Five-nucleon simultaneous and sequential transfer in the $^{12}C(^{11}B,^{6}Li)^{17}O$ and $^{12}C(d,^{7}Li)^{7}Be$ reactions

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Measurements of the angular distributions of the $^{12}C(^{11}B,^{6}Li)^{17}O$ reaction were performed at three energies of a ^{11}B beam: 28, 35, and 40 MeV. The results were analyzed in the frame of the exact finite range distorted wave Born approximation of the first and the second order assuming the simultaneous and sequential transfer of the neutron and the α particle. Such an analysis was also performed for previously measured angular distributions of the $^{12}C(d,^{7}Li)^{7}Be$ reaction at E_{lab} = 78 MeV. In both reactions under investigation dominance was found of the simultaneous transfer of the α particle and the nucleon correlated to the ^{5}He (^{5}Li) cluster in the ground or the first excited state. [S0556-2813(96)01507-5]

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I. INTRODUCTION

Convincing evidence for direct five-nucleon transfer processes has been presented in many publications concerning reactions induced by protons [$(p,^{6}Li)$ on ^{12}C [1–5] and ^{13}C [1]], deuterons [$(d,^{7}Li)$ and/or $(d,^{7}Be)$ on ^{10}B [6], ^{12}C [7], ^{13}C [8], ^{16}O [9], ^{17}O, ^{18}O [8], and ^{19}F [8,10]], and heavy ions [$^{11}B(^{12}C,^{7}Li)^{16}O$ [11], $^{11}B(^{14}N,^{9}Be)^{16}O$ [12], $^{12}C(^{6}Li,p)^{17}O$ [13], $^{12}C(^{7}Li,^{12}C)^{7}Li$ [14], $^{12}C(^{9}Be,^{4}He)^{17}O$ [15], $^{12}C(^{13}C,^{8}Be)^{17}O$ [16], $^{13}C(^{6}Li,p)^{18}O$ [17,18], $^{13}C(^{9}Be,^{14}C)^{8}Be$ [19], $^{15}N(^{12}C,^{7}Li)^{20}Ne$ [20], $^{16}O(^{11}B,^{16}O)^{11}B$ [21], and $^{17}O(^{12}C,^{17}O)^{12}C$ [22]].

Quantitative analysis of these reactions has been usually performed under the assumption of the single-step transfer of inert ^{5}He or ^{5}Li clusters [1–8,10,16,19,22]. The success of such an analysis was treated as proof of the presence of ^{5}He or/and ^{5}Li clusterization in light nuclei. It is, however, possible that the five nucleons are transferred, being noncorrelated to ^{5}He or/and ^{5}Li, most likely via transfer of the α particle and the nucleon. Such a mechanism can be quite important because transfers of nucleons as well as of the α particles are known to proceed with large cross sections. These particles can be transferred simultaneously in a one-step reaction or sequentially in two-step processes. It is important to note that simultaneous transfer is a more general mechanism than transfer of a single five-nucleon cluster because the α particle and the nucleon can change the state of their relative motion during the reaction. Such a mechanism will be called in the present paper "uncorrelated transfer." Only specific simultaneous transfer of the nucleon and the α particle, i.e., "correlated transfer," in which transferred nucleons form a cluster with quantum numbers of ^{5}He or ^{5}Li, is equivalent to single five-nucleon cluster transfer.

The sequential transfer of the nucleon and the α-particle (or vice versa) was investigated quantitatively only in Refs. [7,16,23] and the simultaneous transfer of these particles only in Ref. [23].

The results of the study of five-nucleon elastic transfer in the $^{11}B+^{16}O$ system [23] performed according to the above described model showed that simultaneous (α-p) transfer is the dominant process. Furthermore, it was found that the largest cross section corresponds to correlated transfer with the five transferred nucleons forming a cluster with quantum numbers of ^{5}Li in the ground or the first excited state. Thus one could infer the presence of the ^{5}Li clusterization of the ^{16}O nuclei.

