STUDY OF THE MECHANISM OF THE FIVE-NUCLEON TRANSFER REACTION $^{12}C(^{13}C, ^{8}Be)^{17}O$*

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Excitation functions (E_{cm} = 13.4 – 16.8 MeV) and angular distributions (E_{cm} = 13.8 and 16.38 MeV) of $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction have been measured and analysed by means of statistical and direct reaction mechanism models. The direct reaction analysis includes one and two step processes. For this purpose measurements and analyses were also performed for the reactions $^{12}C(^{13}C, ^{9}Be)^{16}O$ (at E_{cm} = 13.8 MeV) and $^{16}O(^{9}Be, ^{8}Be)^{17}O$ (at E_{cm} = 10.3 and 12.8 MeV). The results were used to estimate the magnitude of the direct two-step (n-^{4}He) and (^{4}He-n) transfers in the $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction. These two-step transfers as well as the compound nucleus mechanism, account only for approximately 10% of the experimental cross sections. Thus a dominance of the one-step five-nucleon transfer is concluded. Estimates of the direct ^{5}He-cluster transfer describe the data qualitatively.

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1. Introduction

A variety of investigations has been performed in recent years to study five-nucleon transfer reactions [1–13]. Most of them were induced by light particles: protons [1–3], deuterons [4–8] or alpha particles [9]. Investigations of heavy-ion induced reactions are rather scarce [10–13]. All of these works report an important contribution of a direct reaction mechanism and some of them, e.g. [8, 11], demonstrate a preferential one-step reaction

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mechanism with a transfer of five nucleons. This interesting result shows that the concept of a multinucleon direct transfer may be applied to groups of nucleons heavier than alpha particles.

There still remains, of course, the one question whether the five nucleons are transferred as an uncorrelated group or as ^{5}He- or ^{5}Li-cluster.

The aim of the present work is to investigate the mechanism of the $^{12}C(^{13}C, ^8Be)^{17}O$ reaction. This reaction is a promising candidate for the observation of a one-step five-nucleon transfer because both in the target system $^{12}C+^{17}O$ [10, 11] and in the projectile system $^{13}C+^8Be$ [13] a transfer of a ^{5}He-cluster seems to occur with a significant probability. There are, however, various possible competing mechanisms as e.g. two-step direct processes [12] or compound nucleus contributions [18]. Therefore, we performed a series of measurements and gathered all the data which are necessary to estimate reliably the contributions of the two-step direct processes and of the compound nucleus reactions. The experimental procedure is described in the second chapter of this paper while the theoretical analyses based on compound nucleus and direct reaction models are presented in the third and fourth chapters, respectively.

2. Experimental procedure and results

The measurements were performed at the tandem accelerator of the ETH Zürich. A sputter type negative ion source provided the ^{9}Be, ^{12}C, and ^{13}C beams used in the experiment [14], while ^{16}O ions were produced in a duoplasmatron source. In order to cover the whole angular region from 15° to 165° in the cm system by measurements at angles in the forward hemisphere only, the target and beam nuclei were interchanged. The beam was focused onto a target placed in the middle of a large (70 cm diameter) scattering chamber.

The ^{8}Be ions emitted as reaction products were detected in three counter pairs measuring in coincidence the α-particles from the decay of ^{8}Be [15]. The counters were placed at 15° intervals and rotated simultaneously to cover the angular region from 8.5° to 65° in 1.5° steps. The energy resolution was sufficient to resolve peaks in the ^{8}Be spectra corresponding to the transitions to the ground state and to the first 0.875 MeV excited state of the residual ^{17}O nucleus. The absolute values of the cross sections were calculated using the counter efficiency determined by a Monte Carlo method [16].

The ^{9}Be particles in the $^9Be+^{16}O$ exit channel were detected in four $\Delta E-E$ telescopes. In three of these telescopes the semiconductor detectors with thickness of 8.7 μm, 10.3 μm and 14.4 μm were applied as ΔE counters. In one telescope, placed at extreme forward angles, an ionisation chamber [17] was used as ΔE detector in order to avoid the damage of the semiconductor transmission detector by a high rate of elastically scattered particles.

Table I gives a compilation of information on the performed experiments. The angular distributions for all the reactions under investigation were measured at two energies. Apart from the angular distributions the excitation curves were also measured for the $^{12}C(^{13}C, ^8Be)^{17}O$ reaction in order to get information on the compound nucleus contribution.

TABLE I

List of the experiments performed; angular distributions and excitation functions

Entrance channel		Exit channel				
target	beam					
			Angular distributions			
			beam energy MeV lab	θ_{min}	θ_{max}	$\Delta\theta$
				lab system		
^{12}C	^{13}C	$^{8}Be+^{17}O$	28.77	10.0°	58.0°	1.5°
			33.99	8.5°	56.5°	1.5°
^{13}C	^{12}C		26.56	10.0°	56.5°	1.5°
			31.33	8.5°	53.5°	1.5°
^{9}Be	^{16}O		28.67	9.0°	59.0°	2.0°
			35.60	10.0°	55.0°	2.5°
^{16}O	^{9}Be		16.12	11.0°	65.0°	2.0°
			20.00	10.0°	55.0°	2.5°
^{12}C	^{13}C	$^{9}Be+^{16}O$	28.77	10.0°	64.0°	1.0°
^{13}C	^{12}C		26.56	10.0°	64.0°	1.0°
			excitation curves			
			θ lab	E_{min} MeV	E_{max} MeV	ΔE MeV
^{12}C	^{13}C		20°	27.91	33.96	0.42
			35°			
			50°			
^{13}C	^{12}C		20°	25.77	31.9	0.38
			35°			
			50°			

The absolute normalization of the cross section was obtained from the comparison with elastic scattering in the entrance channel. The error bars attached to the experimental points contain the statistical errors of the individual cross section only. The error of the absolute normalization is estimated to be 7%.

