Nucleon and delute cluster transfer in the reactions ^{6}Li + ^{9}Be

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Abstract. The results of experiments on studying nucleon and cluster transfer processes in the reactions of the ^{6}Li (68 MeV) ions with the ^{9}Be target nuclei are presented. The angular distributions for the reaction channels ^{9}Be(^{6}Li,α)^{11}B$_{g.s}$ and ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ have been measured. To describe the possible contributions of sequential transfer of nucleons and alpha clusters, as well as direct transfer of the ^{5}He cluster, the DWBA method (FRESCO) is used, the spectroscopic amplitudes are obtained for the configurations of (^{9}Be+d) and (^{6}Li+^{5}He) in the ^{11}B nucleus and (^{6}Li+α) in the ^{10}B nucleus. The results of the theoretical analysis agree with the experimental data and indicate a strong correlation between a neutron and an α-cluster, leading to the formation of the ^{5}He cluster in the transfer processes.

1 Introduction

The studies of nucleon and cluster transfer processes in reactions with light nuclei are of great importance, for example, for understanding astrophysical processes [1]. Numerous works are devoted to studying nuclear reactions with the beams of the ^{6}Li nuclei, both from experimental and theoretical points of view [2-6].

The cluster configurations in light nuclei can manifest themselves in nuclear reactions even in the form of such exotic systems, as multi-neutrons, ^{5}He, etc. [7]. In [8, 9], it was shown that the breakup of the ^{9}Be nucleus leads, with a high probability, to the exit channels n+^{8}Be and, predominantly, ^{5}He+α. The domination of the simultaneous transfer of an α-cluster and a neutron in the form of ^{5}He was observed in the reaction ^{12}C(^{11}B,^{6}Li)^{17}O [10]. In the reaction ^{9}Be(d,α)^{7}Li, the ^{5}He transfer makes a large contribution to the differential cross sections at large angles .

The success of the quantitative analysis of transfer reactions under the assumption of the simultaneous transfer of five nucleons in the form of the ^{5}He cluster is interpreted as its presence in light nuclei [10-13]. At the same time, the mechanism of the sequential transfer of an α-cluster and a neutron is also possible. Such a mechanism can be quite important, because the cross sections for neutron and α-cluster transfer reactions are large [17]. Therefore, to analyze experimental data on direct reactions of stripping and pickup, it is extremely important to consider the probabilities of both simultaneous and sequential transfer of nucleons and clusters.

In this work, we present new experimental data on the energy spectra and angular distributions of nucleon and cluster transfer products in the reactions ^{6}Li+^{9}Be at E_{lab} = 68 MeV. The data are analyzed using the DWBA method to determine the contribution of the mechanisms of simultaneous nucleon (cluster) and sequential (nucleon-nucleon, cluster-nucleon) transfer to the reaction cross sections. The obtained results provide a deeper understanding of the mechanisms of nucleon and cluster transfer processes and complement the previously published data [14, 15].

2 Experiments

The experiments on reactions with light nuclei ^{6}Li+^{9}Be were carried out at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research, Dubna, Russia. The measurements were performed in the reaction chamber of the high-resolution magnetic analyzer MAVR [16]. The beam of the ^{6}Li ions (E_{lab} = 68 MeV) was accelerated by the U-400 cyclotron. The average intensity of the bombarding ion beam on targets was 20 nA. The targets were self-supporting foils of metallic beryllium and carbon with thicknesses of 10 μm.

The reaction products were registered and identified using three three-layer telescopes: ΔE_1 (12 and 50 μm thick) and ΔE_2 (100 μm thick) for measurement of specific losses, and E_r (3200 μm thick) for measurement of the residual energy. The telescopes were rotated relative to the target in the range of angles θ_{lab} = 10°-122° with a step of 2°. The registration of reaction products was performed in a wide range of

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charge numbers, from Z = 1 (p, d, t) to Z = 5. The two-dimensional identification matrices are shown in Fig. 1 the reaction products were unambiguously identified. The inclusive method with measuring angular distributions and energy spectra of the emitted particles allowed us to identify elastic and inelastic scattering channels, as well as nucleon transfer channels. The identified products for the reactions $^{6}Li+^{9}Be$ (Fig. 1) were ^{1-3}H, $^{3,4,6}He$, $^{6,7,8}Li$, $^{7,9,10}Be$, ^{10}B and ^{1-3}H, $^{3,4}He$, $^{6,7}Li$, $^{7,9}Be$, ^{10}B respectively.

