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Knocking Out Nucleon Associations From the Nucleus With Light Nuclei

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Abstract. The cluster model applied to study associative knocking out light nuclei in the A(X, XY)A-Y processes. Contemporary quantum - mechanical description of cluster characteristics of atomic nuclei are discussed. Within this model, interaction of the associations is described by local potential. The internal structure of the associations is neglect and effects of the Pauli principle between the nucleons in the associations are taken into account by introducing short range repulsion between the associations. It is assumed that the amplitude of the interaction of nucleons of the incident nucleus with the nucleons of the target nucleus are the same as in the case of a collision free nucleons. Since the formation of associations, most likely on the surface area of the nuclei, then to study them in the first place it is necessary to carry out studies of nuclear processes, extending to the surface of the nucleus. These are direct nuclear reactions. The association effect is significant when the scattering particles with light nuclei has intermediate energy and it appears the stronger the higher the energy of the incident particle. When the energy of the incident particle is large compared nucleon energy in the nucleus, the transit time of a particle in the nucleus will be small in comparison with the characteristic time for the exchange of nucleons associations. Therefore such a particle sees, that these core consisting of associations, as during its interaction with the nucleus, the associations did not have time to exchange by nucleons. Study was carried out in the impulse approximation with plane waves and based on Gaussian potential. Analysis of cross section held at the microscopic level. The considered energy region lies below the threshold meson production. The results are given in the work related to the analysis of the effective cross section. However, it is not difficult to extend the considered model to calculate the angular dependence of the characteristics of the reactions that are associated with the off-diagonal elements of the density matrix, such as the polarization of the final particles.

Keywords: Nucleon association, scattering, impulse approximation, Gaussian potential, 25.40-Ep

1. INTRODUCTION

The nuclear structure, as we know now, is a roughly homogeneous distribution of neutrons and protons. However, the association phenomena is important to determine the structure of light nuclei. If we are taking into account the interaction between nucleons (as it is in reality) in the model approach, we can expect the formation of associations. Calculations show that the associations occur on the surface of the nucleus, where the density of nuclear matter less than in the center of the nucleus. Association is a natural energy minimization mechanism. Although for light nuclei at an excitation energy close to the particle separation value there are experimental evidences of such structure effects, this is still not the case for heavier nuclear systems [1].

Since the formation of associations, most likely on the surface area of the nuclei, then to study them in the first place it is necessary to carry out studies of nuclear processes, extending to the surface of the nucleus. These are direct nuclear reactions. The association effect is significant when the scattering particles with light nuclei has intermediate-energy and it appears the stronger the higher the energy of the incident particle. When the energy of the incident particle is large compared nucleon energy in the nucleus, the transit time of a particle in the nucleus will be small in comparison with the characteristic time for the exchange of nucleons associations. Therefore such a particle sees, that these core consisting of associations, as during its interaction with the nucleus, the associations did not have time to exchange by nucleons.

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The orthogonality condition model and excluded state model treat the clusters as elementary particles, but include effects of the Pauli principle in a more microscopic way. Wheeler's resonating group method is a fully microscopic theory for calculating properties of cluster systems. It makes simplifying assumptions about the internal structure of the clusters but takes the Pauli principle explicitly [2].

As mentioned in [3], cluster decay is well known to be a process intermediate between alpha particle decay and spontaneous fission. The cluster model neglect the internal structure of the associations and effects of the Pauli principle between the nucleons in the clusters are taken into account by introducing short range repulsion between the clusters. The relative motion of the clusters could be described by means of a local attractive potential between the constituents nuclei. In light nuclei potential gives a rather Gaussian-like smooth shape to the potential and we left the depth as a free parameter to be fitted to the cluster-core binding energy of some selected state of a bound.

In this paper, we obtain an expression for the cross section of the ejection nucleon associations based on Gaussian potential. We considered energy region lies below the threshold meson production, the impulse approximation is used. It is assumed that the amplitude of the interaction of nucleons of the incident nucleus with the nucleons of the target nucleus are the same as in the case of a collision free nucleons. The considered energy region lies below the threshold meson production.

2. SCATTERING CROSS SECTION OF THE PROCESSES WITH EJECTION NUCLEON ASSOCIATIONS

Let the number of nucleons in the nucleus A is N_A and in the nucleus X is N_X. Wave function for X+A nucleons divided into 2 clusters is as follows A-Y and XY. The wave function of the nucleons (1, ..., m) in first cluster is $\Psi_{A-Y} \equiv \Psi_{A-Y}(r_1 ... r_m)$ and the wave function of the nucleons

(m+1, ..., N_A+N_X) in second cluster is:

$$\Psi_{XY} \equiv \Psi_{XY}(r_{m+1} ... r_{N_A+N_X})$$

Wave function of the initial (A+X) state we choose as

$$\Psi_i = e^{ik_X r_X} \varphi(J_X M_{J_X} \xi_X) \Psi_A(J_i M_{J_i} \xi_A), \quad (1)$$

where $e^{ik_X r_X}$ is wave function of the incident proton, ξ- a set of other quantum numbers, $\varphi(J_X M_{J_X} \xi_X)$ - internal wave function of the nucleus X.

