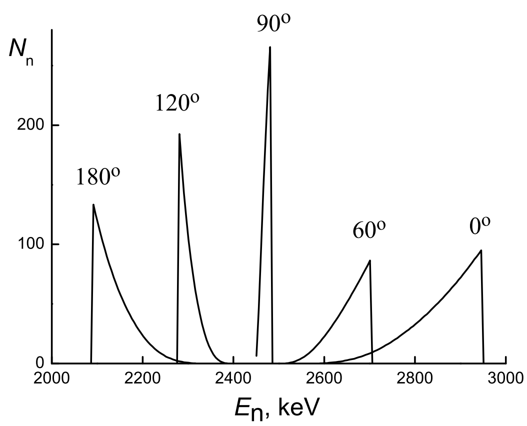

Fig.6. *Neutron spectra from the (d+D)-reactions*

Spectral characteristics of neutron-generated TiT and TiD-targets will change both during their operation, and at their long storage. It is connected with change in a form of distribution of hydrogen isotopes in targets. At storage and use of targets there can be a depletion of a surface layer by the hydrogen isotopes [13], redistributions of hydrogen isotopes on depth due to driving of accelerated deuterons in a target [14], and etc. To account these processes the opportunity of carrying out of calculations of spectra and yields of particles at the set form of distribution of hydrogen isotopes in a target is included in the program algorithm. The information on the last can be taken from the experimental spectra of charged particles from the (d+T) and (d+D)-reactions. For this purpose in calculations it is necessary to consider the energy resolution of the charged particle detector according to (7) and (8).

Calculated spectra of α-particles from the (d+T)-reaction radiated in a solid angle of 1 steradian are shown in Fig.7 ($t = 10\,s$, $\theta = 170^0$, $I_d = 1\,\mu A$). The spectra 2 and 3 are received from the spectrum 1 according to (7). Calculations are performed for the detector resolution (8) with value of $\sigma = 30\,keV$. The tritium distributions in TiT-targets are shown in Fig.7 at the top right corner. The curve 2 concerns to a constant form with parameter $\eta = N_T/N_{Ti} = 1$, the curve 3 displays changes of this parameter in depth X of a target.

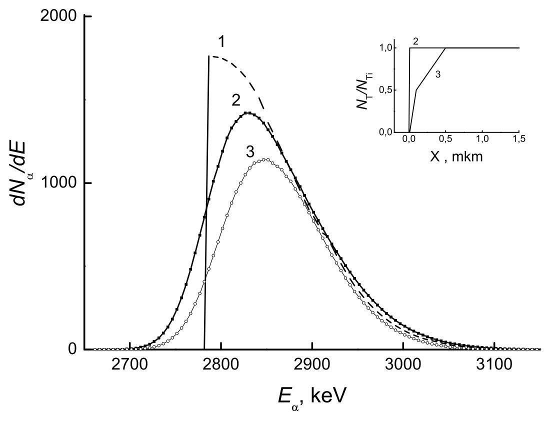

Fig.7. *^{4}He spectra from the (d+T)-reaction ($\theta = 170^0$);*

1 - The initial spectrum of α-particles; 2 - the simulated spectrum of α-particles registered by the detector without taking into account a protective film (see Fig.1) for a constant form of tritium distribution in a TiT-target; 3 - the simulated spectrum of α-particles for a variable form of tritium distribution

4. CONCLUSIONS

The code was developed for calculation of spectra and yields of particles from the two-particle nuclear reactions proceeding in solid-state targets. Calculations of absolute and relative angular dependencies of spectra and yields of neutrons and charged particles from (d+T) and (d+D)-reactions proceeding in neutron-generating TiT and TiD-targets were performed. Obtained data are important for planning researches with neutrons and experimental results processing. They are the basis for carrying out the precision measurements of nuclear reaction cross-sections in experiments with neutron generators.

