MULTICENTER EIKONAL APPROXIMATION IN REARRANGEMENT REACTIONS

V.V. DAVYDOVSKYY, A.D. FOURSAT

Institute for Nuclear Researches, Nat. Acad. Sci. of Ukraine
(47, Nauky Prosp., Kyiv 03028, Ukraine; e-mail: odavi@kinr.kiev.ua)

UDC 539.17

Formulae describing the single-nucleon-transfer reactions taking into account the many-nucleon structure of nuclei have been obtained in the framework of the distorted-wave approximation using the wave functions of the relative motion of particles in the eikonal approximation. The calculations of the angular distribution of deuterons in the ^{4}He(p,d)^{3}He reaction at $E_p = 770$ MeV point to a certain role of multiple scattering effects and a large sensitivity of the observable characteristics to the details of the nuclear structure.

1. Introduction

When high-energy nucleons and nuclei collide with other nuclei, rather complicated processes besides elastic and inelastic scattering may take place, being accompanied by a redistribution of the particles in the colliding systems. They include, for example, nucleon-transfer reactions, where one or several nucleons are transferred from one system to another. The simple examples of the inelastic processes with particle redistribution are the stripping (d,p) and pick-up (p,d) reactions. Those reactions have been used for a long time as a spectroscopic method for studying the characteristics of nuclear states at low energies. The analysis of such reactions is based mainly on the distorted-wave Born approximation (DWBA), where the direct mechanism of nucleon transfer or its generalizations, where the coupling of channels is considered, dominate. In the simplest case, it may be a two-step process, whose essence lies in exciting the initial or final nucleus.

The single-nucleon pick-up reactions, A(p,d)B, are characterized at intermediate energies by a significant value of the momentum transferred. Here, they are similar to the (π^+,p) and (γ,p) reactions, where a single nucleon also leaves a nucleus, with the latter obtaining a large momentum. Therefore, it is natural to expect for the (p,d) reactions at high energies to give information of a new type concerning the nuclear wave functions, e.g., about their high-momentum components and the nucleon-nucleon and nucleon-nucleus interactions, and to be a good means for the determination of details of the nuclear structure, in particular, the effects of the fragmentation of the hole states caused by a residual interaction. In addition, the experimental spectra of (p,d) reactions at energies of 700–800 MeV at nuclei ^{12}C, ^{16}O, and ^{28}Si [1], when comparing them with the spectra obtained at energies of protons less than 200 MeV, showed that a number of new states, which are occupied very slightly at low energies, are excited with a great probability in that reaction, which is related either to a change of the mechanism of their excitation or to the involving of the π-meson degrees of freedom of the nucleus. At high energies, the reaction appears much more sensitive to the D-wave of a deuteron wave function than to the S-wave, contrary to the case of low energies.

The situation became rather dramatic, when an attempt to describe the angular distribution of deuterons in the ^{4}He(p,d)^{3}He reaction at 770 MeV was made [2]. As the researches, careful enough, showed [2,3], the DWBA method with the use of the wave functions of helium nuclei, which are consistent with the charge formfactors, was unable to reproduce the experimental data even qualitatively. This testifies to that the mechanism of the (p,d) reaction at energies of about 700—800 MeV is not clear enough yet. In particular, the behavior of the reaction excitation function [4, 5] suggests that the simple pole-involved mechanism of single-nucleon pick-up does not dominate in this energy region, at least for light nuclei. Therefore, a number of other mechanisms of the reaction, which contain some other processes with the participation of intermediate π-mesons [5, 6], were proposed. The introduction of intermediate π-mesons makes the redistribution of the large transferred momentum over the motions of many nucleons in the bound nuclear system possible. Nevertheless, as will be shown below, this can be achieved also through the mechanism of multiple scattering.

The mechanisms, taking into account the participation of π-mesons or based on the triangular diagram, allow the behavior of the reaction excitation function to be explained qualitatively. Nevertheless, for the quantitative calculations of the corresponding cross-sections, the detailed knowledge of amplitudes and vertices of a number of processes involving π-mesons, which are known badly, is necessary. Therefore, the analysis of the (p,d) reaction with the help of such mechanisms was not carried out in this work. The calculations of the energy dependences of the cross-section of the (p,d) reaction at high energies and a comparison of the obtained results with the data of [4, 5] would be crucial for the establishment of its mechanism.

At high energies, obviously more natural are the approaches based on the Glauber—Sitenko diffraction theory of multiple scattering. The theory of the stripping (d,p) and (d,n) reactions in the diffraction approximation was proposed in [7, 8], where the expressions for the energy spectra and angular distributions of the nucleons formed were obtained. Those formulae correspond to the cross-sections summed up over all the states of the final nuclei being formed, which reduces, to some extent, the value of those approaches.

The diffraction theory of the processes with particle redistribution has been formulated for the first time in [9], where the formula for the cross-section of the stripping reaction, at which one of the particles included into the bombarding system is captured by the scattering center, was derived. The cross-section of the process was determined from the reduction of the flux density of captured particles. It corresponds to the integral value of the cross-section summed up over all the final states of a captured particle. This theory was applied in [10] for the description of the angular distribution of deuterons in the ^{4}He(p,d)^{3}He reaction at $E_p = 770$ MeV. In so doing, a hypothesis about the peripheral character of the reaction mechanism had to be introduced for the theory to agree with experiment. The same reaction was investigated in [11] with the help of the method of eigenstates. The concept of eigenstate has been introduced for the first time in [8, 12], when considering the processes of diffraction interaction of deuterons with nuclei. This method was widely used further, when considering the diffraction dissociation of hadrons and the processes of creation of mesons.

The purpose of the present work is to extend the techniques of the multicenter eikonal approximation [14] onto the reactions with particle redistribution and to consider, as an example, the pick-up reaction (p,d) discussed above. The results of numerical calculations obtained with the use of the theory developed by us are compared with the experimental data on the angular distribution of deuterons. The method of analysis of the pick-up reaction, suggested below, is, in essence, the DWBA-method, in which the distorted waves take into account the many-nucleon structure of nuclei and are expressed through the free amplitude of the NN-scattering similarly to how the many-nucleon T-operator is constructed in the Glauber–Sitenko theory. But, contrary to [13], the longitudinal component of the transferred momentum is taken into account more correctly in the expressions connecting the distorted waves with the free amplitude of the NN-scattering, which appears very essential in the case of the reactions under study.

2. Eikonal Model of the Pick-up Processes

Consider the process of neutron pick-up by a proton in the nuclear reaction A(p,d)B. Let the bombarding proton have the coordinate $\mathbf{r}_p$, let the neutron, which is picked up from nucleus A and, binding to the proton, creates a deuteron, have the coordinate $\mathbf{r}_n$, and let the residual nucleus $B = A - 1$ can be in both the ground and excited states. In the DWBA, the matrix element of the transition operator is written as

$$\Im_{f\,i} = (\psi_f^{(-)}, V_{n\,p}\varphi_i^{(+)}), \tag{1}$$

where $V_{n\,p}$ is the operator of the proton-neutron interaction and the distorted wave functions satisfy the following operator equations:

$$\varphi_i^{(+)} = \chi_i + \frac{1}{E_i - H_i + i0}V_p\varphi_i^{(+)} =$$

$$= \chi_i + \frac{1}{E_i - H_i - V_p + i0}V_p\chi_i, \tag{2}$$

$$\psi_f^{(-)} = \chi_f + \frac{1}{E_f - H_f - i0}V_d\psi_f^{(-)} =$$

$$= \chi_f + \frac{1}{E_f - H_f - V_d - i0}V_d\chi_f. \tag{3}$$

Here, V_p and V_d are the operators of interaction of the residual nucleus with the bombarding proton and a deuteron which is formed, respectively:

$$V_p = \sum_{j=1}^{B} V_{p\,j}(\mathbf{r}_p - \mathbf{r}_j), \quad V_n = \sum_{j=1}^{B} V_{n\,j}(\mathbf{r}_n - \mathbf{r}_j),$$

ISSN 0503-1265. Ukr. J. Phys. 2005. V. 50, N 3

$$V_d = V_n + V_p. \tag{4}$$

They are assumed independent of spin.

