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STUDY OF THE ENERGY DEPENDENCE OF THE $^{16}O(d, {}^6Li)^{12}C$ REACTION

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Abstract: $^{16}O(d, {}^6Li)^{12}C$ reaction cross sections have been measured at incident deuteron energies of 80, 65, 60 and 50 MeV. The experimental angular distributions for the ground state transitions have been analyzed by finite range DWBA calculations, employing different values for the potential depths of the ^6Li optical potential. Alpha-transfer spectroscopic factors for the 0^+ ground state, for the 2^+ first excited and for the 4^+ state at 14.08 MeV in ^{12}C have been extracted. The variations of these spectroscopic factors are discussed in terms of an energy dependent optical model parametrization.

E | NUCLEAR REACTION $^{16}O(d, {}^6Li)$, $E = 80$, 65, 60 and 50 MeV; measured $\sigma(E_{^6Li}, \theta)$. Gas and solid NiO_2 targets. Finite-range DWBA calculations.

1. Introduction

Four-nucleon transfer reactions, e.g., (d, ^6Li) or the inverse (^6Li, d) reaction, have been used to study α-cluster spectroscopic factors in nuclei and to test theoretical shell-model and/or cluster-model predictions [1]). Generally, the experimental data are analyzed within the framework of a finite-range (FR) or zero-range (ZR) distorted wave Born approximation (DWBA). In an earlier paper [2]) the $^{16}O(d, {}^6Li)^{12}C$ reaction was investigated at a deuteron energy of 80 MeV and FR and ZR DWBA calculations were performed to extract α- spectroscopic factors for several transitions from ^{16}O to states in ^{12}C. It was found that:

(i) The empirical spectroscopic factors depend on the choice of the bound state radius parameters for both the four-nucleon cluster in the target nucleus and the α-d = ^6Li system;

(ii) the transition to an individual state in ^{12}C has its own optimum form factor radius parameter value for the best possible fit of the DWBA calculations to the experimental angular distribution; and (iii) the optimum choice of the bound state parametrization appears to be influenced by the optical-model potentials used. In addition, little is known about ^6Li optical model potentials.

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In a recent publication [3]) a search on the bound state radius parameter was presented, resulting in a consistent use of parameters for both the α-d and the α-core systems. Employing a radius parametrization of $R = r_0 (A_c^{\frac{1}{3}} + 4^{\frac{1}{3}})$, where $r_0 = 0.97$ fm and A_c denotes the mass of the core, the angular distributions of ground state transitions in the sd shell were well fitted with DWBA calculations. The corresponding α-spectroscopic factors agree reasonably well with shell-model predictions. The same bound state parametrization also works well for the (d, ^{6}Li) reaction on Cr isotopes [4]).

In this contribution we present results of (d, ^{6}Li) reactions, performed on ^{16}O at deuteron energies of 80, 65, 60 and 50 MeV. Restricting our changes of parameters for the FR DWBA calculations to the potential depths of the real and imaginary volume part of the ^{6}Li optical-model potential only, we study the energy dependences of the extracted α-transfer spectroscopic factors. An analysis only within the framework of the DWBA is presented, with the aim of obtaining a consistent description of the direct cluster transfer reaction mechanism. Second order processes are not regarded.

2. Experimental procedure

The four-nucleon pick-up reaction was performed with deuteron beams of the Jülich Isochronous Cyclotron JULIC at E_d = 80, 65, 60 and 50 MeV. The reaction products were detected by use of a conventional $\Delta E - E$ detector technique; two to four telescopes were used for the various experiments.

For the 80 MeV data, a gas target at 350 Torr was used. The data have been presented earlier [2]). Three small angle data points have been added, which were taken using a double-focusing magnetic analyzer of low dispersion [5]). A nickel oxide target was used for the experiments at 65, 60 and 50 MeV deuteron energy. It was prepared by surface oxidation on a thin nickel foil. The absolute cross sections for the 80 MeV data were determined as usual for gas targets. The amount of oxygen in the nickel oxide target was determined by normalizing 80 MeV data taken with the solid NiO_2 target at four different angles to the gas target data.

The relative cross sections of a measurement at one energy are believed to be more accurate than 10 %; for the relative cross sections of the measurements between different energies an error of 15 % is more realistic. The error for the absolute cross sections is less than 20 %. These values are appropriate as long as the statistical uncertainties, (as shown in the angular distributions) which are due to counting statistics and background subtraction only, are small.

