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

O.O. Beliuskina, V.I. Grantsev, K.K. Kisurin, S.E. Omelchuk, Yu.S. Roznyuk, B.A.Rudenko, V.S. Semenov, L.I. Slusarenko, B.G. Struzhko *

Institute For Nuclear Research of NAS of Ukraine, 03680, Kiev, Ukraine

(Received January 21, 2013)

The energy distributions of deuterons from the reaction $D + D \rightarrow p + n + d$ were measured in the angular range of $15° \leq \theta_{c.m.} \leq 35°$ 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 $\bar{d}$.

PACS: 24.30.Cz, 13.75.Cs, 21.30.Fe, 21.60.Jz

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 Vatson [16,17] and, later on, using theory of G.C.Phillips, T.A.Griffy, L.C.Biedeenharn [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 $15° \leq \theta_{c.m.} \leq 35°$ 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 $15° \leq \theta_{c.m.} \leq 35°$ 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 $\theta_d = 15°$ 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 $\theta_d \leq 30°$ 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 deuterium and hydrogen are presented in Fig. 1,(b) for the scattering angle $\theta_d = 15°$.

*Corresponding author E-mail address: beliuskina@gmail.com

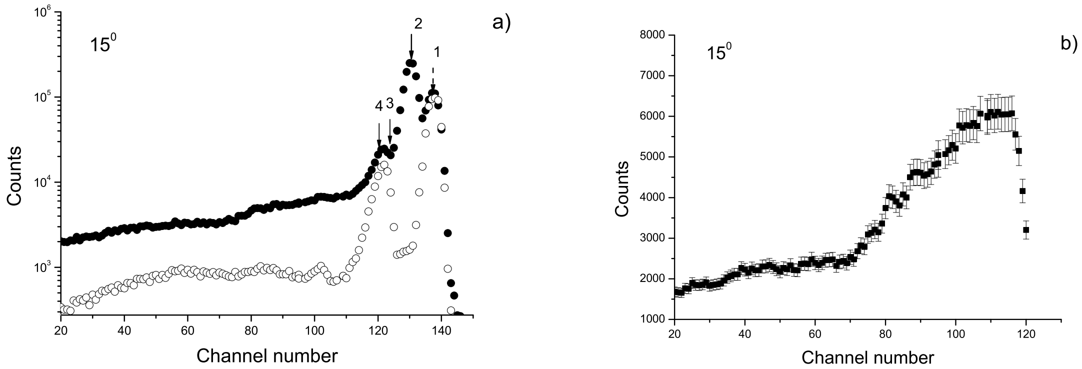

Fig.1. *a)The inclusive deuterons spectra on target CD_2 (points) and C (circles) at the angle $\theta_d = 15°$ for deuterons energy $E_D = 36.9\,MeV$. Arrows designate peaks of the elastic and inelastic scattering of projectile deuterons on carbon (1, 3), deuterium (2) and hydrogen (4). b) The spectra 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 $D + D \to p + n + d$ at the angles $\theta_d = 15°$, $20°$, $29°$ and $35°$ at deuterons energy $36.9\,MeV$ are presented in Fig. 2.

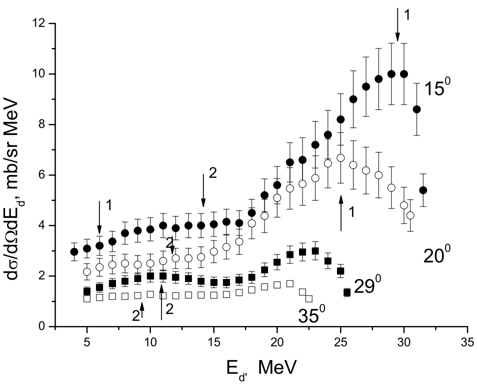

Fig.2. *The energy distribution of deuterons from the reaction $D + D \to p + n + d$ at the angles $\theta_d = 15°$, $20°$, $29°$ and $35°$ at the incident energy of deuterons $E_D = 36.9\,MeV$. The arrows show the deuterons energy corresponding to the cross section maximums calculated in the quasi-free 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*

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 $\theta_d = 35°$.

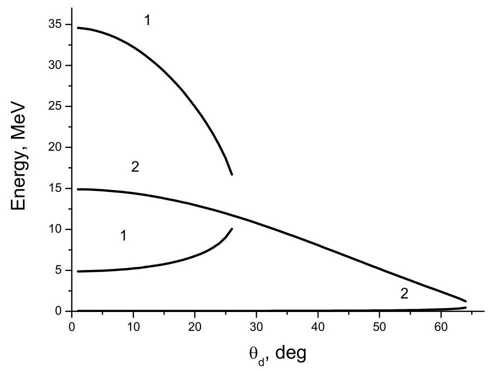

Fig.3. *The angular dependence of the energy of maximum cross section E_d for deuterons from the reaction $D + D \to p + n + d$. The curves 1 and 2 show the kinematical points corresponding to the target nuclei break-up and projectile break-up due to the quasi-free scattering, respectively*

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

The quasi-free three-body process $D + D \to p + n + d$ 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 $\theta_d \le 30°$ – 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 $\theta_d \sim 60°$.