The present study was undertaken with the aim to investigate in detail the mechanism of five-nucleon transfer for other nuclear systems, checking, in particular, whether the situation described above is generally typical for five-nucleon transfer. For this purpose two nuclear reactions were selected, namely, $^{12}C(^{11}B,^{6}Li)^{17}O$ and $^{12}C(d,^{7}Li)^{7}Be$. These reactions enable us to study situations in which the same nuclei play different roles, i.e., of a donor or an acceptor of five nucleons. Thus they put more stringent requirements for the theoretical model of the reaction mechanism. In the first one the ^{11}B nucleus plays the role of a donor for the neutron and the α particle while in the $^{11}B(^{16}O,^{11}B)^{16}O$ reaction the ^{11}B is the core of the acceptor nucleus. The ^{12}C nucleus, which in the $^{12}C(^{11}B,^{6}Li)^{17}O$ reaction is a core of ^{17}O acceptor, becomes a donor in the $^{12}C(d,^{7}Li)^{7}Be$ reaction. The last reaction allows for observation of the contributions of (neutron–α-particle) and (proton–α-particle) transfers to the same angular distribution. This is because ^{7}Li ejectiles emerging at forward scattering angles (in the c.m. system) originate mainly from d projectiles which picked up five nucleons (neutron and α particle) from the ^{12}C target nucleus, while ^{7}Li emerging at backward angles originates mainly from the target being cores of ^{12}C target nuclei. Thus (neutron–α-particle) and (proton–α-particle) transfers can be studied under the same conditions.

In the present work measurements of the angular distributions of $^{12}C(^{11}B,^{6}Li)^{17}O$ reaction were performed at three

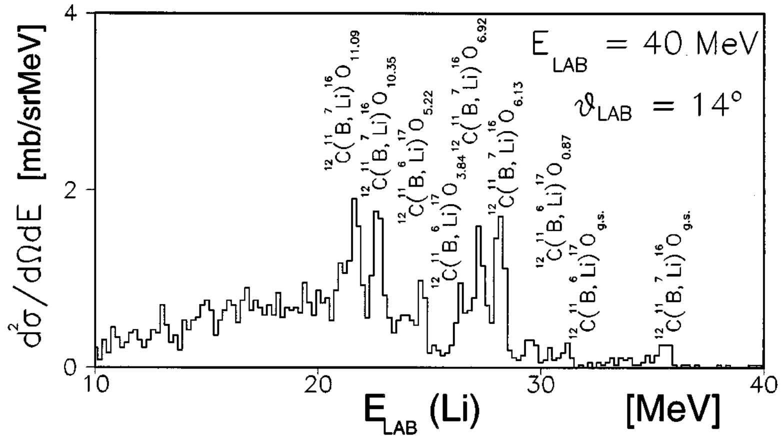

FIG. 1. Experimental spectrum of lithium ions (^{6}Li as well as ^{7}Li) measured at $\theta_{\rm lab}$ = 14° for the ^{12}C + ^{11}B interaction at a ^{11}B beam energy $E_{\rm lab}$ = 40 MeV.

energies of a ^{11}B beam: 28, 35, and 40 MeV. The experimental procedure and results are discussed in the next section. In the analysis the results of measurements of angular distributions of ^{12}C(d,^{7}Li)^{7}Be reaction at a laboratory energy of deuterons, 78 MeV [7], were also included. A theoretical analysis of five-nucleon transfers is presented in the third section of this work and results are summarized and discussed in the last section.

In heavy ion reactions the compound nucleus contribution corresponding to evaporation of heavy fragments could not be *a priori* ruled out. In fact, the emission of ^{6}Li fragments in some heavy ion reactions, e.g., started with ^{10}B + ^{16}O or ^{12}C + ^{14}N entrance channels [35], was treated as evaporation from a compound nucleus. Thus in the present work such possible admixtures from compound nucleus processes were checked in statistical model calculations based on the results of a separate experiment.

II. EXPERIMENTAL PROCEDURE

The measurements were performed at the Laboratorio Nazionale del Sud (LNS) in Catania using the 13 MV SMP Tandem Van de Graaff accelerator. A beam of ^{11}B was focused on a ^{12}C target of about 100 μg/cm^2 thickness, placed in the center of a scattering chamber of a diameter of 75 cm.

The measurements were done at laboratory energies of 28, 35, 40 MeV. The ΔE-E counter telescopes were applied for particle identification. The ionization chamber was used as the ΔE counter and the silicon position-sensitive detectors were used as E counters. The range of laboratory angles was from 7° to 27° divided in 2° steps. The energy resolution of the ΔE counter allowed a good charge identification of the detected reaction products. The overall energy resolution of the telescopes was about 500 keV. The details of the measurements are described elsewhere [24]. The energy calibration of the detector system allowed the determination of the excitation energies corresponding to the observed peaks with an accuracy of about 300 keV. The absolute values of the cross sections were determined from the measured counting rates, the target thickness, the solid angles of the detecting system, and the integrated beam charge. The uncertainty of the absolute normalization was estimated to be 7%.

