THE INVESTIGATION OF THE NEUTRON YIELD DEPENDENCE FROM REACTIONS D(d, n) He^3 AND T(d, n) He^4 ON THE IRRADIATION TIME

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The dependence of the neutron yield from deuterium and tritium targets on the irradiation time was investigated experimentally. An explanation is given of the increase of the neutron yield at the beginning of the irradiation time with the increase of the temperature of the deuterium, or tritium, impregnated titanium layer of the target. The experimental apparatus with the help of which the above mentioned dependences were measured is also described.

I. INTRODUCTION

For the production of neutrons in neutron generators mainly the reactions $D(d, n)$ He^3 and $T(d, n)$ He^4 are used. The authors of paper [1], dealing with the investigation of the neutron yield dependence — from reactions $D(d, n)$ He^3 and $T(d, n)$ He^4 — on the irradiation time, or on the charge impinging on a target mention that the shape of this dependence for the $D(d, n)$ He^3 reaction is not changed in the case of the ZrD target and that for the $T(d, n)$ He^4, the reaction shows an continuously decreasing character. The same results were obtained by A. Greil and others in paper [2], following the dependence of the neutron yield from deuterium targets on time, where polythene, polycaprolactam (nylon) and polyvinylchloride (PVC) were enriched by deuterium. Another qualitative result was reached by Fabian [3], where the mentioned dependence of TiT targets was investigated. He showed that the curve characterizing the above dependence has a rising tendency at the beginning up to a certain maximum, which is reached in 7 min. after the beginning of irradiation by a deuterium beam of an intensity of 200 μA, an energy of 200 keV and an effective diameter of the target of 4 mm. Then after ≈15 min the curve begins to drop monotonously.

The aim of this paper is to prove the result of paper [3] and to investigate,

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whether a similar maximum of the dependence of the yield on the irradiation time appears also at the deuterium TiD targets and to explain the increase of the yield at the beginning of the irradiation by the increase of temperature of the titanium layer which is saturated by deuterium or tritium. The paper describes the dependences of the yields on the irradiation time for TiT and TiD targets obtained at the Institute of Physics of the Slovak Academy of Sciences, Bratislava. Questions connected with the course of the individual dependencies are discussed too.

II. DESCRIPTION OF THE MEASURING APPARATUS AND THE MEASURING METHOD

The scheme of the device used for the measuring of the neutron yield and the neutron generator are in Fig. 1. Ions taken from the ion source by the extracting electrode are accelerated by a system of electrodes. The high-voltage source which is connected with the system of electrodes permits the change of the ion energy within the range of 40—500 keV. The separation of the deuteron beam resulted in the TiD, resp. TiT target being impinged only by