3. Compound nucleus contribution

The entrance energy in the $^{12}C+^{13}C$ system used in the present work is not high enough to neglect contributions to the cross section from compound nucleus formation. Indeed, strong fluctuations of the cross sections have been found in several investigations of reactions involving the $^{12}C+^{13}C$ system [18–25]. Therefore, in the present study an estimate of the magnitude of the compound nucleus contribution to the reaction under investigation

was performed. This was done in two independent ways, namely a) by statistical analysis of the $^{12}C(^{13}C, ^{8}Be)^{17}O$ excitation functions measured in the present work and b) by Hauser-Feshbach model calculations with parameters taken from the literature.

3.1. Statistical analysis of the excitation functions

The phenomenological formula given in the Ref. [26]

$$\Gamma(\text{MeV}) = 14 \exp(-4.69(A/E_{\text{exc}})^{1/2}),$$

where A corresponds to the mass number and E_{exc} (in MeV) to the excitation energy in the compound system, gives an average coherence width of $\Gamma = 185-285$ keV for the $^{12}C+^{13}C$ system in the energy range studied in the present work. Therefore, a statistical analysis of excitation functions measured in energy steps of $E_{\text{cm}} = 200$ keV, comparable with the coherence width, should provide meaningful information. Nevertheless, as a first step of the analysis Γ has been estimated in two ways in order to check the applicability of statistical methods to these data: the coherence width Γ was determined by the counting-of-maxima method and from the shape of the autocorrelation functions.

The counting-of-maxima method [27] estimates the coherence width Γ from the number k of maxima in the excitation function in the unit energy interval: $\Gamma = 0.55\, b/k$ where b is a correction factor for the finite energy step in the measurement of the excitation functions. In our case b is equal to 0.6 ± 0.1 [28].

The autocorrelation function method is based on the fact that the expected shape of the autocorrelation function $R(\varepsilon)$ is given by the formula [29]:

$$R(\varepsilon) = \frac{\Gamma^2}{\Gamma^2+\varepsilon^2} R(0),$$

where the autocorrelation function $R(\varepsilon)$ is defined as

$$R(\varepsilon) = \left\langle \left(\frac{\sigma(E)}{\langle \sigma(E) \rangle} - 1 \right) \left(\frac{\sigma(E+\varepsilon)}{\langle \sigma(E+\varepsilon) \rangle} - 1 \right) \right\rangle .$$

Here $\sigma(E)$ is the differential cross section at the energy E and "$\langle\ \rangle$" denotes energy averaging. The outer averaging has to be performed over the total energy interval considered, while the inner averaging of the cross sections should be done over a smaller energy interval, which is, however, big enough to smooth out the fluctuations of the cross section. In the present calculations a double running arithmetic average over 5 points (1 MeV) has been applied.

The values of the coherence width thus determined are 230 ± 40 keV for the maximum counting method and 225 ± 80 keV for the autocorrelation analysis. These values were averaged over all excitation functions and were corrected for finite range of the data, finite step of the energy and finite energy resolution according to prescription given in Ref. [30]. The coherence widths from the statistical analysis are in good agreement with those calculated from the phenomenological formula; thus we applied statistical methods in the further analysis of the present data.

TABLE II

Direct reaction contribution to the cross section estimated by means of two methods: statistical analysis of excitation curves (ST) and by subtracting the cross section of Hauser-Feshbach model from the energy averaged experimental cross section (HF)

Exit channel	θ_{CM}	N_{eff}	y_D(ST)	y_D(HF)
$^8Be+^{17}O_{GS}$	42°	4	0.90	0.92
	73°	6	0.82	0.94
	106°	6	0.88	0.95
	113°	6	0.95	0.91
	142°	4	0.93	0.89
$^8Be+^{17}O_{0.87}$	42°	1	0.97	0.96
	73°	2	0.84	0.96
	85°	2	0.90	0.91
	106°	2	0.90	0.92
	113°	2	0.95	0.96
	142°	1	0.97	0.87

The autocorrelation coefficient $R(0)$ for each excitation function gives the direct reaction contribution y_D to the cross section ($y_D = \sigma_D/\langle\sigma\rangle$):

$$R(0) = \frac{1-y_D^2}{N_{eff}},$$

where N_{eff} is the so called "effective number of independent basic cross sections" [29], which may be calculated on the basis of the Hauser-Feshbach model [18]. Here it is estimated by interpolation between the minimal and maximal values at 180° and 90° cm respectively. The values of y_D obtained in this analysis are listed in Table II together with the number of independent basic cross sections used in the calculations. It is seen that the direct reaction mechanism clearly dominates the experimental data under investigation; in average it accounts for about 90% of the cross sections. We thus conclude that the compound mechanism gives only a small part of the average cross sections but that it cannot be completely neglected because the interference with the direct reactions can give rise to significant fluctuations of the cross sections.

It is interesting to check whether the observed energy variations of the cross sections are consistent with pure statistical fluctuations alone or whether they indicate the presence of some nonstatistical resonant effects. To do this two different statistical methods have been applied: the analysis of the cross correlation coefficients C_{ij} and of the energy dependent deviation function $D(E)$.