In Fig. 1 an example of the experimental energy spectrum of an outgoing Li for a beam energy of 40 MeV is presented. Since the detection system does not allow mass separation, both outgoing ^{6}Li and ^{7}Li appear together in the spectra. The peaks corresponding to outgoing ^{6}Li are seen for the ^{17}O ground state and 0.87 and 3.84 MeV excited states. The higher excited states cannot be identified since they overlap with ^{16}O levels excited in the reaction ^{12}C(^{11}B,^{7}Li)^{16}O. Besides these peaks the transitions with outgoing ^{7}Li are observed for ^{16}O in the ground state and 6.13, 6.92 MeV and some higher excited states. The obtained experimental angular distributions are presented in Fig. 2 for the ^{17}O ground state transition only. The error bars correspond to the statistical uncertainties of individual experimental points only.

III. THEORETICAL ANALYSIS

The formalism used in the present analysis is based on the distorted wave Born approximation (DWBA) of the first or-

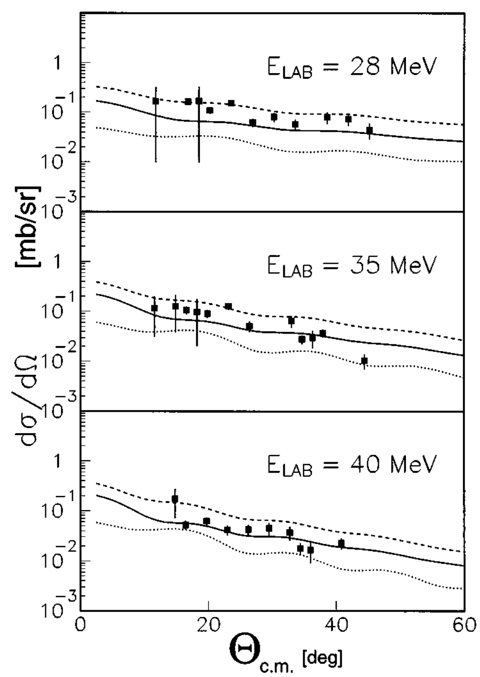

FIG. 2. Experimental angular distributions of the ^{12}C(^{11}B,^{6}Li)^{17}O reaction at $E_{\rm lab}$ (^{11}B) = 28, 35, and 40 MeV and results of the calculations of simultaneous transfer of a neutron and an α particle. The dashed line corresponds to correlated simultaneous transfer, the dotted line represents uncorrelated simultaneous transfer, and the solid line shows their coherent sum.

TABLE I. One-cluster spectroscopic amplitudes ''SA'' used for the calculation of two-step contributions for the reaction ^{12}C(^{11}B,^{6}Li)^{17}O. The isospin Clebsch-Gordan coefficents are included in the listed values.

Nucleus	Core	Cluster	n	l	$2j$	SA	Ref.
^{13}C	^{12}C	n	0	1	1	+0.78	a
^{11}B	^{10}B	n	0	3	1	−1.05	a
^{11}B	$^{10}B_{0.72}$	n	0	1	1	−0.437	a
^{11}B	$^{10}B_{0.72}$	n	0	1	3	−0.267	a
^{11}B	$^{10}B_{2.15}$	n	0	1	1	+0.263	a
^{11}B	$^{10}B_{2.15}$	n	0	1	3	−0.679	a
^{10}B	^{6}Li	α	0	4	8	+0.060	b
^{10}B	^{6}Li	α	1	2	4	−0.002	b
$^{10}B_{0.72}$	^{6}Li	α	2	0	0	+0.762	b
$^{10}B_{0.72}$	^{6}Li	α	1	2	4	−0.270	b
$^{10}B_{2.15}$	^{6}Li	α	2	0	0	+0.163	b
$^{10}B_{2.15}$	^{6}Li	α	1	2	4	+0.559	b
^{17}O	^{13}C	α	1	3	6	+0.364	c
^{16}O	^{12}C	α	2	0	0	−0.485	b
^{11}B	^{7}Li	α	2	0	0	−0.509	b
^{11}B	^{7}Li	α	1	2	4	+0.629	b
^{17}O	^{16}O	n	0	2	5	+0.90	c
^{7}Li	^{6}Li	n	0	1	1	+0.557	a
^{7}Li	^{6}Li	n	0	1	3	+0.616	a

[a]Ref. [27] shell model value.
[b]Ref. [28] shell model value.
[c]Ref. [25] experimental value.

der (for simultaneous transfer of a nucleon and an α particle) and of the second order (for sequential transfers). It is described in detail in Ref. [23].