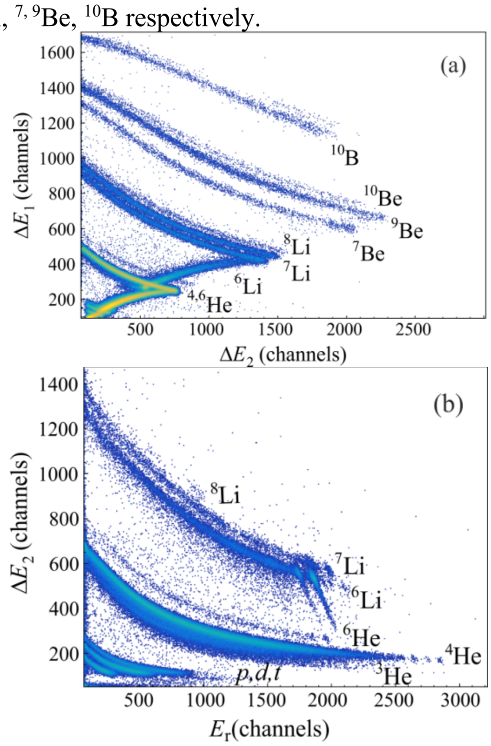

Fig. 1. Two-dimensional identification matrices ΔE_1-ΔE_2 (a) and ΔE_2-E_r (b) for the products of the reaction of ^{6}Li on the ^{9}Be target at an angle of $\theta_{lab} = 20°$.

The energy spectra of the ^{6}Li, ^{4}He, ^{6}He, and ^{10}B nuclei emitted in the $^{6}Li+^{9}Be$ reaction at an angle of $\theta_{lab} = 16°$ are shown in Fig. 2. In the energy spectra of ^{6}Li [Fig. 2(a)], we observe three distinct peaks corresponding to the population of the ground state ($3/2^-$) and the excited states ($5/2^-$, 2.43 MeV and $7/2^-$, 6.38 MeV) of the ^{9}Be nucleus in the $^{9}Be(^{6}Li,^{6}Li)^{9}Be$ reaction channel. In the case of ^{4}He [Fig. 2b)], we see the peaks in its energy distribution corresponding to the population of the ground state ($3/2^-$) and the excited states ($1/2^-$, 2.12 MeV and $5/2^-$, 4.45 MeV) of the complementary product ^{11}B. This is an indication of the two-body exit channel $^{9}Be(^{6}Li,^{4}He)^{11}B$, when the ground state and the low-lying excited states are populated. However, at energies of the detected ^{4}He nuclei lower than 70 MeV, a large number of events are observed arising from multibody exit channels. The energy spectrum of ^{10}B [Fig. 2c] has a broad peak corresponding to the formation of ^{5}He with the population of its ground state ($3/2^-$) in the $^{9}Be(^{6}Li,^{10}B)^{5}He_{g.s.}$ reaction channel. Such a broad peak is typical for the ground state spectrum of ^{5}He [9]. In the energy spectrum of ^{6}He [Fig. 2d)], we observe the ground state ($3/2^-$) and the excited state ($5/2^-$, 2.35 MeV) of the complementary nucleus ^{9}B in the $^{9}Be(^{6}Li,^{6}He)^{9}B$ reaction channel, even though ^{9}B is an unbound nucleus. This is another evidence of a two-body exit channel, as in our previous works [8 9].

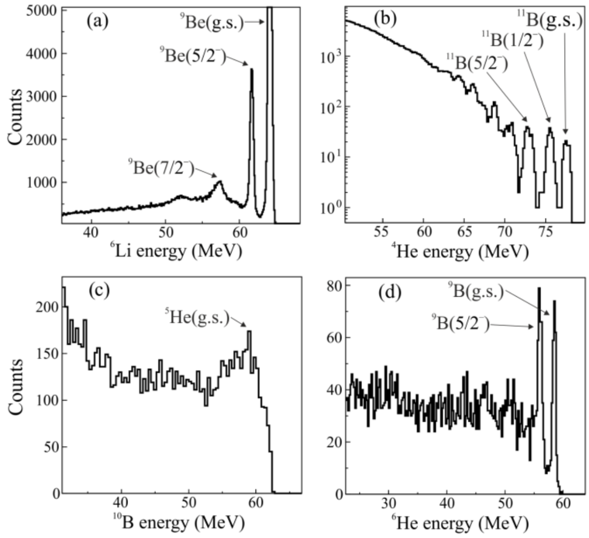

Fig. 2. Energy spectra of the ^{6}Li (a), ^{4}He (b), ^{10}B (c), and ^{6}He (d) nuclei emitted in the $^{6}Li+^{9}Be$ reaction at an angle of $\theta_{lab} = 16°$.