We emphasize that the distortion of the incident waves in Eq. (2) is not induced by the initial nucleus A as a whole but only by its core B, whereas the usual DWBA-calculations suppose the distortion to be connected only to the elastic scattering by the whole initial nucleus. It is obvious that, for such a light nucleus as ^{4}He, this assumption is not justified. The channel wave functions for the given reaction,

$$\chi_i = (2\pi)^{-3} \exp(i\mathbf{k}_p\mathbf{r}_p + i\mathbf{k}_A\mathbf{R}_A)\, \Phi_{J_A M_A}(\mathbf{r}_n, \xi)\chi_{\frac{1}{2}\mu_p},$$

$$\chi_f = (2\pi)^{-3} \exp(i\mathbf{k}_d\mathbf{R}_d + i\mathbf{k}_B\mathbf{R}_B)\times$$

$$\times\Phi_{J_d M_d}(\mathbf{r}_p, \mathbf{r}_n)\Phi_{J_B M_B}(\xi), \tag{5}$$

satisfy the equations

$$H_i\chi_i \equiv (H_A + K_A + K_p)\chi_i = E_i\chi_i,$$

$$H_f\chi_f \equiv (H_B + H_d + K_B + K_d)\chi_f = E_f\chi_f. \tag{6}$$

Here, H's are the internal Hamiltonians of the nuclei, K's are the operators of kinetic energy, and $\xi = (\mathbf{r}_1 \ldots \mathbf{r}_B)$ is the set of coordinates of the nucleons of the residual nucleus.

At the energies of bombarding protons and formed deuterons considerably larger by the absolute value than those of the corresponding channel interactions and when the wavelengths of the proton and deuteron are much less than the nucleus size, it is possible to take advantage of the eikonal solutions of Eqs. (2) and (3)

$$\varphi_i^{(+)} = \chi_i \prod_{j=1}^{B} \exp\left\{-\frac{i}{v_p}\int\limits_{-\infty}^{z_p - z_j} V_{p\,j}(\mathbf{b}_p - \mathbf{b}_j, \zeta)\, d\zeta\right\},$$

$$\psi_f^{(-)*} = \chi_f^* \prod_{j=1}^{B} \exp\left\{-\frac{i}{v_d}\int\limits_{z_p - z_j}^{\infty} V_{p\,j}(\mathbf{b}_p - \mathbf{b}_j, \zeta)\, d\zeta - \right.$$

$$\left. -\frac{i}{v_d}\int\limits_{z_n - z_j}^{\infty} V_{n\,j}(\mathbf{b}_n - \mathbf{b}_j, \zeta)\, d\zeta\right\}, \tag{7}$$

where v_p and v_d are the relative speeds of the proton and deuteron, respectively. Since the small angles of the deuteron escape are considered, the eikonal trajectory of motion (the z-axis) in Eq. (7) can be chosen along the direction of the momentum $\mathbf{k}_p$.

Using the representations, containing the converging and diverging distorted waves with the asymptotics of type (7), for the amplitude of the elastic NN-scattering, it is possible to get rid of the potentials $V_{N\,j}$ and to express the exponential factors in (7), by means of the inverse Fourier transformation, through the experimental values for the amplitudes of the free NN-scattering. Then the distorted waves are of the form

$$\varphi_i^{(+)} = \chi_i \prod_{j=1}^{B} \Big[1 - \omega^{(+)}(\mathbf{r}_p - \mathbf{r}_j)\Big],$$

$$\psi_f^{(-)*} = \chi_f^* \prod_{j=1}^{B} \Big[1 - \omega^{(-)}(\mathbf{r}_p - \mathbf{r}_j)\Big]\Big[1 - \omega^{(-)}(\mathbf{r}_n - \mathbf{r}_j)\Big], \tag{8}$$

where $\omega^{(\pm)}$ are the generalized nucleon-nucleon profile functions. In the case of the conventional Gaussian parametrization of the elementary amplitude of scattering, we get

$$\omega^{(\pm)}(\mathbf{r} - \mathbf{r}_j) = \frac{1}{2}\omega(\mathbf{b} - \mathbf{b}_j)\left[1 \pm \mathrm{erf}\left(\frac{z - z_j}{2\sqrt{a}}\right)\right], \tag{9}$$

where $\omega(\mathbf{b})$ is the ordinary profile function of a nucleon in the Glauber–Sitenko theory connected to a transverse part of the free amplitude of the NN-scattering by the two-dimensional Fourier transformation:

$$\omega(\mathbf{b}) = \omega_0 \exp\left(-\frac{b^2}{4a}\right), \quad \omega_0 = \frac{\sigma}{8\pi a}(1 - i\rho). \tag{10}$$

It should be emphasized that the profile function $\omega(\mathbf{b})$ is caused exclusively by the transfer of a transverse momentum. The appearance of the longitudinal (dependent on z) part in the profile $\omega(\mathbf{b})$ is related to the explicit account of the longitudinal component of the transferred momentum in the amplitude of the NN-scattering, and, in the framework of the eikonal approximation, corresponds to the account of the "off-shell" effects in the scattering amplitude.

Using expressions (5) and (8) as the wave functions, let us separate the δ-function, which corresponds to the momentum conservation law, from Eq. (1):

$$\Im_{f\,i} = (2\pi)^{-6} \int \prod_{j=1}^{B} d\mathbf{r}_j d\mathbf{r}_p d\mathbf{r}_n \times$$

$$\times \exp\left(i\mathbf{k}_p\mathbf{r}_p + i\mathbf{k}_A\mathbf{R}_A - i\mathbf{k}_d\mathbf{R}_d - i\mathbf{k}_B\mathbf{R}_B\right) \times$$

$$\times \Phi^*_{J_d M_d}\Phi^*_{J_B M_B} V_{np}\Omega(\mathbf{r}_p,\mathbf{r}_n;\xi)\times$$

$$\times\Phi_{J_A M_A}\chi_{\frac{1}{2}\mu_P}\delta\left(\frac{1}{B}\sum_{j=1}^{B}\mathbf{r}_j - \mathbf{R}_B\right)d\mathbf{R}_B, \qquad (11)$$

where the distortion operator Ω is connected to the generalized profile functions of nucleons by the relation

$$\Omega(\mathbf{r}_p,\mathbf{r}_n;\xi) = \prod_{j=1}^{B}\left[1-\omega^{(+)}(\mathbf{r}_p-\mathbf{r}_j)\right]\times$$

$$\times\left[1-\omega^{(-)}(\mathbf{r}_p-\mathbf{r}_j)\right]\left[1-\omega^{(-)}(\mathbf{r}_n-\mathbf{r}_j)\right]. \qquad (12)$$