Exact finite range computer codes were used for computation of the reaction amplitudes. The TPT computer program of Rudy [25], which is capable of evaluating both correlated and uncorrelated transfers, was applied for the simultaneous transfer of both particles. Sequential transfers were calculated as two-step processes using the JUPITER-5 program of Udagawa and Tamura [26].

The reaction amplitudes were weighted by corresponding spectroscopic amplitudes from the literature, and were added coherently to obtain resulting cross sections to be compared with the experimental data. Values of the spectroscopic amplitudes are listed in Tables I and II for one-cluster and two-cluster spectroscopic amplitudes, respectively.

Transition potentials were chosen according to standard prescription of the DWBA as those which are responsible for binding the clusters to the corresponding core nuclei. The *prior* representation of transition potentials was used for single-step transfer and the *prior-post* representation was accepted for two-step reactions. The latter choice of representation assures the cancellation of the so-called ''nonorthogonality terms'' which are present in the two-step DWBA when using other representations [30].

The transition potentials were taken for both simultaneous and sequential reactions in a Woods-Saxon form with geometrical parameters fixed for 1p shell nuclei at the following values: $R=0.85(A_{\mathrm{core}}^{1/3}+A_{\mathrm{cluster}}^{1/3})$ fm, $a=0.65$ fm. Such values of the geometrical parameters were successfully used [7] in a DWBA analysis of multinucleon transfer reactions. For ^{16}O and ^{17}O nuclei, where the influence of the next $2s1d$ shell becomes significant the radius parameter was chosen as $R=1.25(A_{\mathrm{core}}^{1/3}+A_{\mathrm{cluster}}^{1/3})$ fm for the α-particle and neutron pair. The same parametrization was used in Ref. [23]. The depths of the transition potentials were adjusted to reproduce the binding energies of clusters in the corresponding nuclei. The Coulomb terms of the transition potentials were assumed to be in the form of potentials of uniformly charged spheres with radii equal to those of the nuclear binding potentials.

The distorted waves were generated using optical model potentials found from analysis of the elastic scattering and their parameters are listed in the Table III. The analysis was

TABLE II. Two-cluster spectroscopic amplitudes ''SA'' used in the calculations of simultaneous alpha-nucleon transfer for ^{12}C(^{11}B,^{6}Li)^{17}O and ^{12}C(d,^{7}Li)^{7}Be reactions. The two-particle spectroscopic amplitudes are given in the following coupling scheme: nucleus = $\{[\mathrm{core}+\alpha(n_1,l_1,j_1)]+N(n_2,l_2,j_2)\}$ where $j_i=l_i+s_i$, i=1,2, and $J=j_1+j_2$ (s_1, s_2 denote spins of the α particle and nucleon, j_1, j_2 total angular momenta of orbitals of the α particle and nucleon, n_1, n_2 radial quantum numbers, and l_1, l_2 orbital angular momenta of orbitals). The isospin Clebsch-Gordan coefficients are included in the listed values.

Nucleus	Core	n_1	l_1	$2s_1$	$2j_1$	n_2	l_2	$2s_2$	$2j_2$	$2J$	SA	Ref.
^{17}O	^{12}C	2	0	0	0	0	2	1	5	5	−0.46	a
^{17}O	^{12}C	1	3	0	6	0	1	1	1	5	−0.28	a
^{11}B	^{6}Li	1	2	0	4	0	1	1	1	3	+0.307	b
^{11}B	^{6}Li	1	2	0	4	0	1	1	1	5	−0.167	b
^{11}B	^{6}Li	1	2	0	4	0	1	1	3	1	−0.251	b
^{11}B	^{6}Li	1	2	0	4	0	1	1	3	3	−0.148	b
^{11}B	^{6}Li	1	2	0	4	0	1	1	3	5	+0.322	b
^{11}B	^{6}Li	2	0	0	0	0	1	1	1	1	+0.268	b
^{11}B	^{6}Li	2	0	0	0	0	1	1	3	3	+0.344	b
^{12}C	^{7}Be	1	2	0	4	0	1	1	1	3	−0.522	b
^{12}C	^{7}Be	1	2	0	4	0	1	1	3	3	+0.876	b
^{12}C	^{7}Be	2	0	0	0	0	1	1	3	3	−1.057	b
^{12}C	^{7}Li	1	2	0	4	0	1	1	1	3	+0.522	b
^{12}C	^{7}Li	1	2	0	4	0	1	1	3	3	−0.876	b
^{12}C	^{7}Li	2	0	0	0	0	1	1	3	3	+1.057	b
^{7}Li	^{2}d	1	1	0	2	0	0	1	1	1	−0.433	b
^{7}Li	^{2}d	1	1	0	2	0	0	1	1	3	−0.484	b
^{7}Li	^{2}d	0	2	0	4	0	1	1	1	3	−0.493	b
^{7}Li	^{2}d	1	0	0	0	0	1	1	1	1	+0.697	b
^{7}Li	^{2}d	0	2	0	4	0	1	1	3	1	+0.624	b
^{7}Li	^{2}d	0	2	0	4	0	1	1	3	3	+0.493	b
^{7}Li	^{2}d	1	0	0	0	0	1	1	3	3	+0.780	b
^{7}Be	^{2}d	1	1	0	2	0	0	1	1	1	−0.433	b
^{7}Be	^{2}d	1	1	0	2	0	0	1	1	3	−0.484	b
^{7}Be	^{2}d	0	2	0	4	0	1	1	1	3	−0.493	b
^{7}Be	^{2}d	1	0	0	0	0	1	1	1	1	+0.697	b
^{7}Be	^{2}d	0	2	0	4	0	1	1	3	1	+0.624	b
^{7}Be	^{2}d	0	2	0	4	0	1	1	3	3	+0.493	b
^{7}Be	^{2}d	1	0	0	0	0	1	1	3	3	+0.780	b