The experimental data on the angular distributions for the ground states were obtained by separating the corresponding peaks from the energy spectra of the reaction products using the Gaussian approximation. The results together with their analysis are presented in the following section.

3 Angular distributions and data analysis

3.1 Elastic scattering channels $^{9}Be(^{6}Li,^{6}Li)^{9}Be_{g.s.}$

Experimental data on the differential cross sections for elastic scattering of ^{6}Li on ^{9}Be is presented in Fig. 3 [17]. The experimental data were analyzed within the framework of the optical model [18] with the Woods-Saxon form-factors for both the real and imaginary parts optical potential.

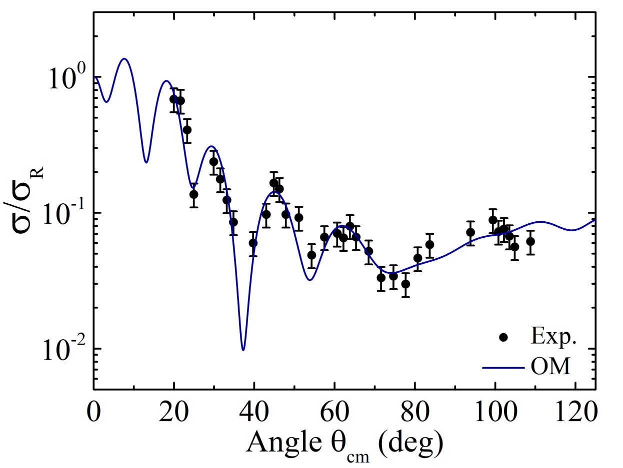

Fig. 3. Angular distributions for the elastic scattering channels $^{9}Be(^{6}Li,^{6}Li)^{9}Be$ [25]. The curve is the results of calculations within the optical model.

All six parameters of the Woods–Saxon potential, the depths $V_{V,W}$ and the geometric parameters $r_{V,W}$, $a_{V,W}$, were varied. It can be seen that we achieved an excellent fit (χ^2/N=1.418) of the experimental data (Fig. 3). The resulting parameters were as follows: V_V= 152.20 MeV, r_V = 0.698 fm, a_V= 0.624 fm, V_W = 12.36 MeV, r_W = 1.388 fm, a_W = 0.930 fm. They were obtained by fitting the initial parametres from [18-20] using the FRESCO code [21].

3.2 Nucleon (cluster) transfer channels ^{9}Be(^{6}Li, α)^{11}B$_{g.s.}$ and ^{9}Be(^{6}Li, ^{10}B)^{5}He

Experimental differential cross sections for the transfer reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ are shown in Fig. 4. The mechanisms of nucleon transfer in the ^{6}Li+^{9}Be reaction were studied by comparing the experimental cross sections with calculations within the DWBA method [18] using the FRESCO code [21, 22]. The transfer of a deuteron cluster makes a significant contribution to the cross section of the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ at small angles ($\theta_{c.m.}$ = 0-90°). In this case, a large contribution of sequential neutron-proton and proton-neutron transfer to the cross section is present in the entire range of angles. As can be seen from the calculations, the contribution of the n-α mechanism to the reaction cross section is larger in comparison with the α-n mechanism. This is due to the lower binding energy of the neutron in the ^{9}Be nucleus (1.66 MeV) compared to the binding energy of the α-cluster (2.468 MeV). The processes of sequential transfer of n-α and α-n do indeed contribute less to the region of large angles, by almost an order of magnitude compared to the ^{5}He transfer assuming its simultaneous transfer. Starting from the angle of $\theta_{c.m.}$ = 130°, the ^{5}He transfer makes a noticeable contribution to the cross section. A similar result was obtained in [10, 23]. A significant contribution of the mechanism of simultaneous transfer of a neutron and an α-cluster in the form of a ^{5}He cluster to the cross section for the reaction channel ^{9}Be(^{6}Li,α)^{11}Bg.s. at large angles is an indication of a high degree of pair correlation between the neutron and the α-cluster in the ^{9}Be nucleus.

