DISTRIBUTION OF DEUTERONS IN THE THREE-BODY BREAK-UP REACTION IN $D + D$ COLLISIONS


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The energy distributions of deuterons from the reaction $D + D \rightarrow p + n + d$ were measured in the angular range of $15^\circ \leq \theta_{c.m.} \leq 35^\circ$ at $E_D = 36.9$ MeV. The experiment was carried out on the cyclotron U-240 of INR NAS of Ukraine. Microscopic diffraction model was used for analysis of experimental data taking into account the interaction of nucleons in the final state. Two types of three-body reactions were considered: 1) break-up of the target nucleus with formation of scattered deuterons $d'$ and 2) break-up incident deuteron with formation of recoil deuterons $\bar{d}$. Experimental energy distributions of deuterons are described satisfactorily both by shape and by absolute value, taking into account total contribution of cross sections of deuterons $d'$ and $\bar{d}$.


1. INTRODUCTION

Three-body break-up reactions $D + D \rightarrow p + n + d$ were mainly studied in $pn-$, $pd-$ and $nd-$ correlation experiments at low and medium energies [1–15]. Reactions $^2H(d,dn)^1H$ and $^2H(d,d)n$ are usually analyzed using plane-wave approximation, distorted waves Born approximation or modification of plane-wave approximation with p-n interaction in the final state. Interaction in the final state was analyzed using theory of Migdal and Watson [16, 17] and, later on, using theory of G.C. Phillips, T.A. Griffy, L.C. Biedenharn [18] that assumed isospin allowed triplet interaction. Theory reproduces only the shape of spectra. The energy distributions of protons and neutrons, especially deuterons, in $D + D \rightarrow p + n + d$ reactions were studied in [19–22]. The three-body theory in the impulse approximation was used to analyze protons and neutrons energy spectra and good qualitative description of experimental data was received. The use of four-body model in [22] for description of protons and deuterons energy distribution could not satisfactory describe both the shape of spectra and angular distributions. In this work, results of experimental energy distribution of deuterons from $D + D \rightarrow p + n + d$ reaction in the angular range $15^\circ \leq \theta_{c.m.} \leq 35^\circ$ at energy $E_D = 36.9$ MeV are presented. For analysis of the experimental data, the microscopic diffraction model with simple expressions for internal wave functions was used.

2. EXPERIMENTAL RESULTS

The inclusive spectra of deuterons from reaction $D + D \rightarrow p + n + d$ in the angular range $15^\circ \leq \theta_{c.m.} \leq 35^\circ$ were measured on cyclotron U-240 INR, NAS of Ukraine at energy $E_D = 36.9$ MeV. The targets from deuterated polyethylene ($CD_2$) and carbonic film were used in the experiment. The experimental technique was published in [23–25]. The typical spectra on the targets $CD_2$ and C at the angle $\theta_d = 15^\circ$ are presented in Fig. 1 (a). The background spectra (on target C) were subtracted from the spectra corresponding to the target $CD_2$. The main difficulty at angles $\theta_d \leq 30^\circ$ consists in the identification of the closely spaced peaks corresponding to the elastic scattering of projectile deuterons on deuterium and hydrogen nuclei in the target. The continuous deuterons spectra after subtraction of the elastic scattering of projectile deuterons on the target deuteron and hydrogen are presented in Fig. 1 (b) for the scattering angle $\theta_d = 15^\circ$.

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Fig. 1. a) The inclusive deuterons spectra on target $CD_2$ (points) and $C$ (circles) at the angle $\theta_d = 15^\circ$ for deuterons energy $E_D = 36.9$ MeV. Arrows designate peaks of the elastic and inelastic scattering of projectile deuterons on carbon (1, 3), deuterium (2) and hydrogen (4). b) The spectra corresponding to the $dd$–scattering (contribution of deuteron elastic scattering on carbon and hydrogen was subtracted from the spectra measured on the target $CD_2$)

The statistical error of measurements was within 3…5%, depending on the particle detection angle. The absolute value of cross sections was defined within 10…15% accuracy accounting an error of target thickness definition. The energy spectra of deuterons from the break-up three-body reactions $D + D \rightarrow p + n + d$ at the angles $\theta_d = 15^\circ$, 20°, 29° and 35° at deuterons energy 36.9 MeV are presented in Fig. 2.