The cross correlation coefficients are defined according to the formula:

$$C_{ij} = \frac{\left\langle \left(\frac{\sigma_i(E)}{\langle\sigma_i(E)\rangle} - 1 \right) \left(\frac{\sigma_j(E)}{\langle\sigma_j(E)\rangle} - 1 \right) \right\rangle}{R_i(0)^{1/2}\, R_j(0)^{1/2}}.$$

In the case of pure statistical cross sections they have a Gaussian distribution $f(C)$ with zero mean value and with standard deviation $s(C)$ corresponding to the finite energy range $E_{\min}$ to $E_{\max}$ of the data [31]:

$$s(C) = (\pi \Gamma_{\text{obs}}/2(E_{\max} - E_{\min}))^{1/2},$$

where Γ_{obs} is the coherence width derived from the autocorrelation analysis without the corrections discussed earlier. For the present experiment this formula yields the value

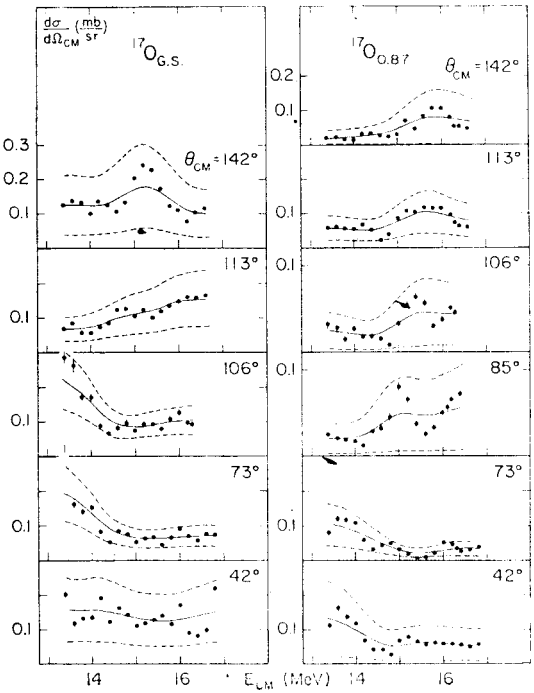

Fig. 1. The experimental excitation curves for the $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction leading to the ground and to the first excited states of ^{17}O. The full lines show the experimental average cross section (determined as double running arithmetic average over five points). The dashed lines present the range of expected fluctuations calculated as three standard deviations of the cross section (for a given constant y_d and N_{eff} listed in the Table II)

$s = 0.36$. The experimental histogram of the cross correlation coefficients is compared in the Fig. 2 with the theoretical probability distribution. The standard deviation 0.295 is in good agreement with the value estimated from the finite range of measurements. The experimental mean value of the cross correlation coefficients is 0.091 with an expected standard deviation of 0.041 (i.e. $0.295/(52)^{1/2}$ since 52 cross correlation coefficients were used in the present analysis). Therefore, we come to the conclusion that within a 1% significance level the individual excitation functions are not correlated.

A second method of looking for nonstatistical effects consists of the study of the energy dependent deviation function $D(E)$ given by:

$$D(E) = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{\sigma_i(E)}{\langle \sigma_i(E) \rangle} - 1 \right)$$

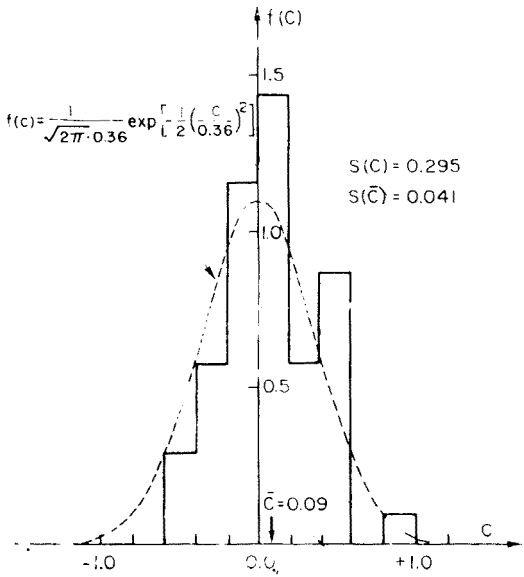

Fig. 2. Experimental histogram of cross correlation coefficients compared with a Gaussian probability distribution f(C) with zero mean value and standard deviation estimated from the finite range of the data as $s = 0.36$

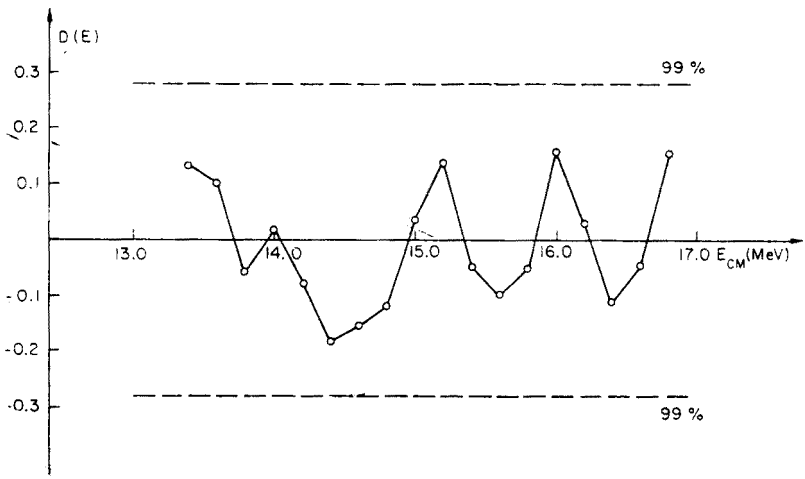

Fig. 3. Experimental energy dependent deviation function $D(E)$ and its lower and upper 99% confidence limits estimated for pure statistical cross sections

the sum extends over N statistically independent excitation functions. The experimental deviation function is presented in Fig. 3 together with the upper and lower 99% confidence limits calculated according to [32] for pure statistical cross sections. As can be seen from the figure there is no evidence for the presence of correlated, nonstatistical structures.

