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TWO-PARTICLE BREAK-UP OF TRITON BY INCIDENT DEUTERON WITH ENERGY OF 37 MeV

© 2010 O. O. Belyuskina, V. I. Grantsev, V. V. Davydovskyy, K. K. Kisurin, S. E. Omelchuk, G. P. Palkin, Yu. S. Roznyuk, B. A. Rudenko, V. S. Semenov, L. I. Slusarenko, B. G. Struzhko, V. K. Tartakovsky

Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv

The break-up reaction $D+T\to d+d+n$ is investigated at the energy of incident deuterons of 36,9 MeV. Inclusive energy spectra as well as angular distributions of deuterons are measured. We described the results of the experiment satisfactorily in the framework of the microscopic diffraction nuclear model taking into account the interaction in the final state. Our calculations have shown that the main process leading to appearance of deuterons in the output channel of $D+T\to d+d+n$ reaction is diffractive break-up of the triton by the incident deuteron, and the scattered deuterons give major contribution to the cross section. The contribution of the processes involving the formation of the intermediate resonances is quite small.

Keywords: break-up, triton, deuteron, diffractive approximation, experiment, cross section, inclusive process.

1. Introduction

In this work, we present the results of our experimental study of the inclusive T(d, dd)n process at the energy of incident deuterons of 36,9 MeV. Two most contributing processes, first, the break-up of triton into deuteron and neutron by an incident deuteron and, second, the scattering of the incident deuteron are described in the framework of the microscopic diffraction nuclear model mainly as a quasi-free process with improbable formation of intermediate short-living resonances. The latter is related, as shown below, to the specifics of the process and the structure of the colliding nuclei, whereas the numerical interpretation of the cross section of the concurrent $D+T\to p+n+t$ reaction is usually not possible without an assumption concerning the formation of the intermediate four-nucleon resonances.

Collision of deuterons at the energy of 35 MeV, which is close to the energy in our experiment, with tritons was investigated in [1]. The results of calculations of the cross sections came into agreement with the experiment even in the plane wave impulse approximation, when quasi-free processes dominate and the final state particle interaction can be neglected. It was shown that both quasi-free reactions and quasi-free scattering are specific for the dt-collisions.

The deuteron-triton reactions were also studied in [2 - 4] at various energies of incident particles.

2. Experiment

The experimental research of $D+T\to d+d+n$ reaction is carried out on the isochronous cyclotron U-240 of the Institute for Nuclear Research of National Academy of Science of Ukraine at the incident deuteron energy of 36,9 MeV.

Inclusive spectra of deuterons are measured on T-Ti and Ti targets in the range of particle escape angles of $15° \le \theta_d \le 52°$ in laboratory reference frame. The threshold of particle detection is approximately 5 MeV. The T-Ti target in the form of titanium film with thickness of 4,9 mg/cm^2 saturated with tritium up to activity of 7,57 Ki is used in the experiment. Earlier obtained data on carbon target [5, 6] are used for the energy calibration. The experimental setup and the measurement procedure are described in [5, 7, 8]. The statistical accuracy of measurement of reaction products varies in range of 1 - 3 % depending on the particle detection angle. The differential cross sections of deuteron production in $D+T\to d+d+n$ reaction are determined (taking into account the absolutization) with the accuracy of approximately 15 %.

Obtained energy distributions of deuterons for their escape angles of 15, 20, 30 and 35° in the laboratory frame are shown in Fig. 1. They are broad maxima steeply inclined in the high-energy region of the spectrum and slowly decreasing in the low-energy region.