[a]Estimated on the basis of single-particle (nucleon and/or α-particle) spectroscopic amplitudes of ^{17}O [25], ^{16}O [28], and ^{13}C [27].
[b]Ref. [29].

TABLE III. Optical model parameters used for the generation of distorted waves in a DWBA analysis. Real parts of all potentials have the Woods-Saxon form with the following parametrization of radii: $R=r_0^* (A_{\rm target}^{1/3} + A_{\rm particle}^{1/3})$. The imaginary potentials from [31] have the volume shape of the Woods-Saxon form while those from [32] use the surface shape of derivative of the Woods-Saxon form.

System	U [MeV]	r_U [fm]	a_U [fm]	W [MeV]	r_W [fm]	a_W [fm]	r_C [fm]	Ref.
^{12}C+^{11}B	50.5	1.094	0.609	36.04	1.182	0.487	1.25	[31]
^{17}O+^{6}Li	195	0.739	0.74	55	0.739	0.74	0.739	[32]
^{16}O+^{7}Li	195	0.739	0.74	55	0.739	0.74	0.739	[32]
^{13}C+^{10}B	50.5	1.094	0.609	36.04	1.182	0.487	1.25	[31]

performed without free parameters. In such a case it is, however, worthwhile to test the stability of the results of calculations to the changes of values of parameters accepted according to some other sources, e.g., parameters of the optical model and geometrical parameters of binding potentials. It was proved in additional calculations that the results are practically independent of the optical model parameters as long as they lead to a good reproduction of the elastic scattering data. As usual in the case of heavy fragment transfer the magnitude of the calculated cross section depends more strongly on the geometry of bound states. However, the performed checks indicated that changing the radii of binding potentials does not influence the relative contribution of different direct process mechanisms.

A. ^{12}C(^{11}B,^{6}Li)^{17}O reaction

The results of calculations of the simultaneous transfer of five nucleons as an α particle and a neutron in the ^{12}C(^{11}B,^{6}Li)^{17}O reaction are presented in Fig. 3 for ^{11}B laboratory energy 40 MeV. The results obtained for 28 and 35 MeV energies are practically the same. The solid line representing the coherent sum of correlated (dashed line) and uncorrelated (dotted line) simultaneous transfers reproduces well the experimental angular distribution. The contribution of correlated transfer of a neutron and an α particle is by a factor of 3–4 larger than that of the uncorrelated one. Furthermore, it was checked that the dominating contribution originates from the transfer of a correlated pair of the neutron and the α particle with quantum numbers of ^{5}He in the ground or in the first excited state. Other correlated transfers are completely negligible due to very small spectroscopic amplitudes.

In the present analysis sequential transfers of a neutron and an α particle were also considered taking into account both possible sequences, i.e., ^{12}C(^{11}B,^{7}Li)^{16}O(^{7}Li,^{6}Li)^{17}O and ^{12}C(^{11}B,^{10}B)^{13}C(^{10}B,^{6}Li)^{17}O reactions. The solid circles in Fig. 3 show the contribution of the first sequence of transfers (i.e., α particle followed by neutron transfer) while the dot-dashed line represents the inversed sequence. These contributions were calculated for ground states of ^{7}Li, ^{13}C, and ^{16}O nuclei while the ground state the first (0.72 MeV) and the second excited (2.15 MeV) states of ^{10}B were taken into consideration with the spectroscopic amplitudes known from the literature. Thus the magnitude of two-step transfers of an α particle and a neutron (or vice versa) can be unambiguously ascertained for transitions via these states. As can be seen in Fig. 3 this sequential contribution to the cross section is almost two orders of magnitude smaller than the experimental data.