3.2. Hauser-Feshbach model predictions

The Hauser-Feshbach theory of compound nucleus processes yields the energy averaged compound cross section of a given reaction in terms of some parameters varying rather smoothly from one nucleus to the other. The crucial parameters of the model are:

— transmission coefficients calculated e.g. from optical model potentials,

— level density parameters of the residual nuclei, i.e. the a-parameter giving the density of states at the Fermi energy and the so called spin cut-off parameter σ^2,

— the fusion angular momentum l_{fus} i.e. the maximum value of the orbital angular momentum in the entrance channel which contributes to the formation of the compound nucleus.

Angular distributions can be calculated according to standard formulae which can be found in many references. In the present work we follow the parametrization of Ref. [33] taking similar values of the level density parameters as in Ref. [18] where the light particle exit channels of the $^{12}C+^{13}C$ system have been studied at energies close to those used in the present study. Optical model parameters were taken from the Perey-Perey compilation [34], l_{fus} was fixed at 7 or 8 for $E_{cm} = 13.8$ or 16.3 MeV, respectively, and a-parameter was assumed as $A/7$ MeV^{-1} (A — mass number). It should be pointed out that also larger values of a-parameter could be encountered in literature e.g. 2.6–3.2 MeV^{-1} as used in Ref. [35] for ^{17}O what would lead to compound cross section considerable smaller than obtained in the present work.

The calculated compound cross sections σ_{HF} were subtracted from the averaged experimental cross sections $\langle\sigma_{exp}\rangle$ to obtain the direct processes contribution: $y_D \equiv (\langle\sigma_{exp}\rangle - \sigma_{HF})/\langle\sigma_{exp}\rangle$ in the $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction. These results are presented in Table II together with values obtained from the statistical analysis discussed earlier. The agreement of y_D from both methods is quite satisfactory. In summary we find by two independent methods, namely a statistical analysis of excitation functions and a direct Hauser-Feshbach calculation of the compound cross section, that the reaction is dominated by processes which are smoothly varying with energy. In addition the statistical analysis shows that no isolated resonances contribute to this exit channel. It is therefore natural to proceed on the assumption that these processes are given by direct reaction mechanisms, which will be calculated in the next sections. We then expect that the direct processes plus the energy averaged compound cross section should properly describe the averaged experimental data.

On the other hand a compound contribution of about 10% is not negligible and must result in fluctuations. We should therefore not expect to describe in the above way the nonaveraged cross sections in detail, neither the excitation functions nor the angular distributions. In the following sections we therefore give the range of possible fluctuations as determined from the statistical analysis.

Since the autocorrelation coefficient is defined as $R(0) \equiv \mathrm{var}\,(\sigma/\langle\sigma\rangle)$, the standard deviation of the cross sections from the average may be written as $(\mathrm{var}(\sigma))^{1/2} = \langle\sigma\rangle \times ((1-y_D^2)/N_{eff})^{1/2}$ where $y_D \equiv \sigma_D/(\sigma_D+\sigma_{HF})$.

To indicate the possible range of statistical fluctuations, in Figs 1, 5 and 10 the calculated 3 standard deviation upper and lower limits are shown as dashed lines.

4. Direct reaction cross sections

The aim of the present work is to investigate the existence of a direct one-step transfer of five nucleons in the $^{12}C+^{13}C$ system. Certainly the mechanism of a five-nucleon transfer must be very complicated. It could proceed as a transfer of a ^{5}He-nucleus in its ground or low excited state, for which a cluster transfer approximation may be useful. Or it might be better described as the simultaneous transfer of a neutron and an α-particle in various states of relative motion. At the moment we are not able to disentangle these various possibilities much less to calculate reliably their absolute magnitudes.

We therefore proceed the opposite route, namely by investigating as completely as possible all other contributing processes. The residual relative to the averaged experimental cross section should then be due to one-step five-nucleon transfer irrespective of its mechanism. Except for the averaged compound contribution the competing processes have to be higher order direct processes, where the five nucleons are transferred in sequential steps as smaller clusters. Here we have to make a subjective choice of the processes that are important. For the present case of transfer of 2 protons and 3 neutrons we assume, that sequential transfers of an alpha particle and a neutron are the dominant processes, where the α-transfer is described in the cluster approximation. These processes can be determined with reasonable certainty by an analysis of the reactions corresponding to the first and second steps of the two step processes. Therefore, in the present study the following procedure has been applied:

(*i*) The contribution of the compound nucleus mechanism was calculated using the parameters described in the previous section,

(*ii*) Two-step direct contributions to the cross sections were calculated using parameters from the analysis of the reactions corresponding to the first and the second step of two-step processes treating them as single step reactions. A neutron transfer followed by an alpha particle transfer and vice versa were assumed to be the leading two-step mechanisms,

(*iii*) A one-step five-nucleon transfer contribution was calculated in the ^{5}He-cluster approximation. As discussed above this is not supposed to prejudice the mechanism of the 5-nucleon transfer but only to give a simple model for it. The experimental data were then compared with the coherent sum of one- and two-step processes and the incoherent sum of the compound nucleus background.

The direct reactions taken into consideration in the present study correspond to transitions between the three partitions $^{12}C+^{13}C$, $^{16}O+^{9}Be$ and $^{17}O+^{8}Be$. In the analysis optical model parameters have been taken directly from the literature for similar reactions at similar energies. Thus no individual fit was made to our specific reactions what sometimes

results in a not optimal description of details of the data. In particular the following parameter choices have been made:

1) The optical potential of Chua et al. [36] was used for the $^{12}C+^{13}C$ channel with an additional linear energy dependence of the depth of the imaginary potential:

$U = 100$ MeV, $W = (-7.25+0.55\,E_{LAB})$ MeV,

$r_U = 1.16\,(A_1^{1/3}+A_2^{1/3})$ fm, $r_W = 1.35\,(A_1^{1/3}+A_2^{1/3})$ fm,

$a_U = 0.49$ fm, $a_W = 0.33$ fm.