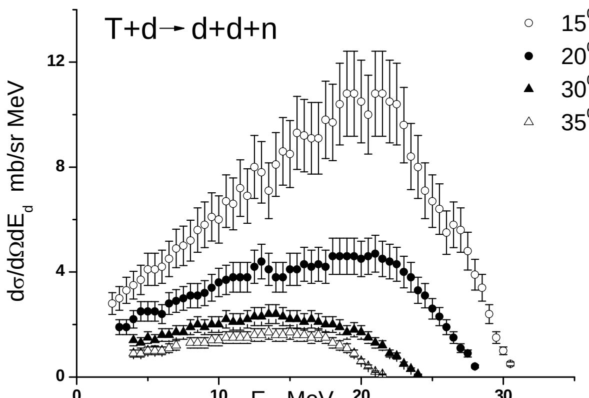

Fig. 1. Energy distributions of deuterons from $D+T\to d+d+n$ reaction for θ_d = 15, 20, 30 and 35°.

The intensity of peaks rapidly decreases with the increase of the scattering angle. The maxima in the deuteron spectra at angles of 15 and 20° are located approximately at the energy of 22 - 23 MeV, and the maxima at angles of 30 and 35° are located approximately at the energy of 12 - 14 MeV. As it will be shown in the Section 4, the contribution to the spectrum mainly comes from deuterons from T(d, d)dn reaction scattered on tritons, causing the break-up of the latter into deuterons and neutrons, and also from deuterons produced due to the triton break-up. At small energies, some contribution from deuterons produced in the decay of the intermediate resonance states ^{4}H*→d + 2n and ^{4}He*→d + d is quite possible.

The differential cross section of deuteron production $d\sigma/d\Omega_d$ is obtained by integrating the cross section $d\sigma/d\Omega_d\, dE_d$ over the energy at the interval $5 \le E_d \le 35$ MeV. Obtained angular distribution of deuterons is shown in Fig. 2 (filled circles represent our experiment, open circles represent our calculations). As it is seen from the figure, the cross section rapidly decreases with the increase of deuteron escape angle up to $\theta_d \approx 45°$ (such behavior is characteristic for the direct nuclear reactions), whereas for the further increase of the escape angle θ_d the cross section is almost constant. The theoretical analysis of the cross section $d\sigma/d\Omega_d$ is given in the Section 4.

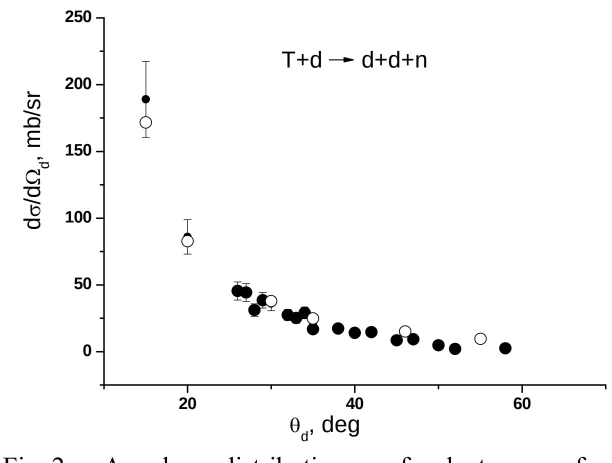

Fig. 2. Angular distributions of deuterons from $D+T \to d+d+n$ reaction at the energy of incident deuterons of 36,9 MeV: filled circles show the experimental data, open circles represent the calculated total contribution from scattered deuterons (d') and deuterons ($\bar{d}$), produced due to the triton break-up.

3. Formalism

At the energy of incident deuterons, used in our experiment, E_d = 36,9 MeV in the laboratory frame, when the wave length of relative motion of colliding deuteron and triton divided by 2π is less by almost an order of magnitude than their nuclear interaction radius, the motion of the particles in initial and final states in the $D+T \to d+d+n$ reaction can be treated as quasi-classical. Therefore, we can use the diffractive approximation at small angles of particle escape [9].