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 $\theta_d = 15°$ and $20°$. Two broad maxima with comparable intensities were observed in the experimental spectra at the angle $\theta_d = 29°$ 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. Tartakovsky [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

$$\frac{d\sigma}{d\Omega dE_d} = \frac{M^{5/2}\sqrt{E_D E_d}}{4\sqrt{2}\pi^5} \times$$
$$\times \int_0^{2E_D} dE_p \sqrt{E_p} \int_0^{\pi} d\theta_p \sin\theta_p \int_0^{2\pi} d\varphi_p \times$$
$$\times \mid A(\vec{q},\vec{u}) \mid^2 \delta_\Delta (T), \qquad (1)$$

here E_D is the icident deuteron energy, E_d is the energy of deuteron formed in the three-body reaction, E_p, θ_p is the energy and angle of the outgoing proton,φ_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 $\vec{k}_p$; $\mid A(\vec{q},\vec{u}) \mid$ 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

$$\varpi = \varpi(\mid \vec{\rho}_{ij} \mid) = \alpha \exp\left(-b^2\rho_{ij}^2\right), \qquad (2)$$

where $\vec{\rho}_{ij}$ 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 m, $\vec{r}_j$ (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:

$$A(\vec{q},\vec{u}) = -\frac{(2\pi)^{7/4}\alpha}{b^2\lambda^{3/2}} e^{-q^2\left(\frac{1}{4b^2}+\frac{3}{32\lambda^2}\right)} \times$$
$$\times e^{-\frac{u^2}{4\lambda^2}} \left(e^{\frac{\vec{u}_\perp\vec{q}}{4\lambda^2}} + e^{-\frac{\vec{u}_\perp\vec{q}}{4\lambda^2}} - 2e^{\frac{q^2}{32\lambda^2}}\right). \qquad (3)$$

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 $D + D \rightarrow \bar{d} + p + n$ with formation of the recoil deuteron $\bar{d}$.
The experimental energy distribution of deuterons from the reaction $D + D \rightarrow p + n + d$, $\frac{d^2\sigma}{d\Omega_d E_d}$, is a sum of cross sections $\frac{d^2\sigma}{d\Omega_{d'} E_{d'}}$, corresponding to the break-up of the target nucleus, and $\frac{d^2\sigma}{d\Omega_{\bar{d}} E_{\bar{d}}}$, corresponding to the break-up of the incident deuteron. Both components are undistinguished 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

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

$$u^2 = \Big[E_D + E_{d'} + 2E_p - 2\sqrt{E_D E_{d'}}\cos\theta$$
$$-2\sqrt{2}\sqrt{E_D E_p}\cos\theta_p + 2\sqrt{2}\sqrt{E_{d'}E_p} \times$$
$$\times (\cos\theta\cos\theta_p + \sin\theta\sin\theta_p\cos\varphi_p)\Big], \qquad (5)$$

$$\vec{u}_\perp\vec{q} = 2M(E_{d'}\sin^2\theta + 2\sqrt{2}\sqrt{E_{d'}E_{d'}} \times$$
$$\times \sin\theta\sin\theta_p\cos\varphi_p), \qquad (6)$$

where θ is the angle between the vectors $\vec{k}_D$ and $\vec{k}_{d'}$. The energy distributions of the deuterons d' for the angles $\theta = 15°, 29°$ 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 ~80% at small angles.

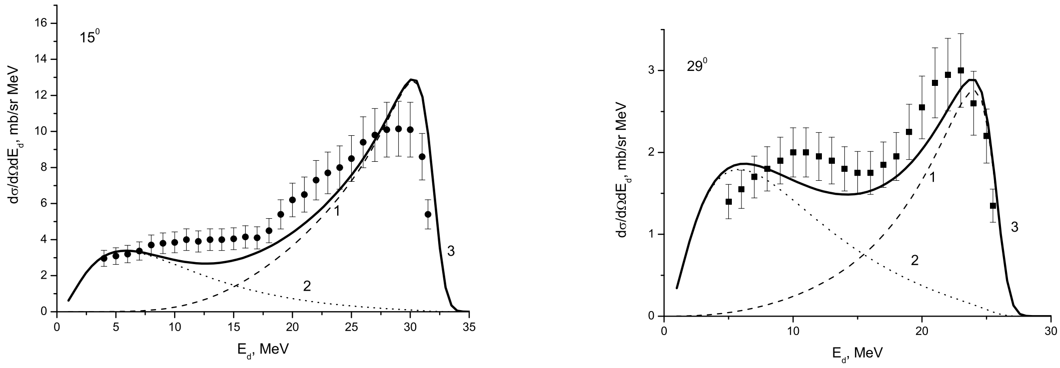

Fig.4. *The comparison of the theoretical calculations with the experimental energy distributions for angles $\theta = 15°, 29°$ at $E_D = 36.9\,MeV$. Curve 1 is the energy spectra of scattered deuterons d' from the reaction $d + D \to d' + p + n$, 2 is the energy spectra of the recoil deuterons from the reaction $d + D \to p + n + \bar{d}$; 3 is the total contribution of both processes*