The optical potential of Ungricht et al. [41], describing well the elastic scattering of ^{9}Be

TABLE III

Spectroscopic information on the orbitals of the transferred particles in the reactions studied. The spectroscopic factors not known from the literature were determined from a fit to the experimental data (are given in parentheses)

Nucleus	Core	Cluster	B.E. (MeV)	N	L	J	C^2S	Ref.
^{9}Be	^{8}Be	n	1.67	0	1	3/2	0.42	[43]
^{13}C	^{12}C	n	4.95	0	1	1/2	0.81	[38]
^{13}C	$^{12}C_{4.44}$	n	9.35	0	1	3/2	1.48 [a]	[38,44]
$^{13}C_{3.09}$	^{12}C	n	1.86	1	0	1/2	0.67 [b]	[38,45]
^{17}O	^{16}O	n	4.14	0	2	5/2	1.03	[46]
$^{17}O_{0.87}$	^{16}O	n	3.27	1	0	1/2	(0.94)	
^{12}C	^{9}Be	^{3}He	26.28	1	1	3/2	1.52	[47]
^{16}O	^{13}C	^{3}He	22.79	1	1	1/2	(0.24)	
^{12}C	^{8}Be	^{4}He	7.37	2	0	0	0.56	[48]
$^{12}C_{4.44}$	^{8}Be	^{4}He	2.93	1	2	2	(0.56) [c]	
^{13}C	^{9}Be	^{4}He	10.65	1	2	2	0.41	[48]
^{16}O	^{12}C	^{4}He	7.16	2	0	0	(0.18)	
^{17}O	^{13}C	^{4}He	6.36	1	3	3	(0.06)	
^{17}O	$^{13}C_{3.09}$	^{4}He	9.45	1	2	2	(0.06) [d]	
$^{17}O_{0.87}$	^{13}C	^{4}He	5.49	2	1	1	(0.09)	
$^{17}O_{0.87}$	$^{13}C_{3.09}$	^{4}He	8.58	2	0	0	(0.06) [d]	
^{13}C	^{8}Be	^{5}He	13.21	1	2	1/2	0.09	[49]
^{17}O	^{12}C	^{5}He	12.20	2	1	5/2	(0.09) [e]	
				1	3	5/2	(0.09) [e]	
$^{17}O_{0.87}$	^{12}C	^{5}He	11.33	2	1	1/2	(0.39)	

[a] Relative magnitude of spectroscopic amplitude for excited ^{12}C core (in comparison to ^{12}C core) was taken from [44].

[b] Relative magnitude of spectroscopic amplitude for excited $^{13}C_{3.09}$ (in comparison to $^{13}C_{gs}$) was taken from Ref. [45].

[c] The spectroscopic amplitude was assumed to be equal to that of $^{12}C_{gs}$.

[d] The spectroscopic amplitude was assumed to be equal to that of $^{17}O_{gs} = {}^{13}C_{gs}+{}^{4}He$.

[e] Equal spectroscopic amplitudes for $L = 1$ and $L = 3$ orbitals were assumed.

ions on light target nuclei was used for the $^{16}O+^{9}Be$ and $^{17}O+^{8}Be$ systems:

$$U = 60 \text{ MeV}, \qquad W = 32.6 \text{ MeV},$$

$$R_U = R_W = 1.1712\,(A_1^{1/3}+A_2^{1/3}) \text{ fm} \quad \text{for} \quad ^{16}O+^{9}Be$$

$$= 1.1725\,(A_1^{1/3}+A_2^{1/3}) \text{ fm} \quad \text{for} \quad ^{17}O+^{8}Be$$

$$a_U = a_W = 0.6 \text{ fm}.$$

2) Binding potentials for the transferred particles (neutron or cluster) to the corresponding cores were parametrized in Woods-Saxon form with the geometrical parameters $a = 0.65$ fm and $R = 1.25\,A_{\text{core}}^{1/3}$ fm for nucleons and $R = 1.25\,(A_1^{1/3}+A_2^{1/3})$ fm for heavier particles. The depths of the potentials were fitted to reproduce the corresponding binding energies.

3) Spectroscopic amplitudes for transfers were taken from the literature wherever possible and were otherwise fitted to the respective experimental angular distributions. The values of spectroscopic amplitudes used to calculate transfer processes are listed in Table III together with the information concerning the orbitals of the transferred particles.

All the DWBA calculations were performed by means of the exact finite range two-step DWBA code JUPITER-5 [11].

4.1. Two-step contribution to the five-nucleon transfer

The leading two-step processes assumed to contribute to the ^{5}He transfer are the sequential (n−^{4}He) and (^{4}He-n) transfers presented schematically in Fig. 4. They involve the following single-step reactions in the first and/or the second step: elastic or inelastic neutron transfer $^{12}C(^{13}C, ^{12}C)^{13}C$, neutron transfer $^{16}O(^{9}Be, ^{9}Be)^{17}O$, and alpha-particle transfers $^{12}C(^{13}C, ^{17}O)^{8}Be$ and $^{12}C(^{13}C, ^{1}Be)^{16}O$.

The $^{12}C(^{13}C, ^{17}O)^{8}Be$ reaction contributes also as one-step process to the backward angles of the five-nucleon transfer.