The amplitude $C(\vec{q},\vec{f})$ of $D+T \to \bar{d}+d'+n$ process, where d' denotes the scattered deuteron, $\bar{d}$ denotes the deuteron, produced as a result of the triton break-up, can be written according to [9] in the following form:

$$C(\vec{q},\vec{f}) = \int d^{(3)}\vec{\rho}_1 \int d^{(3)}\vec{r} \int d^{(3)}\vec{s} \int d^{(2)}R_\perp \Psi^*_{\vec{\chi}}(\vec{R}_\perp) \times$$
$$\times \phi^*_{\vec{f}}(\vec{\rho}_1)\phi^*_{\bar{d}}(\vec{r})\phi^*_{d'}(\vec{s})\Omega_{14}\Omega_{15}\Omega_{24}\Omega_{25}\Omega_{34}\Omega_{35}\phi_t(\vec{\rho}_1\vec{r})\phi_d(\vec{s}). \quad (1)$$

In Eq. (1), $\vec{q} = \vec{k}_d - \vec{k}_{d'}$ is the transferred momentum (in diffraction approximation $\vec{q}$ is two-dimensional vector, which is perpendicular to the momentum $\vec{k}_d$, the z-axis is aligned with $\vec{k}_d$), where $\vec{k}_d$ and $\vec{k}_{d'}$ are the momenta of the incident and scattered deuterons respectively, $\vec{f} = \frac{2}{3}\vec{k}_n - \frac{1}{3}\vec{k}_{\bar{d}} = \frac{2}{3}\vec{q} - \vec{k}_{\bar{d}}$ is relative momentum of the produced neutron with the momentum $\vec{k}_n$ and deuteron with momentum $\vec{k}_{\bar{d}}$, $\vec{\chi} = -\vec{q}$ $(\hbar = c = 1)$.

The matrix Ω_{ij} of scattering of the j-th nucleon from deuteron (j = 4, 5) with radius vector $\vec{r}_j$ on the i-th nucleon from triton (I = 1, 2, 3) with radius vector $\vec{r}_i$ is chosen in the following form [10, 11]:

$$\Omega_{ij} \equiv 1 - \omega_{ij} = 1 - a\exp(-b^2\vec{\rho}^{\,2}_{ij}), \quad (2)$$

where ω_{ij} is the profile function for interaction of the j-th nucleon of the incident deuteron and the i-th nucleon of the target triton; $\vec{\rho}_{ij}$ is the component of the vector $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ perpendicular to $\vec{k}_d$.

The amplitude (1) is expressed in terms of the intrinsic wave functions of triton $\phi_t(\vec{\rho}_1\vec{r})$, incident deuteron $\phi_d(\vec{s})$, scattered deuteron $\phi_{d'}(\vec{s})$, deuteron produced due to the triton break-up $\phi_{\bar{d}}(\vec{r})$ and the wave function of relative motion of that deuteron and neutron from the triton $\phi_{\vec{f}}(\vec{\rho}_1)$. The wave functions depend on the relative radius vectors (Jacobi variables):

$$\vec{\rho}_1 = \vec{r}_1 - \frac{\vec{r}_2 + \vec{r}_3}{2}, \; \vec{r} = \vec{r}_2 - \vec{r}_3, \; \vec{s} = \vec{r}_4 - \vec{r}_5 . \quad (3)$$

$\vec{R}_\perp$ is the perpendicular to $\vec{k}_d$ component of the vector, which connects the centers of gravity of colliding nuclei. The wave function of their relative motion in the plane, perpendicular to $\vec{k}_d$, depends on $\vec{R}_\perp$ [9]

$$\Psi_{\vec{\chi}}(\vec{R}_\perp) = \exp(i\vec{\chi}\vec{R}_\perp), \quad \vec{\chi} = -\vec{q} . \quad (4)$$