Passing in Eq. (11) to the relative variables $\mathbf{r}' = \mathbf{r} - \mathbf{R}_B$ and integrating over $\mathbf{R}_B$, we obtain

$$\Im_{fi} = (2\pi)^{-6}\int\prod_{j=1}^{B} d\mathbf{r}_j^{'} d\mathbf{r}_p^{'} d\mathbf{r}_n^{'} \exp\left[i\left(\mathbf{k}_p - \frac{\mathbf{k}_d}{2}\right)\mathbf{r}_p^{'}+\right.$$

$$\left.+i\left(\frac{\mathbf{k}_A}{A}-\frac{\mathbf{k}_d}{2}\right)r_n^{'} + i\left(\mathbf{k}_p+\mathbf{k}_A-\mathbf{k}_d-\mathbf{k}_B\right)\mathbf{R}_B\right]\times$$

$$\times\Phi^*_d\Phi^*_B V_{np}\Phi_A\chi_p\delta\left(\frac{1}{B}\sum_{j=1}^{B}\mathbf{r}_j^{'}\right)d\mathbf{R}_B \equiv$$

$$\equiv \delta\left(\mathbf{k}_p+\mathbf{k}_A-\mathbf{k}_d-\mathbf{k}_B\right)T_{fi}. \qquad (13)$$

When integrating over the coordinate $\mathbf{R}_B$, we take into account that the wave functions of the nuclei, as well as V_{np} and Ω, depend only on the relative coordinates, i.e. that they are translation-invariant. As a result, we obtain the following expression for the T-matrix element on a momentum surface in the center-of-mass system ($\mathbf{k}_A = -\mathbf{k}_p$, the primes are omitted):

$$T_{fi} = (2\pi)^{-3}\int d\mathbf{r}_p d\mathbf{r}_n \exp\left(i\mathbf{Q}_p\mathbf{r}_p + i\mathbf{Q}_n\mathbf{r}_n\right)\times$$

$$\times\Phi^*_d V_{np}\int\prod_{j=1}^{B} d\mathbf{r}_j\delta\left(\mathbf{R}_B\right)\Phi^*_B\Omega\Phi_A\chi_p, \qquad (14)$$

where

$$\mathbf{Q}_p = \mathbf{k}_p - \frac{\mathbf{k}_d}{2}, \quad \mathbf{Q}_n = -\frac{\mathbf{k}_p}{A} - \frac{\mathbf{k}_d}{2}. \qquad (15)$$

are the momenta transferred. All the coordinates in expression (14) are reckoned from the center of masses of the residual nucleus B. For the simplification of Eq. (14), we will use the condition that the eigenfunctions of the core $\Phi_{J_B M_B}$ compose a complete set. Then

$$T_{fi} = \int\frac{d\mathbf{r}_p d\mathbf{r}_n}{(2\pi)^3}\exp\left(i\mathbf{Q}_p\mathbf{r}_p + i\mathbf{Q}_n\mathbf{r}_n\right)\Phi^*_{J_d M_d}V_{np}\times$$

$$\times\sum_{J_B^{'} M_B^{'}}\int\prod_{j=1}^{B} d\mathbf{r}_j\delta\left(\mathbf{R}_B\right)\Phi^*_{J_B M_B}\times$$

$$\times\Omega\Phi_{J_B^{'} M_B^{'}}\Phi^{J_B^{'} M_B^{'}}_{J_A M_A}\left(\mathbf{r}_n\right)\chi_{1/2\,\mu_P}, \qquad (16)$$

where the overlapping function for the core wave function and the wave function of the target nucleus, which has the meaning of the wave function of a captured neutron, is introduced:

$$\Phi^{J_B^{'} M_B^{'}}_{J_A M_A}\left(\mathbf{r}_n\right) = \int\prod_{j=1}^{B} d\mathbf{r}_j\delta\left(\mathbf{R}_B\right)\times$$

$$\times\Phi^*_{J_B^{'} M_B^{'}}(\mathbf{r}_1...\mathbf{r}_B)\Phi_{J_A M_A}(\mathbf{r}_1...\mathbf{r}_B,\mathbf{r}_n). \qquad (17)$$

The contribution of each final state of the residual nucleus into the basic state of the initial one is defined by the structure factor

$$S^{J_B^{'} M_B^{'}}_{J_A M_A} = \int d\mathbf{r}_n\left|\Phi^{J_B^{'} M_B^{'}}_{J_A M_A}\left(\mathbf{r}_n\right)\right|^2. \qquad (18)$$

Let us transform expression (16) by introducing the notation

$$F^{J_B M_B}_{J_B^{'} M_B^{'}}(\mathbf{r}_p,\mathbf{r}_n) = \int\prod_{j=1}^{B} d\mathbf{r}_j\delta\left(\mathbf{R}_B\right)\times$$

$$\times\Phi^*_{J_B M_B}\Omega(\mathbf{r}_p,\mathbf{r}_n;\mathbf{r}_1...\mathbf{r}_B)\Phi_{J_B^{'} M_B^{'}}. \qquad (19)$$

This function describes the distorting action of the core on the motion of the bombarding proton and departing deuteron. In the plane-wave approximation, it equals $\delta_{J_B J'_B}\delta_{M_B M'_B}$. Then we get

$$T_{f\,i} = \int \frac{d\mathbf{r}_p d\mathbf{r}_n}{(2\pi)^3} \exp\left(i\mathbf{Q}_p\mathbf{r}_p + i\mathbf{Q}_n\mathbf{r}_n\right)\left[V_{n\,p}\Phi_{J_d M_d}(\mathbf{r})\right]^{\dagger}\times$$

$$\times \sum_{J'_B M'_B} F^{J_B M_B}_{J'_B M'_B}(\mathbf{r}_p,\mathbf{r}_n)\,\Phi^{J'_B M'_B}_{J_A M_A}(\mathbf{r}_n)\,\chi_{1/2\,\mu_P} =$$

$$= \frac{1}{(2\pi)^6}\int d\mathbf{k} D^{*}_{J_d M_d}(\mathbf{Q}_p - \mathbf{k})\int d\mathbf{r}_p d\mathbf{r}_n \times$$

$$\times \exp\left[i\mathbf{Q}\mathbf{r}_n + i\mathbf{k}(\mathbf{r}_p - \mathbf{r}_n)\right]\times$$

$$\times \sum_{J'_B M'_B} F^{J_B M_B}_{J'_B M'_B}(\mathbf{r}_p,\mathbf{r}_n)\,\Phi^{J'_B M'_B}_{J_A M_A}(\mathbf{r}_n)\,\chi_{1/2\,\mu_P}, \qquad (20)$$

where $\mathbf{Q} = \mathbf{Q}_p + \mathbf{Q}_n = \frac{A-1}{A}\mathbf{k}_p - \mathbf{k}_d$ and

$$D_{J_d M_d}(\mathbf{k}) = \int d\mathbf{r}\exp\left(-i\mathbf{k}\cdot\mathbf{r}\right)V_{np}(\mathbf{r})\,\Phi_{J_d M_d}(\mathbf{r}) =$$

$$= -(2\pi)^{3/2}\left(\varepsilon_d + \frac{k^2}{M}\right)\Phi_{J_d M_d}(\mathbf{k}). \qquad (21)$$