The first of these reactions, the elastic and inelastic transfer reaction in the system $^{12}C+^{13}C$, has been studied extensively in recent years [36–40], in particular with respect

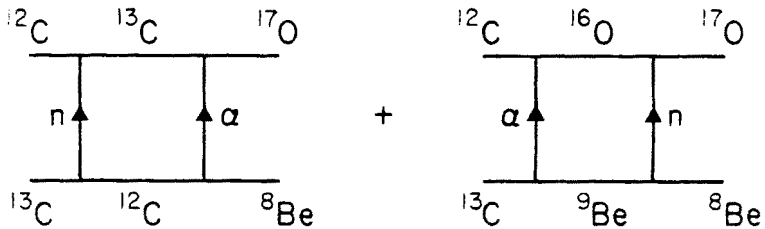

Fig. 4. Schematic graphs of two-step processes contributing to five-nucleon transfer reactions. In the calculations also the first excited states of ^{12}C and ^{13}C in the intermediate partition and the first excited state of ^{17}O in the exit channel partition were taken into account

to the possibility of molecular orbital formation [39, 40]. Rather strong evidence has been found for this at lower bombarding energies, using weakly absorbing optical potentials, although the description of the data was not always very good. At higher energies, such as the ones studied here, such effects should be less important. Data at higher energies,

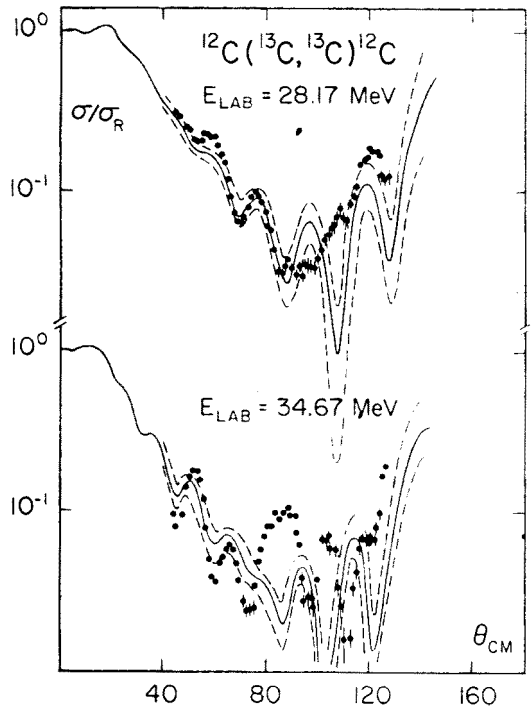

Fig. 5. Experimental cross sections (dots) and theoretical calculations (full line) for the $^{12}C+^{13}C$ scattering. The calculated curves are the coherent sum of potential scattering and elastic neutron transfer. The data are taken from Ref. [36] for two energies which are close to our bombarding energy. The range of expected fluctuations is shown by dashed lines

on the other hand, have been described by a coherent sum of potential scattering and one-step transfer, using a strongly absorbing potential [36]. The comparison of the experimental data [36] for two energies close to our bombarding energies with our calculations including fluctuations is given in Fig. 5. As it is seen there are deviations of the experimental cross sections from the calculation particularly in the interference region which are outside the range of expected fluctuations. These deviations are also seen in the calculations of Ref. [36] and could be removed by a detailed fit at our energy. However, the average magnitude of the cross section is described reasonably well, also in the backward hemisphere.

The neutron transfer reaction $^{16}O(^9Be, ^8Be)^{17}O$ was measured and analyzed in the present work. As can be seen from Fig. 6 the one-step transfer describes well the forward

peak of the angular distributions for the ground state as well as for the first excited state of ^{17}O with spectroscopic amplitudes which are in good agreement with those found in the literature. Due to the adopted optical potential the slope of the forward angular distributions is a little too large in the calculation. Again this could be improved by detailed fitting, but does not affect our conclusions. The backward angle cross section shows a rise

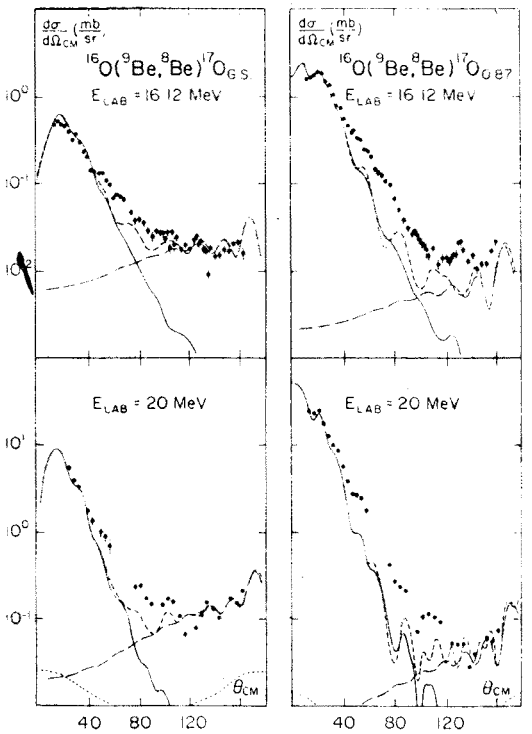

Fig. 6. Experimental and calculated cross sections for the $^{16}O(^{9}Be, ^{8}Be)$ reaction leading to the ground and to the first excited state of ^{17}O. The full line presents the neutron transfer reaction, the long-dashed line the ^{8}Be transfer, the short-dashed line — the sum of neutron and ^{8}Be transfer and the dotted line — the compound nucleus background. The transfer of ^{8}Be was normalized to the backward angle data by multiplying the DWBA cross sections by a product of spectroscopic factors equal to 0.537 for the ground state (the same for orbital $l = 1$ and $l = 3$) and equal to 0.72 for the first excited states

which is reproduced neither by one-step neutron transfer calculations nor by compound nucleus cross sections. It is possibly due to a double-^{4}He or a ^{8}Be transfer. In Fig. 6 a ^{8}Be-cluster transfer calculation with adjusted normalization has been fitted to the data giving reasonable overall agreement. Two-step ^{4}He transfer calculations $^{16}O(^{9}Be, ^{13}C)^{12}C(^{13}C, ^{17}O)^{8}Be$ with the normalization found below give cross sections which have a similar shape but are about three orders of magnitude smaller than the data. Since this contribution is not relevant for the reaction investigated here, the origin of this backward cross section was not investigated further.