5.2. CROSS SECTION OF RECOIL DEUTERONS $\bar{d}$ FORMATION

Replacing E_d in (1) and (5) by $E_{\bar{d}}$ and defining the transferred momentum as

$$q^2 = 4ME_{\bar{d}}, \tag{7}$$

$$\vec{u}_\perp \vec{q} = -2M(E_{\bar{d}} \sin^2\theta + \sqrt{2}\sqrt{E_{\bar{d}}E_p} \times \times \sin\theta \sin\theta_p \cos\varphi_p), \tag{8}$$

the energy distribution of $\bar{d}$ will be received in the accordance with (3). The angle θ is defined by directions of the vectors $\vec{k}_D$ and $\vec{k}_{\bar{d}}$. Fig. 4 illustrates the energy distribution of $\bar{d}$ for angles $\theta = 15°, 29°$ (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 $\theta = 15°$ makes ~20%, and is increasing up to ~ 40...50% at the angle $\theta = 29°$.

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

$$\frac{d^{(2)}\sigma}{d\Omega_d dE_d} = \frac{d^{(2)}\sigma}{d\Omega_{\bar{d}} dE_{\bar{d}}} + \frac{d^{(2)}\sigma}{d\Omega_{d'} dE_{d'}}. \tag{9}$$

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

6. SUMMARY

1. The energy distributions of deuterons from the reaction $D + D \to d + p + n$ in the angular range of $15° \le \theta_d \le 35°$ 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 $D + D \to d + p + n$ reaction at the angles $\theta \le 30°$ 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 $\theta \sim 30°$ is comparable with the recoil deuteron cross sections.

References

1. W.von Witsch, M. Ivanovich, D. Rendic, et al. Proton-neutron final-state interaction in the $D(d, dp)n$ reaction // *Phys.Rev.C.* 1970, v. 2, p. 2144.
2. B.E. Corey, R.E. Warner, R.W. Bercaw. Coincidence study of the reaction $^2H(d, dp)n$ // *Nucl.Phys.A.* 1971, v. 174, p. 468.
3. B.J. Wielinga, A.D. IJpenberg, K. Mulder, et al. Prominent two-body effects in the prosses $p(^3He, pd)p$ and $d(d, pd)n$ // *Phys.Rev.Lett.*

1971, v. 27, p. 1229.

4. J.P. Burg, J.C. Cabrillat, M. Chemarin, et al. Quasifree scattering in deuteron break-up by deuterons // *Nucl.Phys. A* 1972, v. 179, p. 385.

5. V. Valkovic, I. Duck, W.E. Sweeney, G.C. Phillips. Three-body break-up in the $d + d \rightarrow d + p + n$ reaction // *Nucl.Phys. A* 1972, v. 183, p. 126.

6. E. Andrade, V.V. alkovic, D. Rendic, G.C. Phillips. Angular distributions of quasi-free scattering contributions in deuteron break-up by protons and deuterons // *Nucl.Phys. A* 1972, v. 183, p. 145.

7. W. von Witsch, W. Viefers, H. Mommsen, et al. Test of the Treiman-Yang criterion in the $^2H(d, pd)n$ reaction at 20 MeV bombarding energy // *Nucl.Phys. A* 1972, v. 195, p. 617.

8. I.M. Duck, V. Valkovie, G.C. Phillis. Off-energy-shell effects in deuteron-induced deuteron breakup // *Phys.Rev.Lett* 1972, v. 29, N13, p. 875.

9. D.I. Bonbright, R.G. Allas, R.O. Bondelid, et al. $^2H(^2H, dp)n$ reaction // *Phys.Rev.C* 1973, v, 8, N1, p. 114.

10. W. von Witsch, G.S. Mutchler, G.C. Phillips, D. Miljanic. Spatial localization effects in the $^2H(d, pd)n$ reactions // *Phys.Rev.C* 1973, v. 8, N1, p. 403.

11. G. Hrehuss, HKelleter, C. Mayer-Boricke. Measurements on $D(d, d'p)n$ quasifree scattering between 45 and 80 MeV // *Phys.Lett.B.* 1974, v. 51, N5, p. 454.