The reaction amplitude (1) contains an integral of quite high order, therefore, for simplification of calculations, we use simple Gaussian dependencies for the wave functions included in Eq. (1) [10]

$$\phi_t(\vec{\rho}_1, \vec{r}) = \frac{3^{3/4}\alpha^3}{\pi^{3/2}} \exp[-\alpha^2(\rho_1^2 + \frac{3}{4}r^2)],$$

$$\alpha = 0,375 \text{ fm}^{-1}, \quad (5)$$

$$\phi_d(\vec{s}) = \left(\frac{2\lambda^2}{\pi}\right)^{3/4} \exp(-\lambda^2 s^2), \quad \lambda = 0,267 \text{ fm}^{-1}, \quad (6)$$

$$\phi_{\vec{f}}(\vec{\rho}_1) = e^{i\vec{f}\vec{\rho}_1} - \sqrt{8}\exp(-\frac{f^2}{4\alpha^2} - \alpha^2\rho_1^2) . \quad (7)$$

The functions (5) and (6) are normalized to unity, and the functions (5) and $\phi_{\vec{f}}(\vec{\rho}_1)\phi_{\bar{d}}(\vec{r})$ are orthogonal (the functions $\phi_{\bar{d}}(\vec{r})$ and $\phi_{d'}(\vec{s})$ in Eq. (1) have the same form as Eq. (6)). In addition, since the escape angles of the particles in our experiment, as we have seen, are quite small (this fact justifies the use of diffraction approximation), in future we will calculate the amplitude (1) and the cross section of $D + T \to d + d + n$ reaction in the impulse approximation, which is appeared to be sufficient for the description of our experiment.

3.1. Inclusive process with detection of the knocked out deuteron $\bar{d}$

In our experiment, the energy distributions of unresolved scattered deuterons d' and deuterons $\bar{d}$ knocked out of tritons have been measured for a number of their escape angles. We get the expression for the inclusive cross section of the $D + T \to \bar{d} + d' + n$ process with production and detection of only $\bar{d}$ in the following form:

$$\frac{d\sigma}{d\bar{\Omega}_d d\bar{E}_d} = \frac{M^2}{2\pi^5}\sqrt{ME_d\bar{E}_d}\int_0^{E_d} dE'_d\sqrt{E'_d}\int_0^{\pi} d\theta'_d \sin\theta'_d \int_0^{2\pi} d\phi'_d \left|C(\vec{q},\vec{f})\right|^2 \delta_\Delta(T) , \quad (8)$$

$$\delta_\Delta(T) = \frac{1}{\Delta\sqrt{\pi}}\exp(-\frac{T^2}{\Delta^2}), \qquad \lim \delta_\Delta(T) = \delta(T), \Delta \to 0 , \quad (9)$$

$$T = E_d + \varepsilon_{dn} + 3E'_d + 3\bar{E}_d - 4\sqrt{E_d E'_d}\cos\theta'_d - 4\sqrt{E_d\bar{E}_d}\cos\bar{\theta}_d +$$

$$+4\sqrt{\bar{E}_d E'_d}(\cos\bar{\theta}_d\cos\theta'_d + \sin\bar{\theta}_d\sin\theta'_d\cos\phi'_d) , \quad (10)$$

where ε_{dn} = 6,3 MeV is the energy of separation of neutron from deuteron in triton. Here θ'_d, $\bar{\theta}_d$ are the angles between momenta $\vec{k}_{d'}$, $\vec{k}_{\bar{d}}$ and $\vec{k}_d$; ϕ'_d is azimuth angle between vectors $\vec{k}_{\bar{d}\perp}$ and $\vec{k}_{d'\perp}$, which are the components of vectors $\vec{k}_{\bar{d}}$ and $\vec{k}_{d'}$ being perpendicular to $\vec{k}_d$. Numerical value of the energy uncertainty Δ in Eq. (10) is approximately 1 MeV for our experiment.