For the alpha transfer reaction $^{12}C(^{13}C, ^{9}Be)^{16}O$ shown in Fig. 7 a ^{3}He transfer process $^{12}C(^{13}C, ^{16}O)^{9}Be$ has to be included at backward angles. The experimental angular distribution is strongly oscillating whereas both the alpha particle transfer and the ^{3}He transfer produce much smoother angular distributions. Oscillations occur due to the interference of the two processes but are found to be very sensitive to the details of these amplitudes. On the other hand, as shown in Fig. 8, the forward scattering angles corresponding to the alpha particle transfer are well described by the square of the Legendre polynomial of order eight. A similar observation, also shown in the figure, was made for this reaction at higher energies [42]. These features of the angular distributions indicate a somewhat

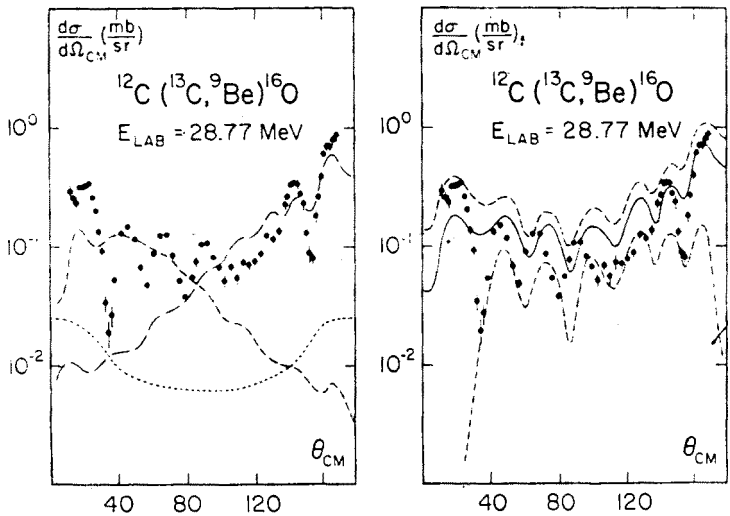

Fig. 7. Left hand side: Experimental data of the reaction $^{12}C(^{13}C, ^{9}Be)^{16}O$ compared with one-step ^{4}He transfer (short-dashed line), one-step ^{3}He transfer (long-dashed line) and compound nucleus background (dotted line). Right hand side: The full line presents the coherent sum of both one-step transfers with the incoherent compound nucleus contribution while the dashed lines define the range of expected fluctuations calculated as three standard deviations of the cross section (see Sect. 3.2)

stronger localization of the reaction than in the present calculations, which could possibly be improved by other parameter choices. At the present stage we are satisfied with the correct description of the magnitude and appropriate shape of the cross section.

The second alpha particle transfer $^{12}C(^{13}C, ^{17}O)^{8}Be$ corresponds to the backward angle region of the five-nucleon transfer reaction and also is one part of the two-step processes considered. It was analyzed as a one-step process. The results for the reaction leading to the ground state and to the first excited (0.87 MeV) state of ^{17}O are shown as one of the curves in Fig. 9 for the lower energy. They are the main contribution to the theoretical cross sections in the backward angle region of Fig. 10. This region is described fairly well with reasonable spectroscopic factors.

The analyses discussed in this Section describe reasonably well the magnitudes of all the one-step processes which constitute the first and/or the second step of the two-step

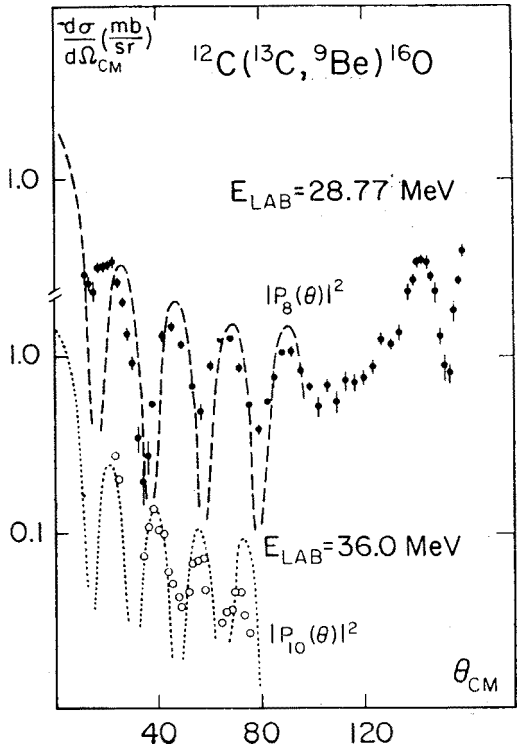

Fig. 8. Experimental data for the $^{12}C(^{13}C, ^{9}Be)^{16}O$ reaction from the present work (black dots) and from the Ref. [42] (open circles) compared with the squares of Legendre polynomials of order eight and ten, respectively

