ELASTIC DEUTERON-TRITON SCATTERING AT 37MeV


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(Received July 30, 2008)

Results of measurement of differential cross section of elastic scattering of deuterons by tritons at the laboratory energy of 37 MeV for the center-of-mass angles \( \theta_{c.m.} \) ranging from 25° to 150° are presented. The experiment is carried out on the U-240 isochronous cyclotron of the Institute for Nuclear Research, National Academy of Science of Ukraine. Obtained experimental data is analyzed theoretically in the framework of microscopic nuclear diffraction model. Angular distributions of deuterons in a region of the main maximum \( (\theta_{c.m.} \leq 60°) \) are described quite well at deuteron energies of 14.4, 37.0 and 39.9 MeV. An explanation of a broad secondary maximum emerging at low deuteron energies is proposed using the phenomenological quasiclassical approximation. The quasiclassical approximation allows to describe the angular distributions only qualitatively at large angles \( 60° < \theta_{c.m.} < 150° \), where the cross sections are quite small.


1. INTRODUCTION

Collisions of deuterons with tritons at energies of tens MeV still remain studied insufficiently [1-7], though they are very informative and are of interest for investigation of both the few-nucleon nucleus structure and the nuclear interaction. Coulomb interaction gives negligibly small contribution (of the order of 1%) into the scattering cross section at the energies of incident deuterons in the interval of 10...40 MeV. Therefore, in considering dt-scattering we will subsequently neglect the Coulomb interaction. For the same reason, the \(^3\)He-scattering [7-9] is very much similar to the dt-scattering.

At the deuteron energies that are being considered, the wavelength \( \lambda \) of the relative motion of \(^2\)H and \(^3\)H nuclei divided by \( 2\pi \) appears to be a few times less than the radius of their nuclear interaction \( R_N \) (approximately 4...6 fm), therefore the diffraction approximation can be used for a calculation of the elastic deuteron - triton scattering cross section. Consideration will be inherently quasiclassical (\( \lambda \ll R_N \)) when an influence of many quantum mechanical effects (the Pauli principle, spins of nuclei, antisymmetrization of wave functions) becomes substantially weaker [10], which simplifies calculations significantly. In addition, as it will be shown, the macroscopic description of the dt-scattering process is also possible. In present work, we consider the dt-collision and solve the very complicated problem of five interacting nucleons of continuous energy spectrum approximately in the framework of nuclear diffration model. The goal of this work is to present the results of our experiment on elastic scattering of deuterons with the energy \( E_d = 37 \text{MeV} \) by tritons as well as to provide the theoretical description and interpretation of our data together with the published data corresponding to other energies \( E_d \) using simple quasiclassical methods of quantum mechanics [10-15].

2. EXPERIMENT

Elastic scattering of deuterons by tritium nuclei with energy of deuterons \( E_d = 37 \text{MeV} \) was experimentally studied on Kiev isochronous cyclotron \( U - 240 \) of KINR, NAS of Ukraine. Measurements were carried on self-maintained titanium-tritium target and on pure titanium target. Ti-T target is a tritium-loaded titanium film with activity of 7.57 Ci.