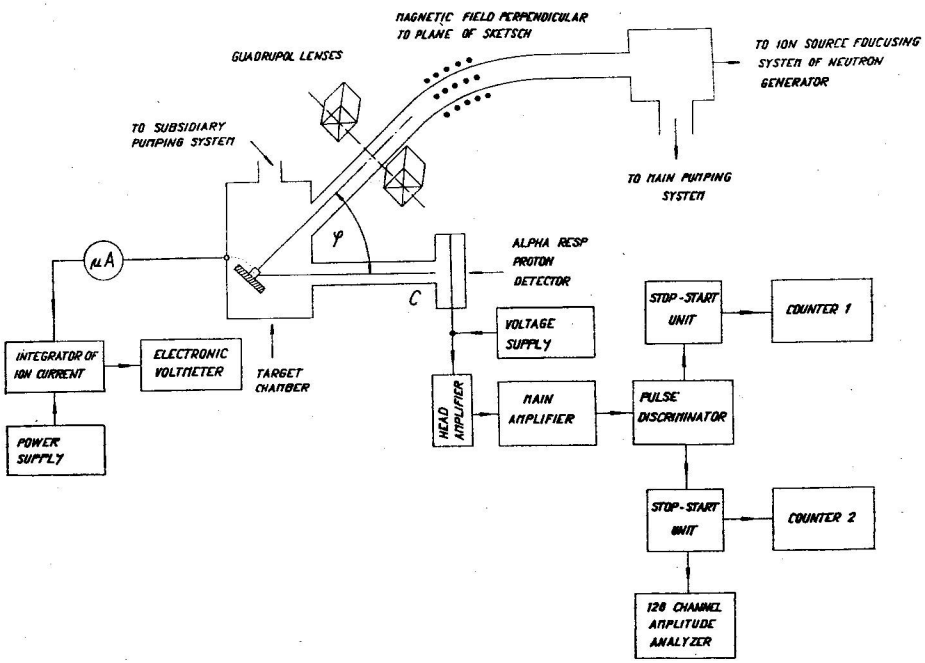


Fig. 1. Diagram of the apparatus measuring the neutron yield in dependence on the irradiation time.

the atomic ions of deuterium D_1^+. Deuterons D_1^+ were focussed by quadripole lenses before impinging on the target. The whole system was pumped off to a vacuum of 10^{-5} torr, which was reached by two diffusion pumps with steam traps, refrigerated by water flow.

The diameter of the D_1^+ beam impinging on the target was ≈ 5 mm. The energy of the deuterons D_1^+ impinging on the TiT target was 120 keV and that of the deuterons D_1^+ impinging on the TiD target was 300 keV $\pm$ 0.06 keV. The ion current of D_1^+ varied and had a value of about 100 μA $\pm$ 15 μA in the case of measuring with tritium targets and a value of about 50 μA, also ± 15 μA in the case of measuring with deuterium targets. The total deuteron current impinging on the target was in the measuring time interval measured by the current integrator.

The neutron yields from the $D(d, n)$ He^3 and $T(d, n)$ He^4 reactions were measured by the associated particle method. Detection of He^3 nuclei produced in the reaction $D(d, n)$ He^3 was highly disturbed by the background originated by the neutrons flying out and by scattering deuterons. The energy of He^3 nuclei is 0.43 MeV. Therefore protons flying out during the competitive reaction $D(d, p)$ T were registered instead of He^3 nuclei. Cross section for both reactions are well known from [4], therefore by the help of protons the exact neutron yield can be determined. The protons were registered by a silicon barrier detector placed at a 250 mm distance from the target at the angle of 135° from the deuteron beam. The entry window of the semiconductor detector was 20 mm². The neutron beam was confined by two diaphragms so that scattered neutrons from the target chamber walls and „protonline" did not impinge on the detector. The space angle where protons were registered was

$$\Delta\Omega_p = 3.2 \times 10^{-4} \text{ sr} \pm 1.8\ \%.$$

The electronics attached to the semiconductor detector consisted of a charge-sensitive pre-amplifier, amplifier, discriminator and registering apparatus. The lower and upper discrimination level were adjusted before measuring by the 128 channel amplitude analyzer at each target so that at the registration of 3 MeV protons the background should not be registered. The neutron yield from TiD deuteriun targets was calculated with regard to the special geometry and anisotropy factor [5], from the equation

$$\Phi_{np} = R_{p\ thick} \left(\frac{Y_{d,n}}{Y_{d,p}} \right)_{thick} \frac{4\pi}{\Delta\Omega_p} \frac{N_p}{\Delta Q_p}, \tag{1}$$

where $R_{p\ thick}$ — is the anisotropy factor, $(Y_{d,n}/Y_{d,p})_{thick}$ — the ratio of the total neutron yield to the total proton yield, $\Delta\Omega_p$ — the solid angle where protons were registered, ΔQ_p — the total charge that impinged on the target

at the measured time interval and N_p — the number of protons flying out from the target after a definite time Δt. According to [5] the values of the constants $R_{p\ thick}$, resp. $(Y_{d,n}/Y_{d,p})_{thick}$ can be determined for a given energy of deuterons bombarding the target and for the given angle at which protons are registered.