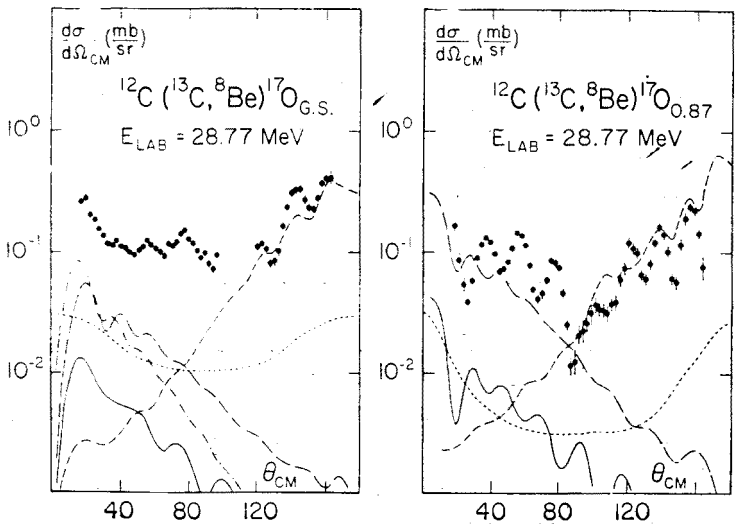

Fig. 9. Comparison of the experimental data for the $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction to the ground and to the first excited state of ^{17}O at $E_{lab} = 28.77$ MeV with theoretical cross sections calculated according to different reaction models: dotted line — compound cross section from the Hauser-Feshbach model; short-dashed line — ^{4}He one-step transfer, long-dashed line ($l = 1$) and dashed-dotted line ($l = 3$) — ^{5}He one-step transfer; full line — sum of contributions of two-step (n-^{4}He) and (^{4}He-n) processes

sequential transfer. Therefore we may expect to obtain a reliable estimate of the magnitude of the two-step contributions to the five-nucleon transfer. To achieve this the cross sections of two-step processes were calculated by means of the same DWBA computer program JUPITER-5 [11], with the same parameters of optical model potentials, binding potentials and spectroscopic amplitudes as those used in the description of one-step reactions. The

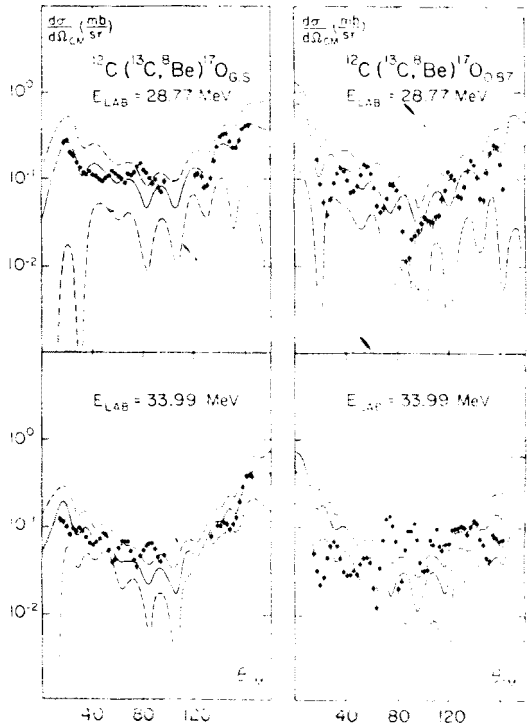

Fig. 10. Experimental and theoretical angular distributions for the $^{12}C(^{13}C, ^{8}Be)^{17}O_{gs}$ and $^{12}C(^{13}C, ^{8}Be)^{17}O_{0.87}$ reactions at the two energies E_{lab} = 28.77 MeV and 33.99 MeV. The full line presents the coherent sum of one-step ^{5}He transfer, one-step ^{4}He transfer and two-step (n-^{4}He) and (^{4}He-n) processes with the incoherent compound nucleus background. Dashed lines present the range of expected fluctuations of the cross section calculated as three standard deviations of the cross section

sum of the two-step contributions is shown in Fig. 9 together with the other contributions to the cross section. As can be seen, the two-step cross section is at least an order of magnitude smaller than the experimental data and is comparable in magnitude to the compound nucleus cross section. Therefore, one is led to conclude that the remaining part of the experimental cross sections is due to one-step direct transfer of the five nucleons, which is then the dominating mechanism in the $^{12}C(^{13}C, ^{8}Be)^{17}O$ reaction.

4.2. ^{5}He cluster transfer

The simultaneous transfer of five nucleons was treated in the present work as a ^{5}He-cluster transfer. As discussed above this is done to obtain a simple estimate of the magni-

tude and effect of this process. The calculations have been performed with the same parameters as the calculations for the other transfers of light particles. The calculated angular distributions are presented in Fig. 9 together with the experimental data and the contributions from the other reaction mechanisms. The spectroscopic amplitudes fitted for the ^{5}He-cluster transfer are listed in Table III.

We show in Fig. 10 the coherent sum of the contributions of the ^{4}He and ^{5}He transfers with those of the two-step (^{4}He-n) and (n-^{4}He) reactions and the incoherent compound nucleus background. It is seen from the figure that the one-step process improves significantly the description of the data using reasonable values of the spectroscopic amplitudes (comparable with the values of alpha particle spectroscopic amplitudes). The detailed shape of the angular distributions is not well described, but the angular oscillations are mostly within the range of the expected statistical fluctuations.

5. *Summary*

Angular distributions and excitation curves for the $^{12}C(^{13}C, ^8Be)^{17}O$ reaction have been measured and analyzed by means of statistical, compound nucleus and direct reaction mechanism models. In the analysis the emphasis was put on identifying and estimating the dominant contributing processes in this rather complicated reaction. An estimate of the contribution of compound reactions based on the statistical analysis of the excitation functions and on the Hauser-Feshbach model established a dominance (in average approximately 90%) of direct reaction processes.

A DWBA analysis was performed including one- and two-step transfer processes in order to understand this direct reaction contribution qualitatively without attempt to fit in detail the angular distributions. By measuring and fitting the reactions of the individual steps of the two-step processes $^{16}O(^9Be, ^8Be)^{17}O$, $^{12}C(^{13}C, ^{17}O)^8Be$, $^{12}C(^{13}C, ^9Be)^{16}O$ and $^{12}C(^{13}C, ^{12}C)^{13}C$, we have obtained an estimate of their magnitude using parameters known from other sources. Since this contribution accounts for only about 10% of the experimental cross section, we conclude that a dominant direct five-nucleon transfer is present. An estimate of this contribution in the cluster approximation yields a qualitative description of the data.

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