Charged particles were detected by three telescopes of counters (\( \Delta E - E \)) placed in reaction plane. Intensity of ion beam passed through the target was detected with Faraday cup connected to current integrator. For determination of angular distribution of elastically scattered deuterons data on elastic scattering of deuterons \( T(d,d)T \) as well as data on recoil tritons were used. Registration was performed in angular range of 15° \( \leq \theta_{lab} \leq 58° \) for deuterons and in angular range of 15° \( \leq \theta_{lab} \leq 52° \) for tritons. \( \theta_{lab} \) is an angle in laboratory system of coordinates. Statistical error of measurement for inclusive spectra was 1...3% depending on angle of detection. Absolute values of cross sections were determined with accuracy \( \sim 15\% \). Measurement procedure and preliminary results were published in [1,6].
Fig.1(a) presents one-dimensional deuteron spectra measured on Ti − T and Ti targets at angle 15°. Fig.1(b) presents recoil tritons spectra at the same angle. Isolation of peaks corresponding to elastic scattering of deuterons on tritons was carried by subtraction of spectra derived on Ti-target from spectra obtained from Ti − T target. The same approach was used for separation of peaks of recoil tritons. Energy spectra of deuterons and recoil tritons from T(d, d)T reaction obtained at 15° and 38° are illustrated on Fig.2(a,b). Analysis of energy spectra is presented in sections 4 and 5. Dependence of differential sections dσ/dΩ for elastic scattering of deuterons on tritons in center-of-mass system (c.m.) is presented on Fig.3(a). Before, the elastic scattering of deuterons on tritons was studied only at low energies (6.6 ...14.4 MeV) [7]. On Fig.3(a) previously published data on dt-scattering at 8.3 and 14.4 MeV are presented together with data obtained in our experiment. Angular distributions have common typical features: sharp decrease of section with scattering angle increasing to θ_{c.m.} ≤ 60° and noticeable rise of cross sections at angles starting from θ_{c.m.} ≈ 130°. However there are considerable differences at 60° ≤ θ_{c.m.} ≤ 130° angle range. Wide maxima observed at θ_{c.m.} ≈ 100° with energies 8.3 MeV and 14.4 MeV, disappears at our energy 37 MeV.

We made comparison with data on elastic d^3He scattering at energies 10.0, 14.4 [7], 17.49, 39.9 MeV [7,8,9]. Comparison is presented on Fig.3(b).

Fig.1. Deuteron spectra measured on Ti − T and Ti targets for the angle of 15° at the deuteron energy of 37 MeV (a); the same for recoil tritons (b)

Fig.2. Energy spectra for elastically scattered deuterons and recoil tritons at the deuteron energy of 37 MeV for the angle of 15° (a); (b) - the same for the angle of 38°. Solid and dashed lines correspond to the calculations based on the microscopic nuclear diffraction model [15,16]

Fig.3. Elastic scattering of deuterons by tritons at the laboratory energies of 8.3 MeV [7], 14.4 MeV [7] and 37 MeV (our data) (a); (b) - deuterons on helions at the laboratory energies of 14.4 MeV [7], 17.49 MeV [7,8] and 39.9 MeV [9]

Nature of dependence of elastic d^3He cross-section at range of low and high angles is identical to dependence of cross-section for elastic dt-scattering. At angular range of 60° ≤ θ_{c.m.} ≤ 130° the similar picture is observed: with deuterons energy increasing the wide maximum at angle θ_{c.m.} ≈ 100° disappears
distorting with energy 39.9 MeV. Data on $^3$He$(d, d)$ scattering obtained at energy 17.49 MeV already indicate maximum disappearing at angle $\theta_{c.m.} \approx 100^\circ$. Deuterons elastic scattering on helions at energy $E_d = 39.9$ MeV has practically the same dependence as elastic scattering of deuterons on tritons at our energy.

3. FORMALISM FOR ANGULAR DISTRIBUTIONS OF SCATTERED DEUTERONS

We consider the deuteron - triton scattering in the center-of-mass frame and use the microscopic diffraction model [10,15], in which an interaction of each of three nucleons of $^3$H nucleus with each of two nucleons of $^2$H nucleus is described by the nucleon-nucleon Gaussian type [10,12,16]:

$$\omega_{ij} \equiv \omega((\vec{p}_{ij})) = a \exp(-b^2 \rho_{ij}^2),$$

(1)

where $\vec{p}_{ij}$ is the component of the vector $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ perpendicular to the incident deuteron momentum $\vec{k}_d$ in the laboratory frame. Here $\vec{r}_i$ is the radius vector of the $i$ - th nucleon of triton ($i = 1, 2, 3$), $\vec{r}_j$ is the radius vector of the $j$ - th nucleon of deuteron ($j = 4, 5$).