Here, $\varepsilon_d = 2.224$ MeV is the binding energy of a deuteron and M is the nucleon mass. The Schrödinger equation is applied to get rid of the potential V_{np}. Using the expansion of a plane wave into the series of partial waves and separating the spin variables, the Fourier transform of the deuteron wave function can be written down as

$$\Phi_{1M_d}(\mathbf{k}) = (2\pi)^{-3/2}\int d\mathbf{r}\exp\left(-i\mathbf{k}\cdot\mathbf{r}\right)\Phi_{1M_d}(\mathbf{r}) =$$

$$= \sum_{\mu_d}\chi_{1\mu_d}\sum_{lm}(-i)^{l}\,C^{1M_d}_{lm\,1\mu_d}Y_{lm}\left(\hat{\mathbf{k}}\right)\varphi_l(k), \qquad (22)$$

$$\varphi_l(k) = \left(\frac{2}{\pi}\right)^{1/2}\int_0^{\infty} dr\, r^2 j_l(kr)\,\varphi_l(r). \qquad (23)$$

As a result, we obtain

$$D_{1M_d}(\mathbf{k}) = \sum_{\mu_d}\chi_{1\mu_d}\sum_{lm}C^{1M_d}_{lm\,1\mu_d}D_{lm}(\mathbf{k}),$$

$$D_{lm}(\mathbf{k}) = -(2\pi)^{3/2}\left(\varepsilon_d + \frac{k^2}{M}\right)(-i)^{l}\,Y_{lm}\left(\hat{\mathbf{k}}\right)\varphi_l(k). \qquad (24)$$

We will indicate below how the effects of antisymmetrization of the wave functions (5) are to be taken into account. As the distorting operator Ω does not depend on the operators of the isotopic spin of nucleons, the procedure of antisymmetrization between protons and neutrons can be avoided. It is more convenient to consider protons and neutrons as different particles and to carry out the antisymmetrization of the wave functions and the reaction amplitudes separately for the coordinates of protons and neutrons. The effect of such an antisymmetrization, provided that the exchange part of the reaction amplitude being small in the forward direction is neglected, is reduced to the multiplication of the amplitude obtained above (20) by a factor of $\sqrt{N}$, where N is the number of neutrons in the initial nucleus ($A = N + Z$), because each of them can be captured by a bombarding proton.

The differential cross-section of the reaction in the center-of-mass system (CMS), i.e. the angular distribution of deuterons that are formed, is equal to

$$\left(\frac{d\sigma}{d\Omega}\right)_{cm} = \frac{k_d}{k_p}\frac{1}{2J_A+1}\sum_{M_A}\frac{1}{2}\sum_{\mu_P}\sum_{M_d M_B}\left|F_{f\,i}\right|^2, \qquad (25)$$

where the reaction amplitude is connected to the element of the T-matrix on the momentum surface by the relation

$$F_{f\,i} = -(2\pi)^2\left(\mu_i\mu_f\right)^{1/2}T_{f\,i}. \qquad (26)$$

where μ_i and μ_f are the reduced relativistic masses in the channels.

3. ^{4}He(p,d)^{3}He Reaction

Let us apply the formalism developed above to the description of the ^{4}He(p,d)^{3}He reaction of a neutron pick-up by a proton. The internal nuclear wave functions are chosen antisymmetric with respect to the rearrangements of proton (1,2) and neutron (3,4) coordinates:

$$\Phi_\alpha = \varphi_\alpha(\mathbf{r}_1...\mathbf{r}_4)\chi_{00}(1,2)\chi_{00}(3,4), \quad \Phi_p = \chi_{\frac{1}{2}\mu_P},$$

$$\Phi_\tau = \varphi_\tau(\mathbf{r}_1...\mathbf{r}_3)\chi_{00}(1,2)\chi_{\frac{1}{2}\mu_\tau}(3),$$

$$\Phi_d = \sum_{l=0,2} \varphi_l(r) \sum_{m,\mu_d} C^{1M_d}_{lm\,1\mu_d} Y_{lm}(\hat{\mathbf{r}}) \chi_{1\mu_d}. \qquad (27)$$

The spin overlapping of those functions has the following form:

$$(\Phi_d\Phi_\tau, \Phi_\alpha\Phi_p) = \frac{1}{\sqrt{2}}(-1)^{1/2-\mu_\tau} \varphi^*_\tau \varphi_\alpha \sum_{lm} \varphi^*_l(r) Y^*_{lm}(\hat{\mathbf{r}}) \times$$

$$\times \sum_{\mu_d} C^{1M_d}_{lm\,1\mu_d} C^{1\mu_d}_{\frac{1}{2}\mu_p\,\frac{1}{2}-\mu_\tau}. \qquad (28)$$

Then, the element of T-matrix (14), taking into account the antisymmetrizing factor $\sqrt{2}$ (as there are two neutrons in a ^{4}He nucleus), can be written down as follows (the insignificant phase multiplier is omitted):

$$T_{fi} = \sum_{lm} T_{lm} \sum_{\mu_d} C^{1M_d}_{lm\,1\mu_d} C^{1\mu_d}_{\frac{1}{2}\mu_p\,\frac{1}{2}-\mu_\tau}. \qquad (29)$$

Here, the partial matrix element, corresponding to the transition into the deuteron state with quantum numbers l and m, is determined as

$$T_{lm} = \frac{1}{(2\pi)^3} \int d\mathbf{r}_p d\mathbf{r}_n \exp\left(i\mathbf{Q}_p\mathbf{r}_p + i\mathbf{Q}_n\mathbf{r}_n\right) D^*_{lm}(\mathbf{r}) \times$$

$$\times \int \prod_{j=1}^{B} d\mathbf{r}_j \delta(\mathbf{R}_\tau) \varphi^*_\tau \Omega \varphi_\alpha, \qquad (30)$$

$$D_{lm}(\mathbf{r}) = \left(-\varepsilon_d + \frac{\nabla^2}{M}\right) \varphi_l(r)\, Y_{lm}(\hat{\mathbf{r}}).$$

Expression (30) is the exact result of the theory. Nevertheless, its straightforward calculation is connected to large technical difficulties. A number of approximations, which simplify the calculation, are made below. We will take into account the circumstance that nuclei ^{4}He and ^{3}He do not have excited bound states, and the contribution of the ground state of the ^{3}He nucleus into the wave function of the ^{4}He one is close to unity, according to the estimations which have been carried out by using formula (18). Therefore, when summing up in (20) over the intermediate states $J'_B M'_B$ of the core of nucleus B, it is possible to confine the sum to only the ground state contribution. As a result, after calculating the spin matrix element in (20) and taking into account the factor $\sqrt{2}$, we obtain expression (29), where the partial T_{lm}-matrix is reduced to

$$T_{lm} = (2\pi)^{-6} \int d\mathbf{k}\, D^*_{lm}(\mathbf{Q}_p - \mathbf{k}) \int d\mathbf{r}_p d\mathbf{r}_n \times$$

$$\times \exp\left[i\mathbf{Q}\mathbf{r}_n + i\mathbf{k}(\mathbf{r}_p - \mathbf{r}_n)\right] F(\mathbf{r}_p, \mathbf{r}_n)\, \Phi(\mathbf{r}_n), \qquad (31)$$

where the function $F(\mathbf{r}_p, \mathbf{r}_n)$ is given by expression (19), where the averaging is carried out over the ground state of the residual ^{3}He nucleus. This function describes the distorting action of the ^{3}He nucleus, which is in its ground state before and after the reaction, on the motions of the bombarding proton and escaping deuteron.