Spectra have the sharp rise on the high-energy side and a slow decrease on the low-energy side up to the energy $\sim 15$ MeV. The cross section of higher energy maximum rapidly decreasing with increase of the scattering angle and the enhancement disappears at the angles larger than $\theta_d = 35^\circ$.

Fig. 2. The energy distribution of deuterons from the reaction $D + D \rightarrow p + n + d$ at the angles $\theta_d = 15^\circ$, 20°, 29° and 35° at the incident energy of deuterons $E_D = 36.9$ MeV. The arrows show the deuterons energy corresponding to the cross section maximums calculated in the quasi-free scattering model: 1 is the scattering of the incident deuterons on nucleons of the target nucleus, 2 is the scattering of nucleons from the incident deuterons on the nuclei of target

Fig. 3. The angular dependence of the energy of maximum cross section $E_d$ for deuterons from the reaction $D + D \rightarrow p + n + d$. The curves 1 and 2 show the kinematical points corresponding to the target nuclei break-up and projectile break-up due to the quasi-free scattering, respectively

3. KINEMATICS IN THE REACTION $D + D \rightarrow p + n + d$

The quasi-free three-body process $D + D \rightarrow p + n + d$ were examined when one of the colliding deuterons scattered on either proton or neutron of another deuteron. The results of calculation are shown in Fig. 3 as the angular dependences of survived deuteron energy. The curve 1 shows angular dependence of the deuterons energy corresponding to the maximum cross section in the spectra when the incident deuteron scatters on the proton or neutron from deuteron of target. It can be seen from Fig. 3 that the energy of scattered deuterons depends strongly on the emission angles. It is implied that we have two broad maximums at the angles $\theta_d \leq 30^\circ$ – one
at the high energy end of spectra and another at the lower part of spectra. The curve 2 shows the angular energy dependence of the cross section maximum position in the spectra of the scattered deuterons that are formed from the scattering of nucleons from the incident deuteron on the deuterium in the target. The energy of deuterons (recoil) is slowly decreasing with the increasing of the angle up to $\theta_d \sim 60^\circ$.

The energies of the expected cross sections maximum positions, corresponding to the kinematical calculations presented in Fig. 3 are shown in Fig. 2 by the arrows and numerals (the numerals indicate the mechanism of reaction). We observe the agreement between the kinematical calculation (curves 1 and 2 in Fig. 3) and the experiment for the angles $\theta_d = 15^\circ$ and $29^\circ$. Two broad maxima with comparable intensities were observed in the experimental spectra at the angles $\theta_d = 23^\circ$ that became almost undistinguishable with the increase of the scattering angle. The kinematical calculations show the position of only one maximum in the low energy region.

4. DIFFRACTION SPLITTING OF DEUTERONS IN THE REACTION $D + D \rightarrow p + n + d$

The deuterons break-up in the three body reaction $D + D \rightarrow p + n + d$ at energy $E_D \approx 40$ MeV in the first approximation can be treated as the quasiclassical process as the consequence of deuteron "looseness"and the diffraction model [26-29] can be used. The application of the diffraction model to the description of $D + D \rightarrow p + n + d$ reaction was developed by V.K. Tartakovskiy [25, 27, 29].

The cross section of deuterons diffraction splitting in the three-body reaction $D + D \rightarrow p + n + d$ can be written as

$$
\frac{d\sigma}{d\Omega dE_d} = \frac{M^{5/2}\sqrt{E_D E_d}}{4\sqrt{2\pi^5}} \times \int_0^{2E_D} dE_p \sqrt{E_p} \int_0^\pi d\theta_p \sin \theta_p \int_0^{2\pi} d\varphi_p \times \times |A(\vec{q}, \vec{u})|^2 \delta(\Delta(T),
$$

here $E_D$ is the incident deuteron energy, $E_d$ is the energy of deuteron formed in the three-body reaction, $E_p$, $\theta_p$, $\varphi_p$ is the energy and angle of the outgoing proton, $\rho_p$ is the azimuth angle between the vectors $\vec{k}_{d' -} \perp$ and $\vec{k}_{p' \perp}$, which are perpendicular to the $\vec{k}_D$ component of the vectors $\vec{k}_d$ and $\vec{k}_{p'}$; $|A(\vec{q}, \vec{u})|$ is the process amplitude that depends on the momentum $\vec{q}$ transferred to the deuteron in the three-body reaction and $\vec{u}$ is the relative momentum of $p$ and $n$. The factor $\delta(\Delta(T))$ takes into account an energy uncertainty. The profile interaction function of nucleons for colliding deuterons was selected in the following form

$$
\omega = \omega(|\vec{r}_{ij}|) = \alpha \exp \left(-b^2 \rho_{ij}^2 \right), \quad (2)
$$

where $\vec{r}_{ij}$ is the component of vector $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ perpendicular to the momentum of the incident deuteron $\vec{k}_D$ in the laboratory system, $\vec{r}_i \ (i = 1, 2)$ is the radius vector of $i$-th nucleon in the target deuteron and $\vec{r}_j \ (j = 3, 4)$ is the radius vector of $j$-th nucleon in the incident deuteron.