For the final (XY+A-Y) state wave function, we have

$$\Psi_f = \Psi_{XY}(J_{XY} M_{J_{XY}} \xi_{XY}) \Psi_{A-Y}(J_{A-Y} M_{J_{A-Y}} \xi_{XY}) \chi(R_{XY} - R_{A-Y}). \quad (2)$$

Here vectors $\mathbf{R}_1$ and $\mathbf{R}_2$ are the centers of mass of the nucleons in the first and second clusters.

In the plane wave approximation the matrix element of the reaction has the form

$$F_{if} = \left(\Psi_f, T_{XY}\Psi_i\right), \tag{3}$$

$$\hat{T}_{XY} = V_{XY} + V_{XY}\frac{1}{E_i - E_{kin.} + U + i\eta}\hat{T}_{XY}, \tag{4}$$

where V_{XY} the potential interaction of the X nucleus with all nucleons association Y; U potential, determines the interaction with other nucleons X nucleons; $E_i = p_X^2 / 2m_X - \varepsilon_{XY} - \varepsilon_{(A-Y)}$ (ε_{XY} and $\varepsilon_{(A-Y)}$ binding energy associations (XY) and (A-Y) respectively in the initial nucleus A); $E_{kin.}$ the total kinetic energy of the fly out of the association.

Instead of exact matrices T we will use local operators -potential of interaction. The operator $\hat{T}$ is introduced by the relation

$$\hat{T}_{XY}\Psi_i = V_{XY}\Psi_i. \tag{5}$$

Choose the potential V_{pX} as the Gaussian potential form:

$$V(r) = -V_0 e^{-r_0^2/r^2}, \tag{6}$$

where r_0 is length of Compton wave of the nucleon.

It is more convenient to use for the considered potential the analytical expression of the type [4]

$$U = -V_0\frac{1 + ch(R/a)}{ch(r/a) + ch(R/a)}, \tag{7}$$

where V_0 the depth of the potential, R and a is radius and diffusivity.

We can deternmine the matrix (4) in impuls approximation, and

$$F_{if} = (2\pi\hbar)^{1/2} F^0 R_{LM_L}(q)\left\langle A-Y, J_f M_{J_F} T_{T_f;} XJ_X M_X T_X \left| e^{iq(r_{A-Y} - r_X)}; AJ_i M_i T_i \right\rangle\right. . \tag{8}$$

Here F^0 is the amplitude of the scattering of free X nuclei and association XY in the center of mass of particles

$$F^0 = \left(e^{iQr}\Psi_X\Psi_{XY}T_{XY}e^{iQ'r'}\varphi'_X\varphi'_{XY}\right), \tag{9}$$

where Q and Q' are wave vectors of mass center and $R_{LM_L}(q)$-radial function of mass center of associations.

The main feature of the integrals appearing in expressions (9) is that the interaction potentials and wave function of the relative movement and distorted waves also depend on the relative different combinations of variables. Furthermore, they are presented in nucleon variables. The problem of separation of variables is very important because of its solution depends on the possibility of analytical calculation of integrals over the angular variables, as well as for those variables that are not associated with the interaction of particles.

The cross section of the reaction $A(X,XY)A\text{-}Y$ in the impulse approximation is of the form:

$$\frac{d\sigma}{d\Omega} = 16\pi m_i m_f \mid F^0 \mid^2 R_{LM_L}(q)^2\ \delta\left(k_0 - k_X - p_{XY} - p_q\right)\delta(E_i - E_f)\sum_{J_f J_i}\theta_{J_i}^{A,X}\theta_{J_f}^{XY,A-Y} \tag{10}$$
$$x\ \left\langle A-Y, J_f M_f \xi_f\, XJ_x M_x \xi_X \left| e^{iq(r_{A-Y}-r_X)}; AJ_i M_i \xi_i \right\rangle^2\right.$$

where $m_i = \frac{M_A m_X}{M_A + m_X}, m_f = \frac{M_{A-Y} m_{XY}}{M_{A-Y} + m_{XY}}$, $\theta_{J_i}^{A,X}$ and $\theta_{J_f}^{XY,A-Y}$ is reduced width of the corresponding channel in units of Wigener limit.

Equation (10) for the cross section of the associative knocking out nucleons obtained in the impulse approximation and scattering matrix is independent of recoil momentum q [5] . If we assume that the scattering cross section depends on q, then (10) is not correct. Included in it F^0 must be renormalized, considering dependence the cross section on q.