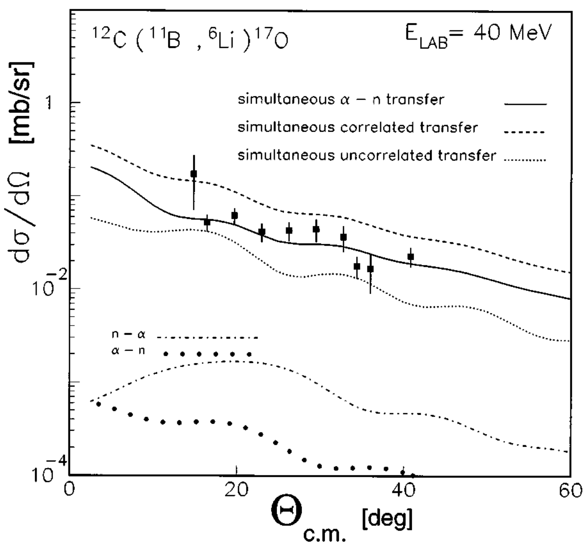

FIG. 3. Experimental angular distribution of the ^{12}C(^{11}B,^{6}Li)^{17}O reaction at $E_{\rm lab}$(^{11}B) = 40 MeV and theoretical angular distributions of simultaneous and sequential transfer of a neutron and an α particle. The dashed line corresponds to correlated simultaneous transfer, the dotted line represents uncorrelated simultaneous transfer, and the solid line shows their coherent sum. Solid circles present the two-step contribution of sequential α-particle and neutron transfer while the dot-dashed line corresponds to sequential transfer of a neutron followed by that of an α particle. The sequential contributions presented here were calculated taking into account only the ground state of ^{13}C and ^{16}O nuclei in the intermediate channels (see text).

While an unambiguous determination of the sequential transfer contribution via ^{7}Li + ^{16}O and ^{10}B + ^{13}C intermediate channels with excited states of ^{13}C and ^{16}O is not conceivable, it is possible to do a realistic estimation of the upper limit of this effect. This was achieved in the following way: The excited states of ^{16}O which are important for the sequential reaction ^{12}C(^{11}B,^{7}Li)^{16}O(^{7}Li,^{6}Li)^{17}O must be strongly populated in the single-step α-particle transfer ^{12}C(^{11}B,^{7}Li)^{16}O reaction. There are 6.13 MeV (3^-), 6.92 MeV (2^+), 10.36 MeV (4^+), and 11.10 MeV (4^+) states of ^{16}O (see spectra of ^{7}Li in Fig. 1 of the present paper). Similarly, using experimental information on the ^{12}C(^{11}B,^{10}B)^{13}C neutron transfer reaction [24], the excited states of ^{13}C, 3.09 MeV ($\frac{1}{2}^+$), 3.68 MeV ($\frac{3}{2}^-$), and 3.85 MeV ($\frac{5}{2}^+$), were selected as likely giving a large contribution to the sequential reaction ^{12}C(^{11}B,^{10}B)^{13}C(^{10}B,^{6}Li)^{17}O. The calculations of two-step transfers were performed assuming a unit value of the unknown neutron and α particle spectroscopic amplitudes of ^{17}O for the above-mentioned excited core nuclei.

It turned out that the contribution from sequential transfers proceeding via these states of intermediate partitions is several times smaller than the experimental data of the five-nucleon transfer reaction ^{12}C(^{11}B,^{6}Li)^{17}O. Taking into consideration the fact that the neutron and the α-particle spectroscopic amplitudes of the ^{17}O nucleus with the excited cores ^{16}O or ^{13}C are certainly smaller than unity, one can state that the sequential contribution is at least an order of magnitude smaller than the experimental data. Thus it can be treated as a small correction to the angular distribution of leading-simultaneous transfer of five nucleons.

The results of the calculations of the simultaneous transfer of five nucleons in the reaction ^{12}C(^{11}B,^{6}Li)^{17}O$_{\rm g.s.}$ are presented in Fig. 2 for three laboratory energies (30, 35, and 40 MeV). The cross sections resulting from simultaneous transfer of the neutron and the α particle (solid line) reproduce well the experimental angular distributions. The same relationship between magnitudes of correlated (dashed line) and uncorrelated (dotted line) transfers is preserved for all energies. Thus, the dominance of single-cluster transfer (^{5}He$_{\rm g.s.}$ and ^{5}He in the first excited state) seems to be established in this five-nucleon transfer reaction. It is, however, not allowed to neglect uncorrelated simultaneous transfer of the neutron and the α particle because its destructive interference with correlated transfer leads to a strong modification of the cross sections (more than a factor of 2). The shape of the angular distributions remains, however, practically not changed by the interference.