The amplitude $A(\vec{q}, \vec{u})$ can be obtained in the explicit form by using simple Gaussian expressions for internal wave functions, the same as in [25]. The obtained amplitude $A(\vec{q}, \vec{u})$ has the following form:

$$
A(\vec{q}, \vec{u}) = -\frac{(2\pi)^{7/4}}{b^2 \lambda^{3/2}} e^{-\frac{q^2}{8\lambda^2}} \times \times e^{-\frac{u^2}{4\lambda^2}} \left( e^{-\frac{e^2}{8\lambda^2} + e^{-\frac{e^2}{8\lambda^2} - 2\epsilon\frac{u^2}{4\lambda^2}}} \right). \quad (3)
$$

5. ANALYSIS OF THE EXPERIMENTAL DATA

Two cases of the three-body reaction were studied: 1) the break-up of the target nucleus $D + D \rightarrow d' + p + n$ with formation of scattered deuteron $d'$ and 2) the break-up of the incident deuteron $D + D \rightarrow d + p + n$ with formation of the recoil deuteron $d$.

The experimental energy distribution of deuterons from the reaction $D + D \rightarrow p + n + d$, $\frac{d^2\sigma}{d\Omega dE_d}$, is a sum of cross sections $\frac{d^2\sigma}{d\Omega dE_{d'}}$, corresponding to the break-up of the target nucleus, and $\frac{d^2\sigma}{d\Omega dE_d}$, corresponding to the break-up of the incident deuteron. Both components are undistinguishable experimentally.

5.1. CROSS SECTION OF SCATTERED DEUTERONS $d'$ FORMATION

The energy distribution of deuterons $d'$ was calculated by using (1) and (3) assuming that $E_d = E_{d'}$. Then terms in (3) would be determined as

$$
q^2 = 4M \left( E_D + E_{d'} - 2\sqrt{E_D E_{d'}} \cos \theta \right), \quad (4)
$$

$$
u^2 = \left[ E_D + E_{d'} + 2E_p - 2\sqrt{E_D E_{d'}} \cos \theta \right. - 2\sqrt{E_D E_p} \cos \theta_p + 2\sqrt{E_{d'} E_p} \times \times (\cos \theta \cos \theta_p + \sin \theta \sin \theta_p \cos \varphi_p), \quad (5)
$$

$$
\bar{u}_{12} q^2 = 2M (E_{d'} \sin^2 \theta + 2\sqrt{E_{d'} E_p} \times \times \sin \theta \sin \theta_p \cos \varphi_p), \quad (6)
$$

where $\theta$ is the angle between the vectors $\vec{k}_D$ and $\vec{k}_{d'}$. The energy distributions of the deuterons $d'$ for the angles $\theta = 15^\circ, 29^\circ$ are shown in Fig. 4 by dotted curve 1. The scattered deuterons give the considerable contribution in the high-energy region of the spectrum reaching $\sim 80\%$ at small angles.
5.2. CROSS SECTION OF RECOIL DEUTERONS d FORMATION

Replacing $E_d$ in (1) and (5) by $E_d$ and defining the transferred momentum as

$$q^2 = 4 M E_d,$$

(7)

$$\vec{u}_1 \cdot \vec{q} = -2 M (E_d \sin^2 \theta + \sqrt{2} E_d E_p \times$$

$$\times \sin \theta \sin \theta_p \cos \varphi_p),$$

(8)

the energy distribution of $\bar{d}$ will be received in the accordance with (3). The angle $\theta$ is defined by directions of the vectors $\vec{k}_D$ and $\vec{k}_d$. Fig. 4 illustrates the energy distribution of $\bar{d}$ for angles $\theta = 15^\circ, 29^\circ$ (curve 2). The recoil deuterons give the main contribution to the low-energy region of the spectrum. The contribution of the recoil deuterons $\bar{d}$ at the angle $\theta = 15^\circ$ makes $\sim 20\%$, and is increasing up to $\sim 40\ldots 50\%$ at the angle $\theta = 29^\circ$.