The amplitude of elastic deuteron - triton scattering in the diffraction impulse approximation [11]

$$A(\chi) = \int d^3(\vec{p}_1) \int d^3(\vec{r}) \int d^3(\vec{s}) \int d^2(\vec{R}_\perp) \phi_2^2(\vec{s}) \times \phi_1^2(\vec{p}_1, \vec{r}_1) \psi_3^2(\vec{R}_\perp) \psi_0(\vec{R}_\perp) \times (\omega_{14} + \omega_{15} + \omega_{24} + \omega_{25} + \omega_{34} + \omega_{35}),$$

(2)

where

$$\vec{s} = \vec{r}_{45}, \quad \vec{r} = \vec{r}_{23}, \quad \vec{p}_1 = \vec{r}_{1} - \frac{\vec{r}_{2} + \vec{r}_{3}}{2}.$$

It describes well the corresponding diffraction cross section

$$\frac{d\sigma}{d\Omega} = \frac{k^2}{(2\pi)^2} |A(\chi)|^2 d\Omega,$$

$$k = \frac{3}{5} k_d, \quad |\chi| = 2k \sin \frac{\theta}{2}.$$  

(3)

In a region of the main diffraction maximum, where the scattering angle $\phi \equiv \theta_{c.m.}$ does not exceed 65º (in the laboratory frame this angle does not exceed approximately 40º), simple intrinsic wave functions of deuteron $\phi_d(\vec{s})$ and triton $\phi_t(\vec{p}_t, \vec{r})$ in Gaussian form [10,12,16] are used:

$$\phi_d(\vec{s}) = \left(\frac{2\lambda^2}{\pi}\right)^{3/4} e^{-\lambda^2 s^2},$$

$$\lambda = 0.267 \text{ fm}^{-1},$$  

(4)

$$\phi_t(\vec{p}_t, \vec{r}) = \frac{3^{3/4}}{\pi \alpha^2} e^{-\alpha^2(p_t^2 + 3r^2/4)},$$

$$\alpha = 0.375 \text{ fm}^{-1}.$$  

(5)

The relative motion of deuteron and triton before and after scattering is described by the following wave functions [11]:

$$\psi_0(\vec{R}_\perp) = 1, \quad \psi_3(\vec{R}_\perp) = e^{i\chi \vec{R}_\perp},$$

(6)

where $\chi$ is the transferred momentum ($\chi \vec{k}_d = 0$), $\vec{R}_\perp$ is the component of vector $\vec{R}$, which connects the centers of mass of deuteron and triton ($h = c = 1$), perpendicular to $\vec{k}_d$.

On using the equations (1) - (6), we get the following compact expression for the angular distribution of deuterons in elastic scattering in explicit form:

$$\frac{d\sigma}{d\Omega} = \frac{9a^2k^2}{b^4} \exp \left[-\chi^2 \left(\frac{1}{2}\lambda^2 + \frac{1}{9}\alpha^2 + \frac{1}{10}\lambda^2\right)\right], \quad \chi = 2k \sin \frac{\theta}{2}, \quad k = \frac{2\chi}{\lambda} = \frac{6}{5} \sqrt{M E_d}, \quad \theta \leq 65^\circ,$$

(7)

where $M$ is the nucleon mass.