At last, we will use the zero-radius approximation, which is verified by standard DWBA-calculations [3, 15] under the conditions of the experiment considered below. The experimental data, obtained in [2] for the ^{4}He(p,d)^{3}He reaction at a proton energy of 770 MeV and the angles of the deuteron escape from 3 to 45° in the CMS, correspond to the values of the transferred momenta Q_p and Q in the ranges of $2.2 - 3.5$ and $2 - 4$ Fm^{-1}, respectively. The contribution of the S-state of the deuteron wave function into the cross-section is very small in this region in comparison with that of the D-state. On the other hand, the function $D_{lm}(\mathbf{k})$ changes smoothly in this region in comparison with the Fourier transform of the neutron wave function $\Phi(\mathbf{r}_n)$. Therefore, the function $D_{lm}(\mathbf{Q}_p - \mathbf{k})$ in (31) can be factored outside the integral symbol at the point $\mathbf{k} = 0$. It is connected also to the following fact. In the plane-wave approximation, the second integral in (31) is proportional to $\delta(\mathbf{k})$, and, taking the distortion into account, its $\mathbf{k}$-dependences will be characterized by a sharp maximum at $\mathbf{k} \sim 0$. It is easy to understand, if one takes into account that the introduction of the distorting factor $F(\mathbf{r}_p, \mathbf{r}_n)$ results in the appearance of the smooth dependence on $\mathbf{r}_p$ (the eikonal phase) at the distances of about the wavelength of a moving particle. At the same time, the Fourier component of the function, which varies smoothly, will be maximal at small values of the momentum $\mathbf{k}$. The adopted approximation considerably simplifies calculations. As a result, we obtain

$$T_{lm} = (2\pi)^{-3} D^*_{lm}(\mathbf{Q}_p) \int d\mathbf{r} \exp\left(i\mathbf{Q}\cdot\mathbf{r}\right) F(\mathbf{r})\, \Phi(\mathbf{r}). \qquad (32)$$

Carrying out the averaging over the initial magnetic quantum numbers in (25) and the summation over the final ones, we obtain

$$\left(\frac{d\sigma}{d\Omega}\right)_{cm} = (2\pi)^4 \mu_i \mu_f \frac{k_d}{k_p} \cdot \frac{3}{2} \sum_l \frac{1}{2l+1} \sum_m |T_{lm}|^2. \qquad (33)$$

On summing up in (33) over m with the help of the relation

$$D_l^2(Q_p) \equiv \frac{1}{2l+1}\sum_m |D_{lm}(\mathbf{Q}_p)|^2 =$$

$$= 2\pi^2\left(\varepsilon_d + \frac{Q_p^2}{M}\right)^2 \varphi_l^2(Q_p), \quad (34)$$

the ultimate form for the differential cross-section of the reaction is

$$\left(\frac{d\sigma}{d\Omega}\right)_{cm} = \frac{3}{4}\mu_i\mu_f\frac{k_d}{k_p}|I(\mathbf{Q})|^2\left(\varepsilon_d + \frac{Q_p^2}{M}\right)^2 \sum_{l=0,2}\varphi_l^2(Q_p). \quad (35)$$

In this expression,

$$I(\mathbf{Q}) = \int d\mathbf{r}\,\exp(i\mathbf{Q}\cdot\mathbf{r})\,F(\mathbf{r})\,\Phi(\mathbf{r}), \quad (36)$$

$$F(\mathbf{r}) = \int d\mathbf{r}_1 d\mathbf{r}_2 d\mathbf{r}_3 \delta(\mathbf{R}_\tau)\,|\varphi_\tau(\mathbf{r}_1\mathbf{r}_2\mathbf{r}_3)|^2\times$$

$$\times\prod_{j=1}^{3}\left[1-\omega^{(+)}(\mathbf{r}-\mathbf{r}_j)\right]\left[1-\omega^{(-)}(\mathbf{r}-\mathbf{r}_j)\right]^2,$$

$$\Phi(\mathbf{r}) = \int\prod_{j=1}^{4} d\mathbf{r}_j\,\delta(\mathbf{R}_\tau)\,\delta(\mathbf{r}-\mathbf{r}_4+\mathbf{R}_\tau)\times$$

$$\times\varphi_\tau^*(\mathbf{r}_1\mathbf{r}_2\mathbf{r}_3)\,\varphi_\alpha(\mathbf{r}_1\mathbf{r}_2\mathbf{r}_3\mathbf{r}_4). \quad (37)$$

The nucleon-nucleon profile functions $\omega^{(+)}$ and $\omega^{(-)}$ correspond to the energies of the entrance (770 MeV) and exit (496 MeV) channels, respectively. In the calculations, we used the parameters of the NN-amplitudes averaged over the protons and neutrons. This does not affect the results substantially, but strongly simplifies calculations.

4. Numerical Calculations of the Angular Distribution of Deuterons in the ^{4}He(p,d)^{3}He Reaction

Specific calculations of the angular distributions of formed deuterons were carried out for an energy of bombarding protons of 770 MeV. The spatial parts of the internal wave functions of the ground states of nuclei ^{4}He and ^{3}He were taken as the superpositions of the Gaussians:

$$\varphi_\alpha = N_\alpha\left\{\exp\left[-\frac{\alpha_1}{2}\sum_{j=1}^{4}(\mathbf{r}_j-\mathbf{R}_\alpha)^2\right] -\right.$$

$$\left.-D_\alpha\exp\left[-\frac{\alpha_2}{2}\sum_{j=1}^{4}(\mathbf{r}_j-\mathbf{R}_\alpha)^2\right]\right\}$$

$$\varphi_\tau = N_\tau\left\{\exp\left[-\frac{\beta_1}{2}\sum_{j=1}^{3}(\mathbf{r}_j-\mathbf{R}_\tau)^2\right] -\right.$$

$$\left.-D_\tau\exp\left[-\frac{\beta_2}{2}\sum_{j=1}^{3}(\mathbf{r}_j-\mathbf{R}_\tau)^2\right]\right\}. \quad (38)$$

where N_α and N_τ are the normalizing factors. The radial wave functions $\varphi_l(r)$ for a deuteron were taken in the form

$$\varphi_0(r) = N_S\exp\left(-\frac{\gamma}{2}r^2\right), \quad N_S^2 = 4\pi\left(\frac{\gamma}{\pi}\right)^{3/2}P_S,$$

$$\varphi_2(r) = N_D\,r^2\exp\left(-\frac{\delta}{2}r^2\right),\ N_D^2 = \frac{16\pi}{15}\delta^2\left(\frac{\delta}{\pi}\right)^{3/2}P_D, \quad (39)$$

where P_S and P_D are the weight factors of the S- and D-waves, respectively, in the ground state of a deuteron. In accordance with (23),

$$\varphi_0(k) = \frac{N_S}{\gamma^{3/2}}\exp\left(-\frac{k^2}{2\gamma}\right),$$

$$\varphi_2(k) = N_D\frac{k^2}{\delta^{7/2}}\exp\left(-\frac{k^2}{2\delta}\right). \quad (40)$$

The parameters of the phenomenological functions (38) and (39) were found in [16], provided that they can serve as a basis for the description of charge formfactors of nuclei in a wide range of the transferred momenta :

$\alpha_1 = 0.85$ Fm^{-2}, $\alpha_2 = 0.93$ Fm^{-2}, $D_\alpha = 1.1$,

$$\beta_1 = 0.70\ \mathrm{Fm}^{-2}, \quad \beta_2 = 2.24\ \mathrm{Fm}^{-2}, \quad D_\tau = 1.9,$$

$$\gamma_1 = 0.19\ \mathrm{Fm}^{-2}, \quad \delta_2 = 1.49\ \mathrm{Fm}^{-2}, \quad P_D = 0.07. \qquad (41)$$

The parameters of the NN-amplitudes, averaged over the protons and neutrons of the nuclei, for the energies of the entrance and exit channels were taken from [13] (see the table). The same parameters were used in [11], when interpreting the same ^{4}He(p,d)^{3}He reaction with the help of the method of eigenstates. Those two absolutely different approaches happened to give equally good descriptions of the experimental data without using any additional fitting parameters for this purpose.