Structural factors $\theta_{J_i}^{A,X}$ and $\theta_{J_f}^{XY,A-Y}$ are multidimensional matrices, so that the calculation of the amounts in (10), is a rather complex mathematical problem. First of all, in the formula (10) can reduce the number of summations by assuming that the formfactors independent on excitation energy. This decreased the number of coherent sums in (10) into two. To simplify the general expression (10) does not itself important type of reaction, and restrictions on the values of the corresponding points, then according to the simplified formula can calculate the cross-section of any multi-nucleon transfer reactions in which moments have a single value.

The main feature of the integrals appearing in the expressions (8) and (10), is that they are presented in nucleon variables. Correlations, in particular cluster formation, has to be considered in low-density nuclear systems. Any single-nucleon quasiparticle approach fails in that region. A possible approach is the introduction of associations as effective degrees of freedom in the model description. The full antisymmetrization (Pauli blocking) is indispensable at increasing densities.

In Figures 1 and 2 shows a comparison of the experimental and calculated values of the reaction cross sections $^{13}C(d,\alpha)^{11}B$ and $^{13}C(^3He,\alpha)^{12}C$, respectively. As follows from the figures, the mechanism of the pick-up of the association to form the final nucleus, is dominant on the front of the hemisphere of corner θ. The consent of the absolute values of the calculated and experimental cross sections achieved

without the introduction of additional normalization factors. In the work [6] by DWBAFR method these reactions have been studied and satisfactory results were obtained.

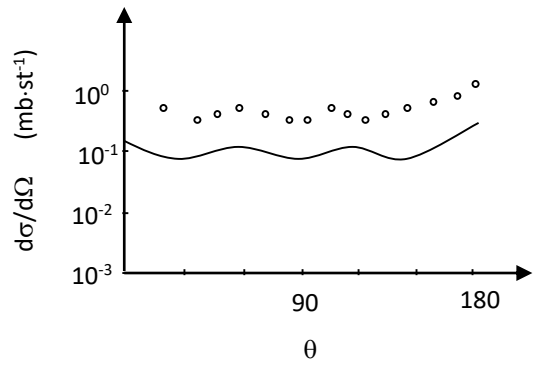

Fig.1. The angular dependence of the differential cross sections for the reaction $^{13}C(d,\alpha)^{11}B$ when E_d = 15,3 MeV. The solid lines show the theoretical data, the points - experimental data from [7].

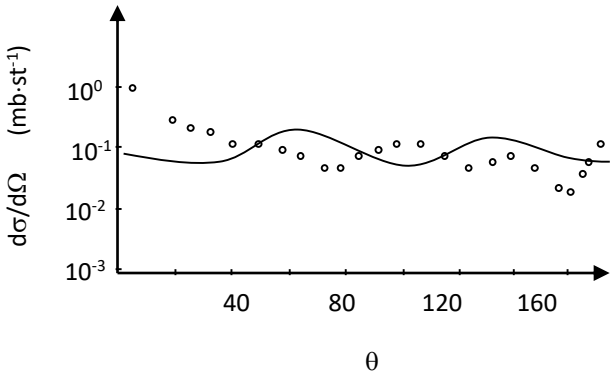

Fig.2. The angular dependence of the differential cross sections for the reaction $^{13}C(^3He,\alpha)^{12}C$ when E_{He} = 18 MeV. The solid lines show the theoretical data, the points - experimental data from [8].

CONCLUSION

The association model constitutes a phenomenological semi-microscopic approach to study associative knocking out nucleons characteristics. Associations in the nucleus are virtual formations and the probability of their existence is determined by the nuclear structure.

For direct processes in cases when the section is factored in the kinematic and structural factors, the shape of the angular distribution for a single transmitted moment *l*, does not depend on the spectroscopic factor that how this factor only normalizes the absolute value of the cross section. If the reaction of several possible values of *l*, the shape of the angular distribution, even for direct processes depends essentially on the respective relations of spectroscopic factors.

The results are given in the work related to the analysis of the effective cross section. However, it is not difficult to extend the considered model to calculate the angular dependence of the characteristics of the reactions that are associated with the off-diagonal elements of the density matrix, such as the polarization of the final particles.

The study of nuclear states built on associations bound by valence nucleons in their configurations is a field of large interest, which is being renewed by the availability of exotic beams: clustering is, in fact, predicted to become very important at the drip-line, where weakly bound systems will prevail. This approach usually allows more clearly understand the physical side of various nuclear processes and simplify the calculations of their characteristics. Therefore, understanding and applying state of the art techniques with respect to cluster formation promise to give much better insight into the physics of the investigated phenomena.

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