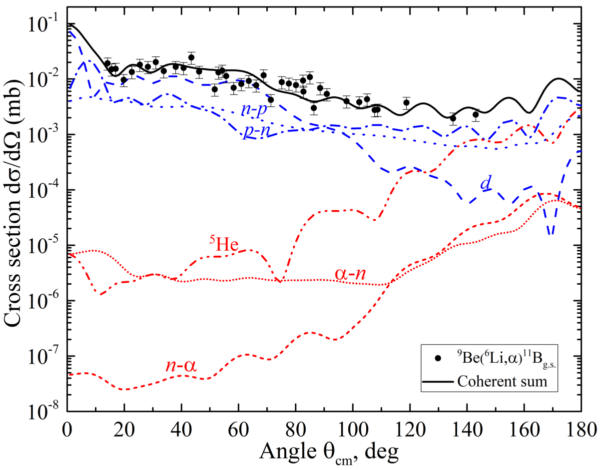

Fig. 4. Experimental cross sections for the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ (circles) compared with the results of DWBA calculations (curves). Transferred particles are indicated.

The nuclei for the reaction channels were represented as bound systems of a core *C* plus a particle *x* (cluster or nucleon); the stationary Schrödinger equation for *x* in the mean field of the nuclei was solved with the potential in the Woods-Saxon form $V\{1+\exp[(r-R)/a]\}^{-1}$. The wave functions of the bound states of the particles *x* were calculated taking into account the equality of the energy eigenvalues to the binding energies taken with opposite signs. The resonance states were considered as quasi-bound states. In the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$, the sequential transfer of *p-n*, *n-p*, *n*-α, and α-*n* may occur with the formation of nuclei that do not have bound states (^{5}He, ^{5}Li, ^{8}Be) in the intermediate reaction channels. To estimate the contribution of sequential transfer to the cross sections of the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$, we used a value close to zero (0.001 MeV) as the binding energy of quasi-bound states for the nuclear systems ^{5}He=α+*n*, ^{5}Li=α+*p*,^{8}Be=α+α. The depth parameter *V* has been fitted to reproduce the (*x*) binding energies. The geometrical parameters were fixed as $R = 1.26\left(A_C^{1/3}+A_x^{1/3}\right)$ fm and a = 0.56 fm.

Most spectroscopic amplitudes S_x used in the present calculations were taken from [16, 17, 22, 24]. In [17], S_x were obtained from the shell model; in [22], the authors used the translation invariant shell model (DESNA code [25]); in [24], S_x were obtained using the effective Cohen-Kurat interaction for *p*-shell nuclei (ANTOINE code [26]. The unknown spectroscopic amplitudes (not given in [9, 10, 23-25]) for the core + cluster (or nucleon) systems ^{5}He=α+*n* (S_x=1.000), ^{5}Li=α+*p* (S_x=0.671), ^{8}Be=α+α (S_x=1.225), ^{10}B=^{6}Li+α (S_x=1.075), ^{11}B=^{6}Li+^{5}He (S_x=0.801), and ^{11}B=^{9}Be+*d* (S_x= 0.566) were determined by fitting for the best description of the experimental data with theoretical curves. The obtained values of S_x show that the nuclear system ^{11}B=^{6}Li+^{5}He (S_x = 0.801) is formed in the ^{11}B nucleus with a larger spectroscopic amplitude than the system ^{11}B=^{7}Li+α (S_x = –0.509 [10]). In the reaction channel ^{10}B(α+*n*,α)^{10}B+*n*, a relatively large value of S_x = 1 was obtained for the unbound nucleus ^{5}He, which is an indication of a strong pair correlation between the neutron and the α-cluster. For the isobar analog nucleus ^{5}Li in the form of the α+*p* configuration, S_x has a smaller value (0.671). The spectroscopic amplitudes used in the calculations for the reaction channels ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ and ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ are presented in Table.

Sequential *p-n* and α-*n* transfer in the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ assumes intermediate steps ^{9}Be(^{6}Li,^{5}He)^{10}B$_{g.s.}$ and ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$, respectively. Experimental differential cross sections for proton and α-cluster transfer in the reaction channel ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ in comparison with the results of calculations are shown in Fig. 5. We used the same potential parameters and spectroscopic amplitudes as for the intermediate channels of sequential transfer (*n*-α and α-*n*) in the channel ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$. As can be seen from Figs. 4 and 5, these parameters provide good agreement between the calculated cross sections and the experimental data for the two reaction channels. The main contribution to the cross section of the reaction channel ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ is from the mechanism of the transfer of a proton from the ^{6}Li projectile nucleus to the ^{9}Be target nucleus with the formation of the ^{5}He and ^{10}B nuclei (see Fig. 5).