12. L.A. Golovach, V.I. Grancev, V.V. Zerkin, et al. Investigations of deuteron breakup mechanisms by deuteron at beam energy 50 MeV // *Izv.AN USSR, ser.phiz.* 1987, v. 51, N1, p. 166.

13. V.I. Konfrderatenko, V.M. Pirnak, B.A. Pylypchenko, et al. Interaction between neuterond and proton in final state of $^2H(d, pd)n$ reaction ar deuteron energy 46.7 MeV// *UFZ* 1997, v. 39, N3,b, p. 274.

14. B. Struzhko. FSI and QFS in the four-body reaction at 46.7 MeV // *Journal of Physical Studies* 1999, v. 3, N4, p. 431 (in Ukraine).

15. A. Ramazani-Moghaddam-Arani, H.R. Amir-Ahmadi, A.D. Bacher, et al. Three-body break-up in deuterion-deuteron scattering at 65 MeV/nuclon // *Phys.Rev.C* 2011, v. 83, p. 024002.

16. K.M. Watson. The effect of final state interactions on reaction cross section // *Phys. Rev.* 1952, v. 88, p. 1163.

17. A.B. Migdal. The theory of nuclear reaction with slow-energy particles prodaction // *ZETF* 1955, v. 28, p. 3.

18. R.J.N. Phillips. Comparison of p-p and n-n final state interactions Original Research Article // *Nucl. Phys.* 1964, v. 53, p. 650.

19. W.T.H. Van Oers, K.W. Brockman. Proton spectra from d+d breakup at 25.3 MeV // *Nucl. Phys.* 1965, v. 74, p. 73.

20. H.W. Lefevre, R.R. Borchers and C.H. Poppe Neutrons from deuteron breakup on D, T and ^{4}He // *Phys.Rev.* 1962, v. 128, N3, p. 1328.

21. C. Pope, N. Buget, C.O. Blyth, et al. A search for spin dependent effects in the three body final state from the $^2H(d, n)pd$ reaction at 11.3 MeV incident deuteron energy // *J.Phys.A:Gen.Phys.* 1972, v. 5, p. L33.

22. K. Fukunaga, T. Ohsawa, S. Kakigi, et al. Energy spectra of deuterons and protons for the $d+d$ reaction at 60 MeV // *Nucl.Phys.A* 1982, v. 390, p. 19.

23. O.O. Beliuskina, S.V. Berednichenko, V.I. Grancev et al. Investigation of nuclear reactions in D+T system // *Yad. Fiz. and Ener.* 2007, v. 3(21), p. 54 (in Ukraine).

24. O.O. Beliuskina, V.I. Grancev, V.V. Davydovskyi et al. Elastic Scattering of Deuterons by Tritons // *UFZ* 2009, v. 54, p. 658 (in Ukraine).

25. O.O. Belyuskina, V.I. Grantsev, V.V. Davydovskyy et al. Quasy free processes at two-particle braekup of triton by deuteron at energy 37 MeV // *Izv.RAN, ser. phiz.* 2011, v. 75, p. 988 (in Russia).

26. A.I. Akhiezer and A.G. Sitenko. Nuclear diffraction processes at high energies // *UFZ* 1958, v. 3, p. 16.

27. V.K. Tartakovsky. About scattering of relativistic deuterons by nuclei // *Izv. Vuzov USSR. Fizika(Tomsk)* 1980, v. 9, p. 3.

28. A.I. Akhiezer and A.I. Pomeranchuk Paricle diffraction scettering by nuclei// *Uspekhi fiz. nauk* 1958, v. 69, N8, p. 593.

29. V.K. Tartakovsky. Deuteron breakup by $^{64}Cu,^{197}Au$ at energies 23 and 26 MeV // *Journal of Physical Studies* 2006, v. 10, p. 29.

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

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

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 $\bar{d}$.

РОЗПОДІЛ ДЕЙТРОНІВ У ТРИЧАСТКОВИХ РЕАКЦІЯХ РОЗЩЕПЛЕННЯ В $D+D$ - ЗІТКНЕННЯХ

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

Виміряно 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 $E_D = 36.9$ МеВ. Експеримент виконано на циклотроні У-240 ІЯД НАН України. Аналіз експериментальних даних виконано за мікроскопічною дифракційною моделлю з урахуванням взаємодії нуклонів у кінцевому стані. Розглянуто два типи тричасткових реакцій: 1) розщеплення ядра мішені з утворенням розсіяного дейтрона d' та 2) розщеплення налітаючого дейтрона з утворенням дейтрона віддачі $\bar{d}$. Експериментальні енергетичні розподіли дейтронів задовільно описуються і по формі, і по величині з урахуванням сумарного внеску перерізів дейтронів d' та $\bar{d}$.