The wave functions, which are given by a realistic Hamada-Johnston NN-potential [17] possessing a rigid repulsive core, were also used for the deuteron in calculations. The approximations of the S- and D-wave parts of those functions as superpositions of exponents are presented in [18]. For the general reasons, it is clear that the rigid core in the NN-potential should result in the most correct values of the large-momentum components in the momentum spectrum of the deuteron ground state, which is very important for the reaction under consideration.

It is convenient to calculate the radial wave function of the captured neutron $\Phi(\mathbf{r})$ (37) in model (38) by introducing, instead of the coordinates $\mathbf{r}_1 \ldots \mathbf{r}_4$, the Jacobi coordinates

$$\mathbf{x}_1 = \mathbf{r}_2 - \mathbf{r}_1, \quad \mathbf{x}_2 = \mathbf{r}_3 - \frac{1}{2}(\mathbf{r}_1 + \mathbf{r}_2)$$

$$\mathbf{x}_3 = \mathbf{r}_4 - \frac{1}{3}(\mathbf{r}_1 + \mathbf{r}_2 + \mathbf{r}_3), \quad R_\tau = \frac{1}{3}(\mathbf{r}_1 + \mathbf{r}_2 + \mathbf{r}_3).$$

Using them, it is easy to obtain that

$$\Phi(r) = \left(2\sqrt{3}\pi\right)^3 N_\tau N_\alpha \Big\{ \Big[(\alpha_1 + \beta_1)^{-3} - D_\tau(\alpha_1 + \beta_2)^{-3}\Big] \exp\left(-\frac{3}{8}\alpha_1 r^2\right) - D_\alpha\Big[(\alpha_2 + \beta_1)^{-3} - D_\tau(\alpha_2 + \beta_2)^{-3}\Big] \exp\left(-\frac{3}{8}\alpha_2 r^2\right)\Big\}. \qquad (42)$$

Parameters of the ^{4}He(p,d)^{3}He reaction channels

Channel	σ, mb	ρ	a, Fm^2
Entrance, 770 MeV	44	−0.2	0.071
Exit, 496 MeV	34	0.4	0.036

The structure factor (18) which corresponds to this function and to parameters (41) is close to unity, as was emphasized above: $S_\alpha^\tau = 0.934$.

As seen from the form of the distorting function $F(\mathbf{r})$ (37), it takes into account all the possible virtual excitations of a ^{3}He nucleus in the course of the reaction. Since, as was already mentioned above, a ^{3}He nucleus has no excited bound states which can make an appreciable contribution to the reaction cross-section, it is natural not to take their contribution into account. In addition, it is seen from expression (12) for Ω that if, for example, the neutron of the escaping deuteron excites the ^{3}He nucleus, the proton has to de-excite it for ^{3}He to be obtained ultimately in the ground state. It is obvious that such processes will promote the destruction of the deuteron; the higher the excitation of the nucleus due to the large momentum transfers to different particles, the more the probability of the destruction. Therefore, the main contribution to the elastic rescattering of deuterons will be made by the ground state of ^{3}He. All the aforesaid allows us to simplify the expression for the distorting function and to write it in the form

$$F(\mathbf{r}) = [1 - f(\mathbf{r})]^3, \quad f(\mathbf{r}) = \int d\mathbf{r}_1 \rho_\tau(\mathbf{r}_1) \times \left\{1 - [1 - \omega^{(+)}(\mathbf{r} - \mathbf{r}_1)][1 - \omega^{(-)}(\mathbf{r} - \mathbf{r}_1)]^2\right\}, \qquad (43)$$

where

$$\rho_\tau(\mathbf{r}) = \int d\mathbf{r}_1 d\mathbf{r}_2 d\mathbf{r}_3 \delta(\mathbf{R}_\tau) \frac{1}{3}\sum_{j=1}^{3} \delta(\mathbf{r} - \mathbf{r}_j) |\varphi(\mathbf{r}_1 \mathbf{r}_2 \mathbf{r}_3)|^2 \qquad (44)$$

is the single-particle mass density of the ^{3}He nucleus.

For the selected model (38),

$$\rho_\tau(r) \equiv \sum_{i=1}^{3} A_i \exp(-B_i r^2) = \left(\frac{9\pi}{2\beta_1}\right)^{3/2} N_\tau^2 \Big\{\exp\left(-\frac{3}{2}\beta_1 r^2\right) - 2D_\tau \left(\frac{2\beta_1}{\beta_1 + \beta_2}\right) \times \exp\left[-\frac{3}{4}(\beta_1 + \beta_2) r^2\right] + D_\tau^2 \left(\frac{\beta_1}{\beta_2}\right)^{3/2} \exp\left(-\frac{3}{2}\beta_2 r^2\right)\Big\}. \qquad (45)$$

Let us calculate now the value of $f(\mathbf{r})$ (43). Using the explicit expressions for the profile functions (9), we can write

$$f(\mathbf{r}) = \int d^2\mathbf{b}_1 dz_1 \sum_{i=1}^{3} A_i \exp\left[-B_i\left(b_1^2 + z_1^2\right)\right] \times$$

$$\times \sum_{j=1}^{5} C_j \exp\left[-D_j\left(\mathbf{b} - \mathbf{b}_1\right)^2\right] f_j(z - z_1) \qquad (46)$$

where the parameters A_i and B_i are those from Eq. (45), while the coefficients C_j, D_j and the functions f_j are as follows:

$$C_1 = \frac{1}{2}\omega_{0\,i}, \quad C_2 = \omega_{0f}, \quad C_3 = -\frac{1}{4}C_2^2,$$

$$C_4 = -C_1 C_2, \quad C_5 = -C_1 C_3,$$

$$D_1 = \frac{1}{4a_i}, \quad D_2 = \frac{1}{4a_f}, \quad D_3 = 2D_2,$$

$$D_4 = D_1 + D_2, \quad D_5 = D_1 + 2D_2,$$

$$f_1 = 1 + \operatorname{erf}\left(\frac{z - z_1}{2\sqrt{a_i}}\right), \quad f_2 = 1 - \operatorname{erf}\left(\frac{z - z_1}{2\sqrt{a_f}}\right),$$

$$f_3 = f_2^2, \quad f_4 = f_1 f_2, \quad f_5 = f_1 f_3.$$

Subscripts i and f of the quantities ω_0 and a serve to indicate the energy, at which those quantities are taken (i for the initial energy and f for the final one). Integrating in (46) over the transverse coordinate $\mathbf{b}_1$, we write down ultimately that

$$f(b, z) = \sum_{i=1}^{3}\sum_{j=1}^{5} A_i C_j \frac{\pi}{B_i + D_j} \times$$

$$\times \exp\left(-\frac{B_i D_j}{B_i + D_j} b^2\right) Z_{ij}(z), \qquad (47)$$

where the definition

$$Z_{ij}(z) = \int_{-\infty}^{\infty} dz_1 \exp\left(-B_i z_1^2\right) f_j(z - z_1) \qquad (48)$$

is introduced.