The amplitude $C(\vec{q},\vec{f})$ in the diffraction approximation can be obtained in explicit form using Eqs. (1) - (3) and the wave functions (4) - (7)

$$C(\vec{q},\vec{f}) = -\frac{16\pi^{7/4}(6\lambda^2)^{3/4}a}{b^2(4\lambda^2+3\alpha^2)^{3/2}}\exp[-\frac{q^2}{4}(\frac{1}{b^2}+\frac{1}{8\lambda^2})]\exp(-\frac{f_z^2}{4\alpha^2})\{\exp(-\frac{(\vec{f}_\perp - \frac{2}{3}\vec{q})^2}{4\alpha^2}) -$$

$$-\exp(-\frac{1}{2\alpha^2}(\frac{1}{2}f_\perp^2 + \frac{1}{9}q^2)) + 2\exp(-\frac{q^2}{4(4\lambda^2+3\alpha^2)})\times$$

$$\times[\exp(-\frac{(\vec{f}_\perp+\frac{1}{3}\vec{q})^2}{4\alpha^2})-\exp(-\frac{1}{4\alpha^2}(f_\perp^2+\frac{1}{18}q^2))]\}\,. \quad (11)$$

The values of parameters of interaction *a* and *b*, which are used in (2) and (11), are taken approximately the same as in [8, 10, 11].

3.2. Inclusive process with detection of deuteron d' and total cross sections

The expression for the inclusive cross section of the $D+T\to\bar{d}+d'+n$ process, when the triton breaks up and the scattered deuteron d' is detected, similarly to Eq. (10), has the following form:

$$\frac{d\sigma}{d\Omega'_d dE'_d}=\frac{M^2}{2\pi^5}\sqrt{ME_dE'_d}\int_0^{E_d}d\bar{E}_d\sqrt{\bar{E}_d}\int_0^{\pi}d\bar{\theta}_d\sin\bar{\theta}_d\int_0^{2\pi}d\bar{\phi}_d\left|C(\vec{q},\vec{f})\right|^2\delta_\Delta(T)\,. \quad (12)$$

Measuring the cross sections (8) and (12) apart is attended with some experimental difficulties; therefore it was more reliable to measure the total cross section

$$\frac{d\sigma}{d\Omega_d dE_d}=\frac{d\sigma}{d\bar{\Omega}_d d\bar{E}_d}+\frac{d\sigma}{d\Omega'_d dE'_d}\,, \quad (13)$$

when the deuterons $\bar{d}$ and d' are not distinguished by the detectors. (In this case, kinematic variables $\bar{E}_d$, $\bar{\theta}_d$ in Eqs. (8) - (10) and E'_d, θ'_d in Eq. (12), which are not integration variables, are replaced by E_d and θ_d respectively.)

The total angular distribution of final deuterons in the reaction $D+T\to\bar{d}+d'+n$ is measured in the same way

$$\frac{d\sigma}{d\Omega_d}=\frac{d\sigma}{d\bar{\Omega}_d}+\frac{d\sigma}{d\Omega'_d}\,, \quad (14)$$

where the “partial” angular distributions are defined in an ordinary way

$$\frac{d\sigma}{d\bar{\Omega}_d}=\int_0^{E_d}d\bar{E}_d\frac{d\sigma}{d\bar{\Omega}_d d\bar{E}_d}\,,\quad \frac{d\sigma}{d\Omega'_d}=\int_0^{E_d}dE'_d\frac{d\sigma}{d\Omega'_d dE'_d}\,. \quad (15)$$

The details will be given with the analysis of the experimental data that we have obtained.

4. Analysis of the results

Fig. 3 illustrates the energy spectra of deuterons from the $D+T\to d+d+n$ reaction at energy E_d = 36,9 MeV for four escape angles: θ_d= 15° (*a*), 20° (*b*), 30° (*c*) and 35° (*d*) in the laboratory frame as well as corresponding results of their theoretical interpretation in the form of calculated curves using the obtained formulae, presented in Section 3.