The full curve 3 in Fig. 4 shows the energy spectrum defined by the sum of both mentioned above processes

$$\frac{d^{(2)} \sigma}{d \Omega \Omega_d E_d} = \frac{d^{(2)} \sigma}{d \Omega \Omega_d E_d} + \frac{d^{(2)} \sigma}{d \Omega \Omega_d E_d},$$

(9)

We see that the diffraction theory explains satisfactorily both the shape and absolute value of the experimental cross sections at the angles $\theta = 15^\circ...35^\circ$ which are changed distinctly with an increasing of the scattering angle.

6. SUMMARY

1. The energy distributions of deuterons from the reaction $D + D \rightarrow d + p + n$ in the angular range of $15^\circ \leq \theta_d \leq 35^\circ$ were measured at the incident deuteron energy $E_D = 36.9$ MeV.

2. The analysis of the experimental data is carried out with the microscopic diffraction model taking into account the interaction of nucleons in the final state and using simple expressions for the internal wave functions. Two types of tree-body reaction were considered: 1) the break-up of the target nuclei with the formation of the scattered deuteron $d'$ and 2) the break-up of the incident deuteron with the formation of the recoil deuteron $\bar{d}$. The experimental energy distribution of the scattered deuterons is described satisfactory both by the shape and absolute value taking into account the total contribution of $d'$ and $\bar{d}$ cross section.

3. It is shown that the main process leading to the production of deuterons in the $D + D \rightarrow d + p + n$ reaction at the angles $\theta \leq 30^\circ$ for the deuterons energy $E_D = 36.9$ MeV is the diffraction break-up of the target deuteron by the incident deuteron. The cross section is reduced sharply upon an increase of the deuteron emission angle and at the angle of $\theta \sim 30^\circ$ is comparable with the recoil deuteron cross sections.

References


РАСПРЕДЕЛЕНИЕ ДЕЙТРОНОВ В ТРЕХЧАСТИЧНЫХ РЕАКЦИЯХ РАЗВАЛА В $D + D$ - СТОЛКНОВЕНИЯХ

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Измерены энергетические распределения дейтронов из реакции $D + D \rightarrow p + n + d$ в диапазоне углов $15^\circ \leq \theta_{c.m.} \leq 35^\circ$ при энергии $E_D = 36.9$ МэВ. Эксперимент выполнен на циклотроне У-240 ИЯИ НАН Украины. Анализ экспериментальных данных проведен по микроскопической дифракционной модели с учетом взаимодействия нуклонов в конечном состоянии. Рассмотрены два типа трехчастичной реакции: 1) развал ядра мишени с образованием рассеянного дейтрона $d'$ и 2) развал налетающего дейтрона с образованием дейтрона отдачи $\bar{d}$. Экспериментальные энергетические распределения дейтронов удовлетворительно описываются как по форме, так и по величине с учетом суммарного вклада сечений дейтронов $d'$ и $\bar{d}$.

РОЗПОДIЛ ДЕЙТРОНIВ У ТРИЧАСТКОВИХ РЕАКЦIЯХ РОЗЩЕПЛЕННЯ В $D + D$ - ЗIТКНЕННЯХ

О.О. Белюскiна, В.І. Гранцев, К.К. Кiсурин, С.Є. Омельчук, Г.П. Палкiн, Ю.С. Рознюк, Б.А. Руденко, В.С. Семенов, Л.І. Слюсаренко, Б.Г. Стружко

Вимірюю енергетичні розподіли дейтронів із реакції $D + D \rightarrow p + n + d$ у діапазоні кутів $15^\circ \leq \theta_{c.m.} \leq 35^\circ$ при енергії $E_D = 36.9$ МeВ. Експеримент виконано на циклотронi У-240 ІЯД НАН України. Аналіз експериментальних даних виконано за мікроскопічною дифракційною моделлю з урахуванням взаємодії нуклонів у кінцевому стані. Розглянуто два типи тричасткових реакцiй: 1) розщеплення ядра мiшени з утворенням розсiяного дейтрона $d'$ та 2) розщеплення налiтаючого дейтрона з утворенням дейтрона вiддачi $d$. Експериментальні енергетичні розподiли дейтронiв задовiльно описуються i по формi, i по величинi з урахуванням сумарного внеску перерiзiв дейтронiв $d'$ та $d$.