The quantity $I(\mathbf{Q})$, defined by integral (36), is estimated numerically in the cylindrical system of coordinates as

$$I(\mathbf{Q}) = 2\pi \int_0^{\infty} db\, bJ_0(Q_\perp b) \times$$

$$\times \int_{-\infty}^{\infty} \exp(iQ_z \cdot z) F(b, z) \Phi(b, z) \equiv \sum_{\lambda=1}^{4} I_\lambda(\mathbf{Q}), \qquad (49)$$

where the four terms in the last part of the equality correspond to the four terms in the expansion of the quantity $F = 1 - 3f + 3f^2 - f^3$ in (44) into the series in the multiplicity factor of scattering. The term with $\lambda = 1$ in cross-section (35) is related to the plane-wave Born approximation (PWBA). In the language of Feynman diagrams, it corresponds to the pole one. In the pole approximation, the cross-section is proportional to the square of the Fourier transform of the neutron wave function $\Phi(Q)$

$$\left(\frac{d\sigma}{d\Omega}\right)_{cm}^{PWBA} = 3\pi\mu_i\mu_f \frac{k_d}{k_p} \sum_{l=0,2} D_l^2(Q_p)\, \Phi^2(Q), \qquad (49a)$$

and, as will be seen below, is generally determined by the behavior of this function.

Fig. 1,*a* shows the Fourier transform of the wave function of a picked up neutron (43) $\Phi(Q)$ with parameters (41) (the solid curve) and with parameters found from the analysis of the elastic scattering of 1-GeV protons by nuclei ^{3,4}He (the dashed curve). In the latter case, for ^{4}He, these parameters coincide with (41) and, for ^{3}He,

$$\beta_1 = 0.45\ \text{Fm}^{-2}, \quad \beta_2 = 3.69\ \text{Fm}^{-2}, \quad D_\tau = 2.7. \qquad (50)$$

The small difference of the neutron functions for these collections of parameters and their rather sharp change (almost by three orders of magnitude) in the experimental region $Q = 2-4$ Fm^{-1} located to the right of the minimum in Fig. 1,*a* call attention to themselves.

The importance of the deuteron D-state is seen from the comparison of the functions $D_0(Q_p)$ and $D_2(Q_p)$ (34) represented in Fig. 1,*b* for the potential from [17] and in Fig. 1,*c* for model (39) with parameters (41). As seen from these figures, the contribution of the D-state exceeds that of the S-state in the region $Q_p = 2.2 - 3.5$ Fm^{-1}, which corresponds to the experiment. It differs sharply from the situation at low energies, where $Q_p < 1$ Fm^{-1}, and the contribution of the D-state is

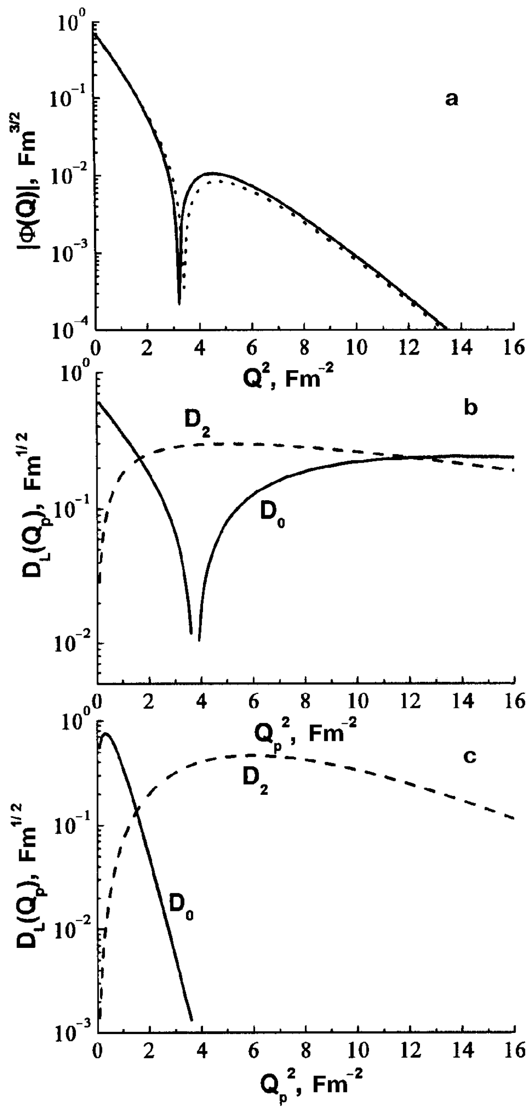

Fig. 1. (*a*) Fourier transform of the neutron wave function $\Phi(Q)$ (42), (*b*) the dependence $D_l(Q_p)$ (34) for the Hamada-Johnston potential [17], (*c*) the same as in (*b*) but for the Gaussian model of a deuteron (39)

small. The prevalence of the D-state points to the necessity of using the exact wave function of a deuteron.

The smoothness of a variation of the function $D_l(Q_p)$ in the indicated interval, in comparison with the change of a neutron wave function, serves a convincing confirmation of the zero-radius approximation made above and means that the reaction cross-section is defined mainly by the behavior of the neutron wave function.

In this connection, the experiment at an energy of 500—600 MeV, when the region, where $\Phi(Q)$ is zero would fall into the kinematically allowable region, would be rather interesting. In this case, the angular distribution of deuterons would have an essentially anomalous behavior in comparison with that at lower or higher energies and would make possible the more exact determination of the zero of the neutron function. This position, in turn, is closely connected to the corresponding zero of the formfactor of the initial nucleus and, to a lesser extent, with that of a residual one.

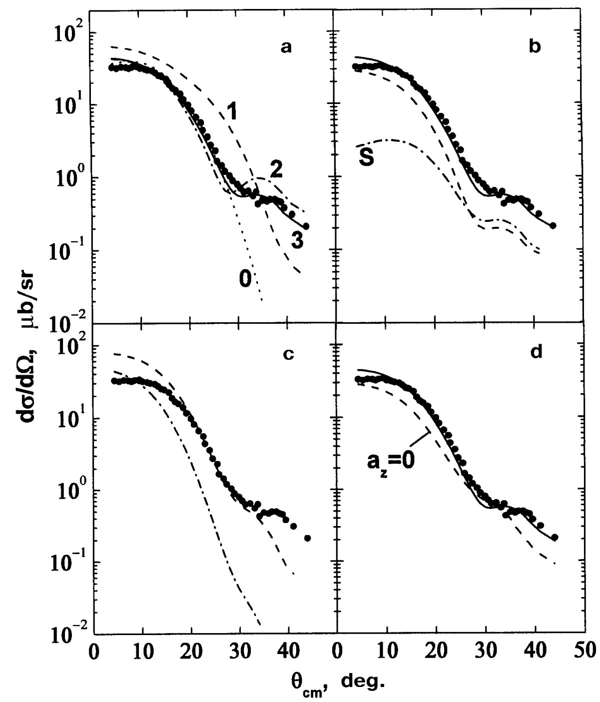

Fig. 2. Comparison of the calculated and experimental cross-sections of the reaction. See the explanations in the text