As was mentioned above the possible contribution from the compound nucleus mechanism should be checked in a model calculation. In our case of a ^{12}C + ^{11}B entrance channel system such calculations can be done in a very reliable way, since in a separate work [33] the compound nucleus reactions were studied carefully in measurements of many reaction channels, including also some light-heavy ejectile correlations, and analyzed in Hauser-Feshbach model calculations. Thus the parameters of the compound model could be easily transferred from this study to the Li case under consideration. The calculations were performed using the CASCADE code [34] with the Gilbert-Cameron parametrization of the level density distribution and spin cutoff and level density parameters taken from [33]. These calculations led to an estimation of the angle-integrated contribution of the compound nucleus reaction to the ^{6}Li cross section, with the ^{16}O residual nucleus in the ground state equal to 2 μb. Comparing this value with the one measured in the present experiment equal to 50 μb, in the angular range covered in the experiment, it is evident that the direct reaction mechanism is prevalently dominating in our case.

B. ^{12}C(d,^{7}Li)^{7}Be reaction

Calculations of the five-nucleon transfer reaction ^{12}C(d,^{7}Li)^{7}Be were performed along the same lines as those for ^{12}C(^{11}B,^{6}Li)^{17}O$_{\rm g.s.}$. The results of the calculations are shown in Fig. 4. In this case the difference between cross sections of the transfer of the proton-neutron correlated pair and the α particle is much larger than in the previous reaction. Namely, the cross sections for correlated transfer are more than order of magnitude larger than those for the uncorrelated one. The interference of transition amplitudes for both transfer mechanisms does not practically change the cross section of the leading process, i.e., the correlated simultaneous transfer. This is visible in Fig. 4 where the solid line shows the cross section obtained by summing all simultaneous transfer amplitudes while the dashed line represents the dominating contribution of correlated simultaneous transfer.

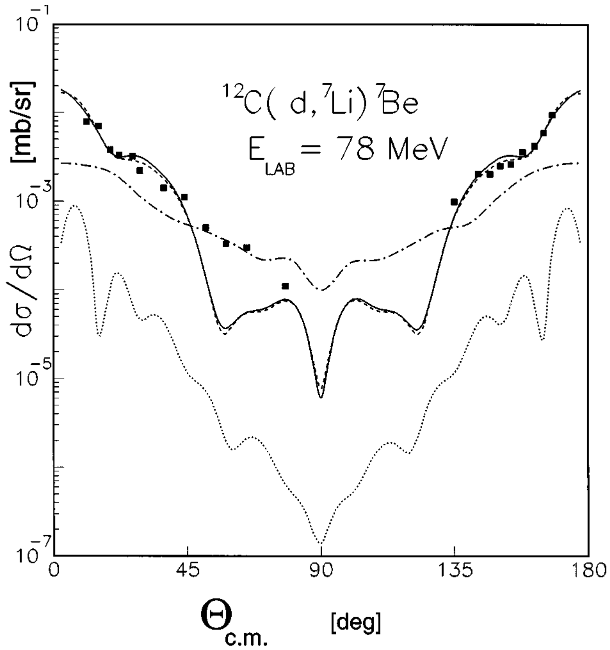

FIG. 4. Experimental angular distribution of the ^{12}C(d,^{7}Li)^{7}Be reaction at $E_{\rm lab}$ = 78 MeV and results of the calculation of simultaneous transfer of a neutron and an α particle (present work) and sequential transfer of these particles [7]. The dashed line corresponds to correlated simultaneous transfer, the dotted line represents uncorrelated simultaneous transfer, and the solid line shows their coherent sum. The dot-dashed line presents the two-step contribution of sequential α-particle and neutron transfer.

The experimental angular distributions as well as the theoretical curves exhibit symmetry around 90° in the c.m. system. This is due to the fact that only one value ($T=0$) of the isospin is present in the entrance channel and, further, the exit channel nuclei (^{7}Li and ^{7}Be) form an isospin doublet ($T=1/2$); thus they are identical from the point of view of the strong interaction. Therefore, the model DWBA amplitudes of proton + α-particle transfer and neutron + α-particle transfer should have the same values (apart from the mirror symmetry around 90°). This symmetry (predicted by the so-called Barshay-Temmer theorem [35]) is well preserved in the present calculations; thus it may be concluded that Coulomb effects, which break the symmetry, are very small in five-nucleon transfer.