α-particles produced in the reaction $T(d, n)$ He^4 were also registered by the silicon barrier detector with an entry window of 20 mm². It was possible to eliminate the interference caused by scattering deuterons and background from 14 MeV neutrons because the energy of α-particles flying out during the reaction is ≈ 3 MeV [6]. α-particles were measured at the angle of 165° from the deuteron beam. Similarly as in the case of registration of protons flying out during the reaction $D(d, p)$ T, the silicon detector was placed at the distance of 250 mm from the target and the beam of α-particles was again confined by two diaphragms. The electronics used for measuring were of the same as in the case of the proton number measuring. The neutron yield from TiT tritium targets was computed from the equation

$$\Phi_{n\alpha} = R_{\alpha\ thick} \frac{4\pi}{\Delta\Omega_\alpha} \frac{N_\alpha}{\Delta Q_\alpha}, \tag{2}$$

where $R_{\alpha\ thick}$ — is the anisotropy factor, $\Delta\Omega_\alpha$ — the space angle under which the α-particles were registered, ΔQ_α — the total charge that impinged on the target during the measured time interval and N_α — the number of α-particles flying out from the TiT target after a definite time Δt. It is possible to determine the values of $R_{\alpha\ thick}$ from the tables of paper [5]. The space angle $\Delta\Omega_\alpha$, where the α-particles were registered was

$$\Delta\Omega_\alpha = 4.818 \times 10^{-5} \text{ sr} \pm 1.8\ \%.$$

The number of protons flying out during the reaction $D(d, p)$ T was measured by the counter after the lower and the upper discrimination levels have been adjusted by the 128 channel amplitude analyzer. The measured time interval $\Delta t = 70$ sec. was selected symmetrically at about 1.3, ..., 17.19 min., so that the yield was measured every 2 min. within the range of 70 sec. up to 20 min. from the beginning of the measuring time. At the time of 22.30, 27.30, ..., 92.30, 97.30 min. the time interval of 250 sec. was symmetrically so that the yield from 20 min. up was measured every 5 min.

The number of α-particles flying out during the reaction $T(d, n)$ He^4 was measured by two impulse computers after the lower and the upper discrimination levels have been adjusted. One of them measured at the same time intervals as in the case of proton counting and the second had the measuring time interval of 50 sec., which was chosen symmetrically at about 2, 4, ..., 18, 20, 25, 30, ..., 95, 100 min. The second computer was switched on by switching

off the first. The same value of ΔQ_p, resp. ΔQ_α did not always correspond to each value of the impulse numbers chosen from the same measured interval. The background was measured at each given target at the time intervals determined beforehand after each measuring. The background of each target moved in an interval of 5—10 % of the measured values of proton number, resp. particle number. If one considers all sources of inaccuracy when evaluating the measuring of the number of neutrons flying out during the reactions $D(d, n)$ He^3 and $T(d, n)$ He^3 (the error associated with the registration of protons resp. α-particles, inaccuracy of determination of the D_1^+ energy value impinging on the target, inaccuracy of the angles φ_p, φ_α at which the protons or α-particles are flying out, inaccuracy of the space angles $\Delta\Omega_p$ and $\Delta\Omega_\alpha$, of the charge impinging on the targets and the ifluence of competing reactions) one finds that the error in the number of neutrons flying out during the reaction $D(d, n)$ He^3 is ≈ 9 % and the error in the number of neutrons flying out during the reaction $T(d, n)$ He^4 is ≈ 11 %.

III. MEASURING RESULTS, EVALUATION AND DISCUSSION

Neutron yield dependences Φ_{np} and $\Phi_{n\alpha}$ on the irradiation time t for the investigated deuterium and tritium targets are presented in Fig. 2 and Fig. 3.

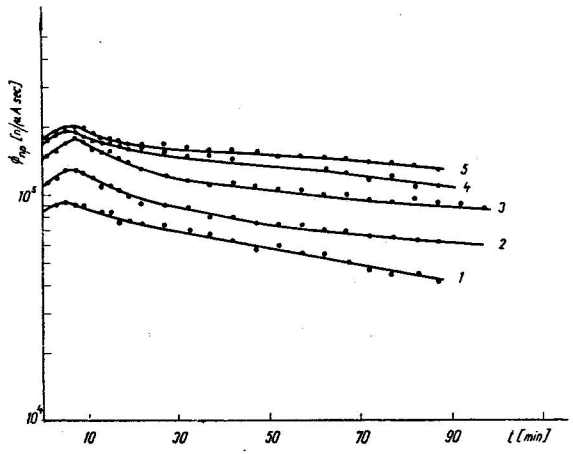


Fig. 2. Dependences of neutron yields on the irradiation time for deuterium targets. Curve 1 corresponds to the neutron yield obtained from the target with a saturation ratio of 0.68; curve 2 was obtained by measuring the target with a saturation ratio of 0.9; curve 3 from the target with a saturation ratio of 1.25; curve 4 from the target with a saturation ratio of 1.41 and curve 5 from the target with a saturation ratio of 1.48. Targets diameters were ⌀ 14.8 mm.