Table 1. Spectroscopic amplitudes S_x of nucleons and clusters (x) used in the calculation of the reaction channel ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ for A (nucleus) = C (core) + x; n, l, j are number of nodes, orbital angular momentum, and vector sum of orbital angular momentum and spin of the transferred particle, respectively.

A	C	x	n	l	j	S_x	
^{6}Li	α	d	2	0	1	1.061	[17]
^{11}B	^{9}Be	d	2	0	1	0.566	
^{6}Li	^{5}He	p	1	1	3/2	0.667	[17]
^{10}B	^{9}Be	p	1	1	3/2	1.185	[17]
^{5}He	α	n	1	1	3/2	1.000	
^{11}B	^{10}B	n	1	1	3/2	1.097	[16]
^{6}Li	^{5}Li	n	1	1	3/2	0.667	[17]
^{10}Be	^{9}Be	n	1	1	3/2	1.535	[29]
^{5}Li	α	p	1	1	3/2	0.671	
^{11}B	^{10}Be	p	1	1	3/2	0.842	[16]
^{9}Be	α	^{5}He	3	1	3/2	0.925	[32]
^{11}B	^{6}Li	^{5}He	3	1	3/2	0.801	
^{9}Be	^{8}Be	n	1	1	3/2	0.866	[17]
^{7}Li	^{6}Li	n	1	1	3/2	0.735	[17]
^{8}Be	α	α	3	0	0	1.225	[29]
^{11}B	^{7}Li	α	2	0	0	0.509	[16]
^{9}Be	^{5}He	α	1	2	2	0.925	[32]
^{10}B	^{6}Li	α	1	2	2	1.075	
^{5}He	α	n	1	1	3/2	1.000	
^{11}B	^{10}B	n	1	1	3/2	1.097	[16]

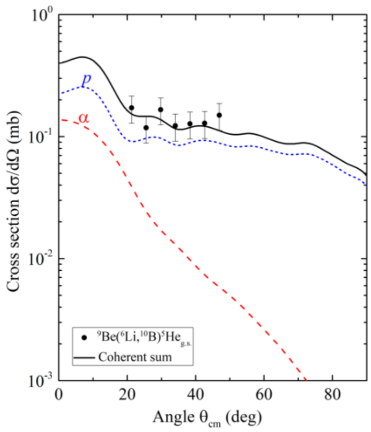

Fig. 5. Experimental differential cross sections for nucleon (cluster) transfer in the reaction channel ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ (circles) compared with the results of calculations (curves). Transferred particles are indicated; the coherent sum of all transfer mechanisms is shown by a solid curve.

4 Conclusions

New experimental data on nucleon and cluster transfer in the reactions ^{6}Li+^{9}Be at an energy of 68 MeV have been obtained. The experimental technique with three-layer telescopes made it possible to reliably identify reaction channels. Using the telescopes, the reaction products were unambiguously identified by charge and mass. The angular distributions for the reaction channels ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$ and ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$ were measured. Experimental evidence has been obtained for the formation of the ^{5}He nuclei in the reaction channel ^{9}Be(^{6}Li,^{10}B)^{5}He$_{g.s.}$

The analysis of the experimental data for the reaction channels ^{9}Be(^{6}Li,α)^{11}Bg.s. within the DWBA method showed a significant contribution of the ^{5}He transfer in the region of large angles. A high degree of pair correlation between the neutron and the α-cluster leads to the formation of the ^{5}He cluster during transfer reactions. The probability of the sequential transfer (α-n or n-α) is much lower than that for the process of the simultaneous transfer of ^{5}He over the entire range of angles. It was also shown that for the reaction channel the sequential α-n transfer process prevails over the n-α transfer process, while for the reaction channel ^{9}Be(^{6}Li,^{4}He)^{11}B$_{g.s.}$, the n-α transfer dominates.

The spectroscopic amplitudes for clusters of the nuclei ^{10}B=^{6}Li+α (1.075), ^{11}B=^{6}Li+^{5}He (0.801), and ^{11}B=^{9}Be+d (0.566) reproduced well the differential cross sections for the transfer channels ^{9}Be(^{6}Li,α)^{11}B$_{g.s.}$.

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