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REFERENCES

1. V.T.Tustanovsky. Nutron generators and the control of technological processes. M.: "Atomizdat", 1980, 152 p.(in Russian).
2. J. Csikai. Utilization of intense neutron generators in science and technology // *NIM.* 1989, A280, p.233-250.
3. M. Segev. Analysis of the amplification of deuterium-tritium neutron sources // *Nuclear Science and Engineering.* 1985, v.91, p.143-152.
4. N.E. Hertel and B.W. Wehring. Absolute monitoring of DD and DT neutron fluences using the associated-particle technique // *NIM.* 1980, v.172, p.501-506.
5. A.I.Bortash, V.S. Kuznetsov. Calculation of neutron energy spectrum from tritium targets of the generator NG-150 // *PAST. Radiation Physics.* 1987, v. 2 (35), p.63-65. (in Russian).
6. P.R.P Coelho, A.A. Silva and J.R. Maiorano. Neutron energy spectrum measurements of neutron sources with an Ne-213 spectrometer // *NIM.* 1989, v.A280, p.270-272.
7. V.Muller and etc. *Hydrides of metals.* M.: Atomizdat, 1973, 327 p. (in Russian)
8. J.F. Ziegler. TRIM-91: Report IBM Research. 28-0. New York. 1991.
9. J.F. Ziegler, J.P. Bicrsack and U. Littmark. The stopping and range of ions in solids. Pergamon Press, New York, 1985.
10. S.V.Putvinsky. About nuclear reaction kinetics in thermonuclear plasma // *PAST. Thermonuclear synthesis.* 1988, v.2, p.3-8. (in Russian).
11. N.A. Vlasov. *Neutrons. M.: Nauka,* 1971, 552p. (in Russian).
12. R.B. Theus, W.I. McGarry and L.A. Beach. Angular distributions and cross-sections for the reactions ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H below 500 keV // *Nucl. Phys.* 1966, v.80, p.273-288.
13. V.M.Gulko, N.F.Kolomiets, A.E.Shikanov, K.I.Jakovlev. Calculation of deuteron paths in targets of neutron generators in view of change of tritium concentration in depth // *Atomic Energy.* 1986, v.61(2), p.131-132. (in Russian).
14. I.Ya.Barit, L.E.Kuzmin, S.A.Makarov, I.M.Pronman. About the mechanism of yield reduction of neutrons from metallotritium targets of neutron generators NG-150 // *Atomic Energy.* 1982, v.52(6), p.423-425. (in Russian).

ВЫХОДЫ И СПЕКТРЫ ПРОДУКТОВ (d+T) И (d+D)-РЕАКЦИИЙ ИЗ TiT И TiD-МИШЕНЕЙ

С.К. Андрухович, В.П. Божко, С.Н. Олейник, Э.А. Рудак, А.Н. Водин, О.И. Ячник

Представлены расчетные энергетические спектры и выходы быстрых нейтронов и сопутствующих заряженных частиц в диапазоне углов 0-180^0, получаемые на нейтронных генераторах типа Кокрофта-Уолтена. Расчеты проведены аналитическим методом для нейтронопроизводящих твердотельных TiT- и TiD-мишеней, облучаемых ускоренными дейтронами. В расчетах моделировалось торможение дейтронов по глубине мишени и выход продуктов (d+T) и (d+D)-реакций с учетом характеристик ядерных реакций, кинематики реакций и содержания изотопов водорода в мишени.

ВИХОДИ ТА СПЕКТРИ ПРОДУКТІВ (d+T) И (d+D)-РЕАКЦІЙ З TiT ТА TiD-МІШЕНЕЙ

С.К. Андрухович, В.П. Божко, С.М Олійник, Е.А. Рудак, О.М. Водін, О.І. Ячник

Представлено розрахункові енергетичні спектри та виходи швидких нейтронів і супутніх заряджених частинок у діапазоні кутів 0-180^0, які одержують на нейтронних генераторах типу Кокрофта-Уолтена. Розрахунки проведено аналітичним методом для нейтроновипромінюючих твердотільних TiT- та TiD-мішеней, що опромінюються прискореними дейтронами. У розрахунках моделювалося гальмування дейтронів за глибиною мішені та вихід продуктів (d+T) і (d+D)-реакцій з урахуванням характеристик ядерних реакцій, кінематики реакцій і змісту ізотопів водню в мішені.