The backing metal of the targets were made of pure electrolytic copper of a thickness of 2.4 mm. The Ti layer, which absorbed the deuterium, resp. tritium atoms, was melted onto the Cu backing by means of an Ag foil, of a thickness of ≈ 0.03 mm. The parameters are summarized in Table 1.

It follows from the results obtained from deuterium (Fig. 2) and tritium targets (Fig. 3) that an observable rise of the neutron yield occurs at the beginning of the irradiation time. In deuterium targets the rise is less obvious than in tritium targets. After a certain time (in deuterium targets ≈ 5 min, in tritium targets ≈ 7 min.) the neutron yield decreases slowly or quickly, depending on the target type. In deuterium targets this decrease is less marked

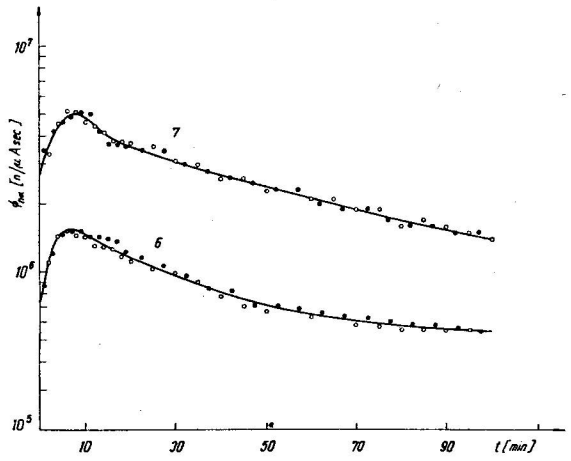


Fig. 3. Dependences of the neutron yield on the irradiation time for tritium targets. Curve 6 corresponds to the neutron yield obtained from the target with a saturation ratio of 0.058 and curve 7 was obtained from the target with a saturation ratio of 0.19. ○ corresponds to the yields measured at 50 sec. time intervals and ● to the yields at 70 sec. and 250 sec. time intervals.

Table 1
Parameters of the measured deuterium and tritium targets

Number	Target	Weight of Ti-foil [mg]	Quantity of sorbed D_2 resp. T_2 [cm^3]	Saturation pressure [torr]	Saturation ratio
1	TiD	37.7	6	162	0.68
2	TiD	36	7.6	154.5	0.9
3	TiD	18	5.3	150.5	1.25
4	TiD	17.2	5.7	153	1.41
5	TiD	6.7	2.3	158	1.48
6	TiT	15.1	0.25	46	0.058
7	TiT	13	0.58	46	0.19

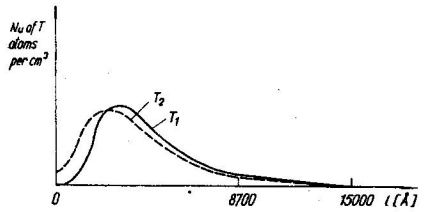
than in tritium targets. Provided that the forming of a carbon layer on the TiD target surface does not occur, the decrease of the neutron yield will not be observed [1]. The decrease of the neutron yield in deuterium targets could characterize the thickness of the carbon layer which is formed on the target during the irradiation time, after stabilizing the temperature equilibrium of the target. From the decrease of the neutron yield of tritium targets it is possible to deduce the half-life of the target. From the results (Fig. 3) it follows that the half-life of these targets is 90 min. This is relatively in a good agreement with the results of half-life of the targets described in paper [3] (≈ 40 min. for D_1^+ deuteron curret bombarding the target by 200 μA).