The present analysis shows that the experimental angular distributions of ^{12}C(d,^{7}Li)^{7}Be can be well reproduced by correlated transfer of five nucleons corresponding to the ^{5}He cluster at forward scattering angles and the ^{5}Li cluster at backward angles. It should be noted that the very good agreement in the neighborhood of 0° and 180° deteriorates for angles closer to 90°. This is not accidental but reflects the contribution of another mechanism, namely, sequential transfer of the nucleon and the α particle. Calculation of this two-step contribution to the reaction under consideration was published in Ref. [7]. The sequential processes result in angular distributions which are less steep than the simultaneous (single-cluster) transfer angular distributions and therefore they are only a small correction to the one-step transfer for angles in the neighborhood of 0° and 180° but start to dominate for angles closer to 90°. As was shown in Ref. [7] the interference of simultaneous and sequential contributions does not influence significantly the angular distributions.

IV. SUMMARY AND DISCUSSION

In the present work the mechanism of five-nucleon transfer was studied for two nuclear reactions $^{12}C(^{11}B,^{6}Li)^{17}O_{g.s.}$ and $^{12}C(d,^{7}Li)^{7}Be$. Since the performed calculation of the compound nucleus contribution to the (^{11}B, ^{6}Li) reaction indicated the prevailing dominance of the direct reaction mechanism, the basic assumption was accepted in the theoretical analysis that five nucleons are transferred between target and projectile. Such a process was treated as a correlated or uncorrelated transfer of a nucleon and an α particle.

It was found that the experimental angular distributions can be well described by the present model and that simultaneous transfer of the α particle and the nucleon dominates in these both reactions. Moreover, the largest contribution corresponds to the transfer of the α-particle and the nucleon correlated to the ^{5}He or ^{5}Li in the ground state or the first excited state. The contribution of other processes to the cross section is several times smaller; however, due to interference, it cannot be neglected.

In the case of $^{12}C(^{11}B,^{6}Li)^{17}O_{g.s.}$ the cross section for the simultaneous transfer of the uncorrelated pair of the proton and the α particle is 3–4 times smaller than the leading correlated transfer process. Sequential (two-step) processes have a very small cross section, almost two orders of magnitude smaller than that of simultaneous transfer.

A different situation appears in the $^{12}C(d,^{7}Li)^{7}Be$ reaction. In this case simultaneous transfer of the uncorrelated pair of the α particle and the neutron (or proton) is two orders of magnitude smaller than the leading process of correlated (^{5}He or ^{5}Li) transfer. Thus the uncorrelated simultaneous transfer may be completely neglected. It turned out, however, that in this case sequential transfer of both particles is quite important [7], especially at scattering angles in the neighborhood of 90° (in the c.m. system), where cross sections of the sequential mechanism surpass those of simultaneous transfer.

It is interesting to compare the results of the present study with the conclusions of the investigation of the (proton–α-particle) transfer reaction $^{16}O(^{11}B,^{16}O)^{11}B$ published in Ref. [23]. It seems that five-nucleon transfer in the $^{11}B+^{16}O$ system exhibits the same features as theq $^{12}C(^{11}B,^{6}Li)^{17}O_{g.s.}$ reaction, i.e., the dominance of correlated simultaneous transfer of the nucleon and the α particle (forming $^{5}He/^{5}Li$ in the ground or the first excited state) with a smaller but significant contribution of uncorrelated simultaneous transfer while the sequential (two-step) mechanism may be neglected.

In summary, five-nucleon transfer in all discussed the above reactions can be well described by a model treating the group of five nucleons as consisting of two structureless parts, i.e., nucleon and α-particle cluster. Simultaneous correlated transfer dominates in all cases, implying that transfer of the entire (^{5}He and/or ^{5}Li) cluster in the ground and/or in the first excited state is the leading process. The contributions of other possible mechanisms, i.e., uncorrelated simultaneous transfer or sequential transfer of two clusters, are several times smaller. They are, however, non-negligible since they can (due to the interference) significantly influence the resulting cross section. The interference seems to be especially pronounced (and destructive) for correlated and uncorrelated simultaneous transfer.

It should be emphasized that a good description of all reactions investigated in the present work was achieved without introducing free parameters. This strongly supports the obtained implication of the presence of $^{5}He/^{5}Li$ clusterization in the light nuclei.

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