In Fig. 2, the calculated angular distributions of deuterons in the ^{4}He(p,d)^{3}He reaction at an energy of protons of 770 MeV are shown together with the experimental data [2]. Fig. 2,*a* displays the contributions of various terms of expansion (49a) in the increasing multiplicity of the rescattering of a bombarding proton and the nucleons of an escaping deuteron by the residual nucleus to the cross-section. The microscopic function of a deuteron [18] and the model functions (38) of a helium nucleus with parameters (41) were used. The dotted curve *0* corresponds to the PWBA (49a) [$\lambda = 1$ in (49)]. It is seen that only a pole mechanism of the reaction cannot explain a value of the cross-section in the region $\theta > 30°$ and results in a strongly underestimated value of the cross-section there. The dashed curve *1* takes into account the single scattering ($\lambda = 1$ and 2), the dash-dotted curve *2* corresponds to the single and double scatterings ($\lambda = 1, 2$ and 3), and the solid curve *3* takes into account all the three multiplicities of the rescattering. Only the complete account of all the distorting rescatterings allows us to describe the experiment quantitatively correctly. The interference of the terms of different multiplicities of scattering results in a considerable diffraction structure in the angular distribution. Contrary to the elastic scattering in the region of small angles, the important role of the terms of the multiple scattering is seen, which is connected to large momenta transferred even at the zero angle of the escape of a deuteron.

In Fig. 2,*b*, we present the dependences of the cross-section on the parameters of the ^{3}He wave function. The parameters correspond to those for the two neutron functions in Fig. 1,*a*. The solid curve is the same as in Fig. 2,*a*, and the neutron function represented in Fig. 1,*a* by the solid line corresponds to this cross-section. Letter S marks the contribution of the S-state of a deuteron to this cross-section. The dashed curve is obtained for parameters (50), which describe well the formfactor of ^{3}He up to the region of the second maximum and the cross-section of the elastic scattering of protons. But, due to a lack of high-momentum components, the value of the reaction cross-section becomes underestimated. As shown in [19], the contribution of high-momentum components is not so important for the elastic scattering even at the backscattering, contrary to the reaction under study.

Fig. 2,*c* illustrates the sensitivity of the reaction cross-section to the parameters of the model wave function of a deuteron (39). The dashed curve corresponds to values (41) for the parameters γ, δ, and P_D; the dash-dotted curve does to $\gamma = 0.17$ Fm^{-2}, $\delta = 0.79$ Fm^{-2}, and $P_D = 0.07$. Parameters (41) were used for a helium nucleus. At those values of the parameters, the deuteron formfactor still agrees well with the experiment, whereas the reaction cross-section appears rather sensitive to the presence of the high-momentum components in the wave function of a deuteron and, owing to their lack in the given collection, is underestimated.

From Fig. 2,*d*, we see the importance for the dependence of the amplitude of the elastic NN-scattering on the longitudinal component of the transferred momentum q_z to be taken into account for the quantitative description of experiments. The dashed curve represents the results of calculations of the cross-section with the use of the profile functions of the standard diffraction theory: $\omega^{(\pm)}(\mathbf{r}) = \omega(\mathbf{b})\theta^{(\pm)}(z)$, for which $a = 0$ in the square brackets in the general expression (9). The solid curve is the same as in Fig. 2,*a*.

Thus, we can draw conclusion that the mechanism of multiple scattering is defining in the ensuring of large momenta transferred, and the correct contents of the high-momentum components in the wave functions are necessary for the quantitative description of the reaction cross-section. The developed formalism and the analysis carried out show that the research of the single-nucleon pick-up reactions in the range of intermediate energies can serve as quite a sensitive means for the determination of details of the structure of nuclei, their wave functions in the region of zeros of the formfactors, and the momentum distribution of nucleons in nuclei. As shown above, the observed behavior of the angular dependences of the reaction cross-sections can be explained, in the main features, not only by meson-exchange currents or intermediate isobars, but also by the effects of multiple rescattering of nucleons in the initial and final states.

1. *Whitten C.A.* // Nucl. Phys. A.— 1980.— **335**, N 1—2.— P. 419—442.
2. *Bauer T., Boudard A., Catss H. et al.* // Phys. Lett. B.— 1977.— **67**, N 3.— P. 265—267.
3. *Rost E., Shepard J.R., Sparrow D.A.* // Phys. Rev. C.— 1978.— **11**, N 4.— P. 1513—1515.
4. *Kallne J., Hutcheon D.A., McDonald W.J. et al.* // Phys. Rev. Lett.— 1978.— **41**, N 24.— P. 1638—1641.
5. *Kallne J., Gugelot T.O.* // Phys. Rev. C.— 1979.— **20**, N 3.— P. 1085—1091.
6. *Wilkin C.* // J. Phys. G: Nucl.Phys.— 1980.— **6**, N 1.— P. 69—80.
7. *Akhiezer A.I., Sitenko A.G.* // Zh. Eksp. Teor. Fiz.— 1957.— **33**, N 4.— P. 1040—1042.
8. *Sitenko A.G.* // Uspekhi Fiz. Nauk.— 1959.— **67**, N 3.— P. 377—444.
9. *Sitenko A.G.* // Ukr. Fiz. Zh.— 1959.— **4**, N 2.— P. 152—163.
10. *Sitenko A.G., Goryachii V.V., Peresypkin V.V.* Inelastic Diffraction Nuclear Processes with Particle Redistribution.– Kyiv, 1979.— (Prepr. Inst. Teor. Fiz. AN UkSSR, ITF-79-110R) (in Russian).
11. *Levshin E.B., Sailer K.G., Foursat A.D.* // Yad. Fiz.— 1982.— **36**, N 5.— P. 1150—1162.
12. *Akhiezer A.I., Sitenko A.G.* // Phys.Rev.— 1957.— **106**, N 6.— P. 1236—1246.
13. *Tekou A.* // Nuovo cim.— 1979.— **A54**, N 1.— P. 25—44.
14. *Levshin E.B., Foursat A.D.* // Yad. Fiz.— 1983.— **38**, N 12.— P. 1572—1581.

15. *Rost E., Shepard J.H.* // Phys. Lett. B.— 1975.— **59**, N 5.— P. 413—415.

16. *Levshin E.B., Foursat A.D.* // Izv. AN SSSR. Ser. Fiz.— 1981.— **45**, N 1.— P. 48—55.

17. *Hamada T., Johnston I.D.* // Nucl. Phys.— 1962.— **34**, N 2.— P. 382—403.

18. *Humberston J.W., Wallace J.B.G.* // Nucl. Phys. A.— 1970.— **141**, N 2.— P. 362—368.

19. *Tekou A.* // J. Phys. G: Nucl. Phys.— 1981.— **7**, N 11.— P. 1439—1454.

Received 09.04.04.
Translated from Ukrainian by O.I.Voitenko

БАГАТОЦЕНТРОВЕ ЕЙКОНАЛЬНЕ НАБЛИЖЕННЯ У РЕАКЦІЯХ З ПЕРЕБУДОВОЮ

В.В. Давидовський, А.Д. Фурса

Р е з ю м е

В рамках методу спотворених хвиль з використанням хвильових функцій відносного руху частинок в ейкональному наближенні одержано формули для опису реакцій однонуклонного передавання з урахуванням багатонуклонної структури ядер. Розрахунки кутового розподілу дейтронів в реакції ^{4}He(p,d)^{3}He при E_p= 770 МеВ вказують на певну роль ефектів багаторазового перерозсіяння і велику чутливість спостережуваних характеристик до деталей структури ядер.