Let us discuss the results of our experiment (Section 2) and their theoretical analysis (Section 3) for the $D+T\to d'+\bar{d}+n$ process. Unlike the $D+T\to p+n+t$ process, the energy spectra and angular distributions of final deuterons in the $D+T\to d+d+n$ reaction (see Figs. 2 and 3), which have been obtained by us, are basically described satisfactorily using only diffraction approximation (thick solid curves in Fig. 3), and the spectra are reproduced quite well by the Eqs. (13) - (20) in quite wide range of variation of the detected deuteron energy E_d. That is, in this case, the quasi-free scattering of incident deuterons (these will be deuterons d' in the final state) and quasi-free process with production of deuterons $\bar{d}$ due to the break-up of the target tritons (see also [1, 2]). The contribution of the processes involving the formation of the intermediate resonances seems to be small (see below).

The experimental and calculated spectra of deuterons in Fig. 3 for a number of deuteron escape angles are broad bell-shaped dependencies (maxima) on the energy of final deuterons E_d (do not confuse with the energy E_d = 36,9 MeV of incident deuterons!). These figures also illustrate the calculated contributions from scattered deuterons d' (curves *1*, plotted using Eqs. (12) and (11)), and the deuterons $\bar{d}$ produced due to the triton break-up (curves *2*, plotted using Eqs. (8) - (11)).

For comparison, Fig. 3 illustrates the results of calculations of the contributions from scattered deuterons d' (curves *1* and *1a*) and produced deuterons $\bar{d}$ (curves *2* and *2a*) for two essentially different values of parameter *b*: 0,4 fm^{-1} (curves *1* and *2*), and 0,1 fm^{-1} (curves *1a* and *2a*) – a special case, the rest of the parameters vary insignificantly. Curves *3* and *3a* illustrate the behavior of the resultant contribution of curves *1* + *2* and *1a* + *2a* correspondingly. Only in the case, when parameter *b* decreases to the value of 0.1 fm^{-1}, the contributions from the deuterons d' and $\bar{d}$ are of the same order of magnitude.