The rise of the neutron yield at the beginning of the irradiation time indicates that the concentration of deuterium, resp. tritium atoms, is rising in the volume of the target, where the reaction $D(d, n)$ He^4 occurs. According to [7, 8] the distribution of the tritium concentration in the absorbing layer is not uniform. The maximum value of concentration is found at the depth of ≈ 2660 Å from the target surface. In this region the atomic ratio of tritium to titanium of the target is bigger than 2 [9]. This signifies that some tritium atoms must be found also in the intermediate points of the lattice. The binding energy of these atoms is small in comparison with the binding energy of tritium atoms, bound directly to the Ti atoms in the lattice [10, 11].

At the beginning of the irradiation also the temperature rise of the titanium layer saturated by deuterium, resp. tritium, occurs. After a certain time depending on the target load by the deuteron current, on the velocity of the target cooling water flow and on the effecting of the contact between the cooling water and the backing metal of the target — the even distribution of the temperature occurs, to which there corresponds a certain temperature difference between the Ti absorbing layer and the water temperature. The influence of these factors on the mentioned temperature difference was studied in [12]. According to the measurements in paper [12] for the TiT target with a Cu layer of a thickness of 0.75 mm and a diameter of 30 mm, onto which cooling fins (7 pieces) were melted with Ag in such way that the cooling liquid could flow among them and the velocity of the cooling water of 200 cm/sec., is the value of this temperature difference of ≈ 30 °C for a load of 30 W/50.2 mm².

By the increase of the target temperature, the deuterium and the tritium atoms, which are slightly bound in neutral points of the Ti lattice of the absorbing layer, may diffuse from the higher region to the lower region — to the region in the direction of the surface. The general effect is as if the equilibrium of the tritium concentration in the region near the target surface were reached (Fig. 4). To each target temperature therefore there corresponds a different distribution of the deuterium, resp. tritium, concentration on the absorbing levels within the layer, saturated by deuterium, resp. tritium.

Fig. 4. Dependence of tritium concentration inside the absorbing layer of the TiT target on the thickness of the saturated layer (the full line corresponds to temperature T_1 and is taken from [7] and the dashed line to temperature T_2, when $T_1 < T_2$).



It results also from the shape of the desorption curves, presented in papers [10, 11] which are measured from the case of deuterium desorption from a Ti sponge. The exact theoretical interpretation of this diffusion phenomenon on the basis of desorption equations is so far impossible, because the mathematical formula describing the unequal distribution of deuterium, resp. tritium, inside the saturated target layer is not known.

In case of deuterium targets, this effect is influenced not only by the diffusion of the weakly bound deuterium atoms at intermediate neutral points of the lattice of the Ti absorbing layer in the direction of the target surface, but also by deuterons that impinge on the target surface. Therefore the deuterons bombarding the target have also an effect on the re-distribution of deuterium atoms in the saturated layer. These deuterons cause also the increase of the deuterium concentration in the Ti layer, mainly in the part of their range, which at the beginning of the measurement also contributes to the increase of the neutron yield.

IV. CONCLUSION

The dependence of the neutron yield from deuterium and tritium targets on the irradiation time was investigated by a well-known method. It was shown from the shape of the measured curves that both in the case of tritium and deuterium targets there occurs an increase of the yield at the beginning of the irradiation. In the case of deuterium targets the increase of the yield is less pronounced than in the case of tritium targets and the temperature equilibrium state is reached after 5 min., while in tritium targets after 7 min., (with deuteron beams bombarding TiD, resp. TiT targets with a current of 50 μA, resp. 100 μA, a deuteron energy of 300 keV, resp. 120 keV, and with approximately the same diameter of D_1^+ beam impinging on the target of ∅ 5 mm). It was found that the half-life of tritium targets is ≈ 90 min. and that there is a relatively good agreement with the result mentioned in paper [3]. Other parameters, as for example the flow velocity of the cooling water were not changed from target to target.

An explanation is also given of the increase of the yield at the beginning

of the irradiation time through the rise of temperature of the Ti target layer, saturated by deuterium, resp. tritium. It was found that by the increase of the target temperature the equalization of the deuterium, resp. tritium, atom concentration is reached in the direction to the Ti absorbing layer surface.

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