For quality description of scattering at large angles ($65^\circ \leq \theta \leq 180^\circ$) in the center-of-mass frame, where the cross section is quite small, we use quasi-classical expression for the scattering amplitude of two colliding impenetrable balls, which represent deuteron and triton, disregarding their internal structure [13]:

$$f(\theta) = i \frac{R_N}{2 \sin \frac{\theta}{2}} \left(2k R_N \sin \frac{\theta}{2}\right) \times$$

$$\times -\frac{i}{2} R_N \exp \left(-2ik R_N \sin \frac{\theta}{2}\right).$$

(8)

4. FORMALISM FOR ENERGY SPECTRA

With the help of the above formulae of the microscopic diffraction model, we obtained the following differential cross sections, which can be used to describe the energy distribution in the laboratory frame (where tritons are in the rest before collision) versus the energy of scattered deuterons $E_d$ and the recoil energy of tritons $E_t$ at fixed deuteron angle $\theta_d$ and triton escape angle $\theta_t$:

$$\frac{d\sigma}{d\Omega_d dE_d} = \frac{9M}{5\pi^2} \frac{E_d^3}{\sqrt{E_d^2}} |A(\chi)|^2 \times$$

$$\times \delta \left(5E_d^3 - E_d - 4\sqrt{E_d^2 \cos \theta_d}\right),$$

(9)

$$\frac{d\sigma}{d\Omega_t dE_t} = \frac{3^{3/2}M}{5\pi^2} \frac{E_t^3}{\sqrt{E_t^2}} |A(\chi)|^2 \times$$

$$\times \delta \left(2\sqrt{6E_d^2 \cos \theta_t - 5E_t}\right),$$

(10)

where $|A(\chi)|^2$ is taken from (3) and (7). In addition, the variable $\chi$ in the amplitude $A(\chi)$ should be expressed in terms of kinematic variables in the laboratory frame. So, we substitute the following expression to (9):

$$\chi = \left[4M(E_d + E_d^2 - 2\sqrt{E_d^2 E'_t \cos \theta_d})\right]^{1/2},$$

(11)
and the following expression to (10):
\[
\chi = \sqrt{6ME_t} = \frac{12}{5} \sqrt{ME_d} \cos \theta_d,
\]
(12)
where the relationships for scattering (escape) angles and energies of nuclei before and after collision in the center-of-mass and laboratory frames were used [14].

In calculations of the cross sections (9) and (10), the delta-functions \( \delta(E) \) were replaced with the finite functions \( \delta_\Gamma(E) \), whose narrow maxima are defined by the finite width \( \Gamma \) [10,16]:
\[
\delta_\Gamma(E) = \frac{\Gamma}{2\pi E^2 + \frac{\Gamma^2}{4}}, \quad \lim_{\Gamma \to 0} \delta_\Gamma(E) = \delta(E).
\]
(13)

5. ANGULAR AND ENERGY DISTRIBUTIONS ANALYSIS

5.1. ANGULAR DISTRIBUTIONS ANALYSIS

Differential cross-sections of elastic dt-scattering \( d\sigma/d\Omega \) in center of mass system obtained at deuterons energy 37.0 MeV as well as published data at energy 14.4 MeV [7] and data on \( d^3He \) scattering at energy 39.9 MeV [9] were used in analysis. Fig.4(a,b,c) presents these data and corresponding theoretical calculations. Curves 1-1a on Fig.4 are derived using equation (7). As shown on Fig.4 experimental angular distributions at the following energies: (a) - 14.4 MeV; (b) - 37 MeV; (c) - 39.9 MeV. Curves 1 and 1a - calculations based on the microscopic nuclear diffraction model (7) with the following parameters: (a) \( R_N = 4.4 \text{ fm}; \) \( b_1 = 0.30 \text{ fm}^2; \) \( a_1 = 0.5; \) \( b_2 = 0.10 \text{ fm}^2; \) \( b_1 = 0.80; \) \( b_2 = 0.31 \text{ fm}^2; \) \( a_1 = 0.65; \) \( b_2 = 0.22 \text{ fm}^2; \) (c) \( R_N = 4.4 \text{ fm}; \) \( b_1 = 0.30 \text{ fm}^2; \) \( b_2 = 0.10 \text{ fm}^2; \) \( b_1 = 0.70; \) \( b_2 = 0.31 \text{ fm}^2. \)