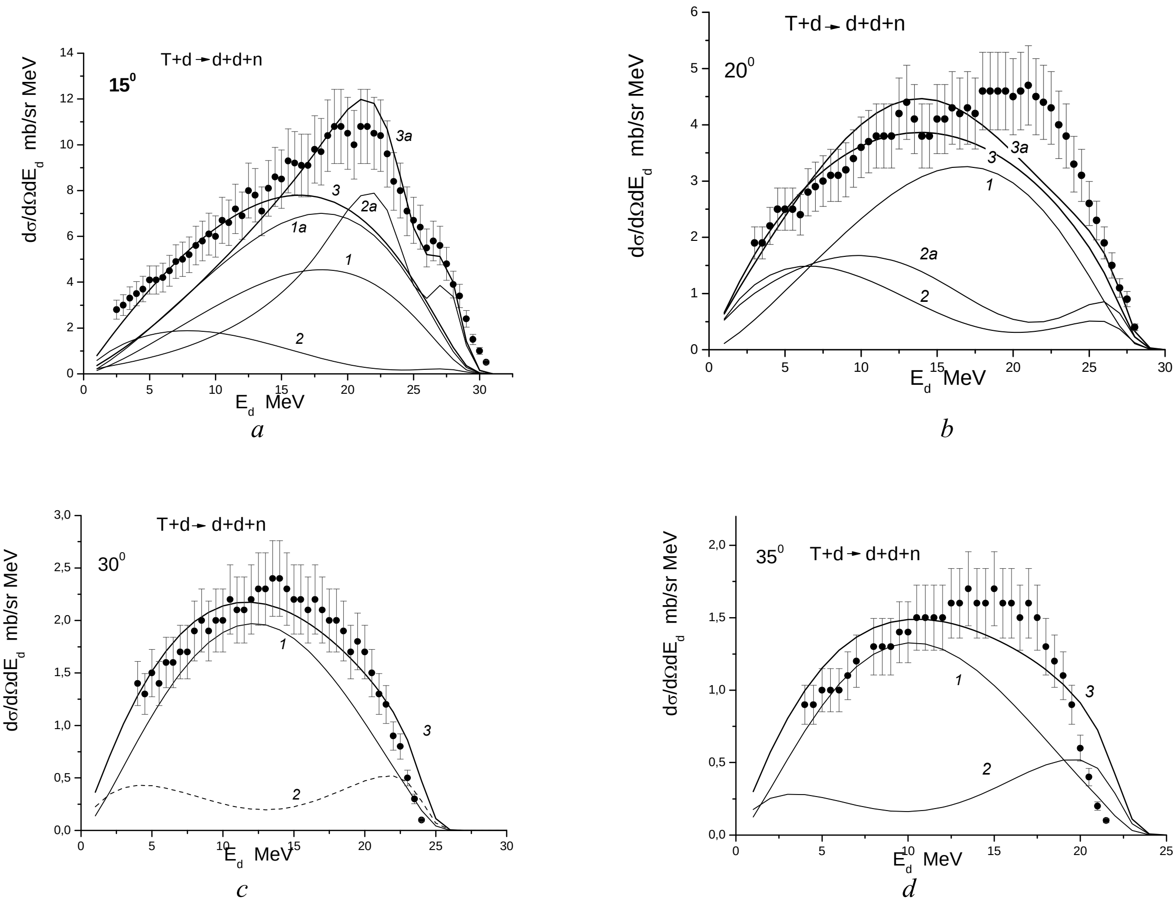

Fig. 3. Comparison of theoretical spectra with experimental data for $D+T \to d+d+n$ reaction at the energy of incident deuterons of 36,9 MeV. Filled circles show the experimental data, curves *1* show: *1a* – differential cross section $d\sigma/d\Omega_d dE_d$ for scattered deuterons (d') at various values of parameters; curves *2* show: *2a* – differential cross section $d\sigma/d\Omega_d dE_d$ for the deuterons ($\overline{d}$), produced due to triton break-up (see in the text). Total cross sections of two processes: *1(1a) + 2(2a)* are shown in Fig. 3 by solid (or dashed) thick curves (*3* or *3a*).

In Fig. 2, the experimental data (filled circles) as well as calculated (open circles) angular distributions of final deuterons from the reaction $D+T \to d'+\overline{d}+n$, obtained by integrating the corresponding deuteron spectra from Fig. 3 over the energy, are presented. Theoretical cross sections calculated within diffraction approximation are in satisfactory agreement with experimental data by absolute magnitude. The angular distributions have big magnitude at small deuteron escape angles, and the corresponding cross sections (both experimental and theoretical) rapidly drop with increase of escape angle θ_d. Such behaviour is specific for the direct nuclear processes.

Notice that the amplitude $C(\vec{q},\vec{f})$, obtained in the explicit form for the $D+T \to d+d+n$ process, as it is seen from Eq. (11), strongly depends on the structure of triton (unlike the amplitude of the process T(d, p)nt). In our approach to the investigation of the $D+T \to d+d+n$ process, the structure of both colliding nuclei as well as interaction in the final state are taken into account in consistent way. It has made possible to explain to a large degree the observed spectra and angular distribution of deuterons in the framework of the microscopic diffraction model only (Figs. 3 and 2). In some cases a small excess of the experimental values of cross sections over the theoretical values, especially at high energies of the produced deuterons (curves *1* and *2* in Fig. 3), is probably related to neglected processes of formation of intermediate resonances (first of all, ^{4}He*) as well as four-particle processes $D+T \to d'+\overline{d}+n \to d'+p+2n$ and $D+T \to d'+\overline{d}+n \to \overline{d}+p+2n$, but their contributions into the cross sections are relatively small. Some contribution to the increase of the cross section far from the diffraction maximum can come from the use of the internal wave functions of the colliding nuclei with correct asymptotics.

In addition, we calculated the resonance cross section $d\sigma_R/d\Omega_d dE_d$ corresponding to the formation of two intermediate resonances ^{4}He*, each decaying to two deuterons. An excitation energy E_1^* for the first such resonance (above the ground state of ^{4}He) is 24,25 MeV [12, 13] with parameters $E_r = 0,403$ MeV and Γ=0,150 MeV, and for the second resonance $E_2^* = 27,42$ MeV, $E_r = 3,573$ MeV, $\Gamma = 8,210$ MeV [13, 14]. The second resonance seems to give greater (though comparatively small) contribution into the cross section.