Line 2 - calculations based on quasiclassical approximation (8) with the following parameters: (a) \( R_N = 5.2 \text{ fm}; \) \( b_1 = 0.15 \text{ fm}^2; \) \( b_2 = 0.10 \text{ fm}^2; \) \( a_1 = 0.65; \) \( b_2 = 0.22 \text{ fm}^2; \) (c) \( R_N = 4.4 \text{ fm}. \)

Curve 3 on (b,cb) denotes the cross section \( \frac{d\sigma}{d\Omega} = \frac{\Gamma}{4\pi R_N^2} \) for deuteron scattering angles \( \theta_d > 70^\circ; \) \( R_N = 2 \text{ fm}. \)

5.2. ENERGY SPECTRA ANALYSIS

Experimental energy spectra at angle \( \theta_{lab} = 15^\circ \) for deuterons (\( \Gamma = 0.69 \text{ MeV} \)) and tritons (\( \Gamma = 0.92 \text{ MeV} \)) are represented on Fig.2(a), and Fig.2(b) shows spectra for deuterons (\( \Gamma = 0.68 \text{ MeV} \)) and tritons (\( \Gamma = 1.07 \text{ MeV} \)) at angle \( \theta_{lab} = 38^\circ \). Location, width \( \Gamma \), and height of maxima are well described with curves calculated by equations (9) - (13), except of cross section \( d\sigma/d\Omega dE_t \) at \( \theta = 15^\circ \) and \( E_t \) in range from 15 MeV to 30 MeV (see Fig.2(a)).

In the angular range \( 65^\circ \leq \theta_{c.m.} \leq 150^\circ \) only qualitative description of cross sections is achieved.
\( \theta_t \) and \( E'_t > 15 \text{ MeV} \) impulse and energy of recoil triton gain high values what can excite inner degrees of freedom of colliding nuclei with its transition into intermediate quasisteady states, majority of which come back to bound states and we detect it in our experiment, minority break up and we don’t detect the decay products.

6. CONCLUSIONS

1. Differential cross sections of the elastic scattering of deuterons with the energy of 37 MeV by tritons are measured for the center-of-mass scattering angles ranging from 25\( ^\circ \) to 150\( ^\circ \).

2. The analysis of the elastic scattering of deuterons by tritons (helions) is carried out for deuteron energies of 14.4 MeV [7], 37 MeV (our data) and 39.9 MeV [9] in the framework of the microscopic nuclear diffraction model. The experimental angular distributions of scattered deuterons in the region of main maximum \( (\theta_{c.m.} \leq 65^\circ) \) are quite well described theoretically for the deuteron energies of 14.4 MeV, 37 MeV and 39.9 MeV.

3. The phenomenological quasiclassical approximation cannot adequately well describe the observed dependence of the cross section on \( \theta_{c.m.} \) in the whole range of angles 25\( ^\circ \leq \theta_{c.m.} \leq 150^\circ \) without taking into account a number of quantum effects and real structure of colliding nuclei. In the range of angles 65\( ^\circ \leq \theta_{c.m.} \leq 150^\circ \), only qualitative description of the cross sections is achieved.

4. An explanation of the broad secondary maximum emerging in the dependence of the observed cross section on the \( \theta_{c.m.} \) in the whole range of angles 25\( ^\circ \leq \theta_{c.m.} \leq 150^\circ \) without taking into account a number of quantum effects and real structure of colliding nuclei.

5. The analysis of measured energy spectra of deuterons and recoil tritons from the reaction \( t(d,d)t \) at the energy \( E_d = 37 \text{ MeV} \) is carried out. Our calculations of the energy distributions, based on the microscopic nuclear diffraction model, are in good agreement with the experiment at width \( \Gamma = 0.68...0.69 \text{ MeV} (15^\circ \leq \theta_{lab} \leq 38^\circ) \) for deuterons and \( \Gamma = 0.92...1.07 \text{ MeV} (15^\circ \leq \theta_{lab} \leq 38^\circ) \) for recoil tritons.

References