5. Conclusions

1. Inclusive spectra of deuterons from the $D + T \to d + d + n$ reaction are measured in wide range of energies of final deuterons at incident deuteron energy of 36,9 MeV. The differential cross sections (angular distributions) of deuterons are determined in the range of their escape angles $15° \le \theta_d \le 52°$ in laboratory frame.

2. The experimental spectra and the angular distribution of deuterons from the $D + T \to d + d + n$ reaction are satisfactorily described in the diffraction approximation taking into account the final state interaction and correct asymptotics of wave functions of colliding nuclei.

3. It is shown that the main process leading to the production of deuterons in the output channel of the $D + T \to d + d + n$ reaction at the energy under consideration is the diffractive break-up of the triton by incident deuteron. The scattered deuterons d' give the main contribution to the cross section (up to 70 - 90 %), whereas deuterons $\bar{d}$ from triton can be observed at quite small or big energies only, at the ends of the spectra.

4. The analysis of some other mechanisms of deuteron-triton interaction with production of deuterons in the output channel of reactions has shown that the contribution of the mechanisms to the corresponding cross section is small.

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ДВОЧАСНИКОВЕ РОЗЩЕПЛЕННЯ ТРИТОНА ДЕЙТРОНОМ З ЕНЕРГІЄЮ 37 МеВ

О. О. Белюскіна, В. І. Гранцев, В. В. Давидовський, К. К. Кісурін, С. Є. Омельчук, Г. П. Палкін, Ю. С. Рознюк, Б. А. Руденко, В. С. Семенов, Л. І. Слюсаренко, Б. Г. Стружко, В. К. Тартаковський

Реакція розщеплення $D + T \to d + d + n$ досліджувалась при енергії дейтронів 37 МеВ. Отримано інклюзивні енергетичні спектри та кутові розподіли дейтронів. Результати задовільно описано в рамках мікроскопічної дифракційної ядерної моделі з урахуванням взаємодії в кінцевому стані. Розрахунки показали, що основний процес утворення дейтронів у вихідному каналі $D + T \to d + d + n$ є дифракційне розщеплення тритона дейтроном, що налітає, а розсіяні дейтрони дають основний внесок у переріз. Внесок процесів з утворенням проміжних резонансів незначний.

Ключові слова: розщеплення, тритон, дейтрон, дифракційне наближення, експеримент, переріз, інклюзивний процес.

ДВУХЧАСТИЧНЫЙ РАЗВАЛ ТРИТОНА НАЛЕТАЮЩИМ ДЕЙТРОНОМ С ЭНЕРГИЕЙ 37 МэВ

**О. О. Белюскина, В. И. Гранцев, В. В. Давыдовский, К. К. Кисурин,
С. Е. Омельчук, Г. П. Палкин, Ю. С. Рознюк, Б. А. Руденко,
В. С. Семенов, Л. И. Слюсаренко, Б. Г. Стружко, В. К. Тартаковский**

Реакция расщепления $D+T \to d+d+n$ исследовалась при энергии налетающих дейтронов 37 МэВ. Измерены инклюзивные спектры и угловые распределения дейтронов. Результаты удовлетворительно описаны в рамках микроскопической дифракционной ядерной модели с учетом взаимодействия в конечном состоянии. Расчеты показали, что основной процесс образования дейтронов в выходном канале реакции $D+T \to d+d+n$ есть дифракционное расщепление тритона налетающим дейтроном, а рассеянные дейтроны дают основной вклад в сечение. Вклад процессов с образованием промежуточных резонансов, вероятно, незначителен.

Ключевые слова: развал, тритон, дейтрон, дифракционное приближение, эксперимент, сечение, инклюзивный процесс.

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