An energy spectrum of the reaction $^{16}O(d, {}^6Li)^{12}C$ is shown in fig. 1 for the case of 60 MeV incident deuteron energy. The dominant feature of the ^{6}Li spectrum, as already observed in the case of 80 MeV deuteron energy, is the rather selective excitation of the 0^+, 2^+ and 4^+ states at 0.0, 4.44 and 14.08 MeV, respectively. Only

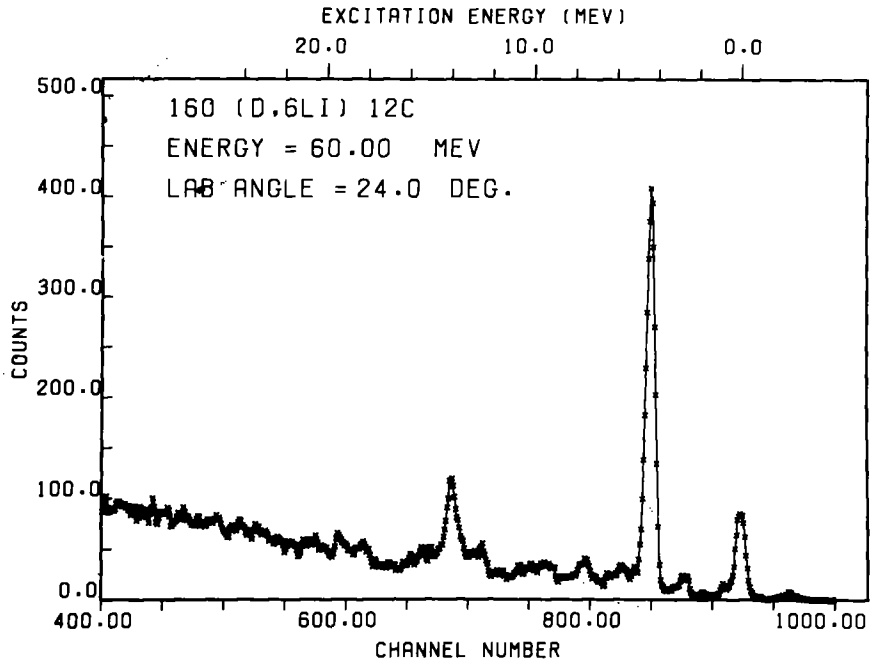

Fig. 1. Energy spectrum of the ^{16}O(d, ^{6}Li)^{12}C reaction at $E_d = 60$ MeV. The target was a nickel-oxide foil. Only the 0^+, 2^+, and 4^+ states at excitation energies as 0.00 MeV, 4.44 MeV, and 14.08 MeV in ^{12}C are studied. Other weakly excited states in ^{12}C and impurity peaks due to the natural nickel foil are observable in the spectrum.

these states are studied in the present investigation. Other weakly excited states in ^{12}C and impurity peaks from the natural nickel foil are observed in the spectrum.

3. DWBA analysis and results

The experimental angular distributions were compared to finite range distorted-wave-Born-approximation (FR DWBA) calculations to extract alpha-spectroscopic factors S_α. The DWBA code LOLA [ref. [6]] was used in the post representation. The spectroscopic factor S_α is defined, assuming the transferred four-nucleon cluster to be in a relative s-state, as:

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{exp} = N_1 S_\alpha (2L+1) W^2(l_1 j_1 l_2 j_2, s_x L) \left(\frac{d\sigma(\theta)}{d\Omega}\right)^{DWBA}_{LOLA},$$

where L denotes the angular momentum transfer and N_1 is the normalization constant. In principle N_1 should be unity in FR DWBA calculations. However, since the DWBA cross section is model and parametrization dependent and since a definite description of the ^{6}Li $\equiv \alpha + d$ system ($S_\alpha^{6Li} \leq 1$) is not available, we introduce the normalization constant into the present formula.

The bound-state wave functions for the transferred α-cluster were calculated in Woods-Saxon wells. If it is not otherwise explicitly stated, the number of radial nodes, N, in the cluster wave function was fixed by the relations $2N+L = 4$, and $2N+L = 2$ for the cluster in the target nucleus and the ^{6}Li particle, respectively. The potential depth of the Woods-Saxon well was adjusted to reproduce the α-particle separation energy. The radius was fixed at $R = 0.97\ (A_c^{\frac{1}{3}}+4^{\frac{1}{3}})$, with A_c denoting the core mass. The diffuseness used was 0.65 fm.

The deuteron optical-model potential was derived from the mass and energy dependent set of parameters from Childs *et al.* [7]). The radius parameter of the real volume potential was increased from 1.15 fm to 1.25 fm and the spin-orbit part of the potential was neglected. The influence of the deuteron spin-orbit part has been tested (using values as given in ref. [7])) and was found to be of minor importance. Furthermore, the rather small effects of increasing the radius parameter and neglecting the spin-orbit part cancel each other to some extent.

The ^{6}Li optical model parameters were chosen according to Chua *et al.* [8]), with Woods-Saxon real and imaginary volume parts. Radius and diffuseness parameters were held fixed. The depths of the real (V_R) and imaginary (W_I) potentials were varied as discussed below.

3.1. THE GROUND STATE TRANSITION

3.1.1. ^{6}Li optical-model potential depth. FR DWBA calculations were performed for the ^{16}O(d, ^{6}Li)^{12}C reaction using the ^{6}Li potential depths as given in ref. [8]), with $V_R = -214$ MeV and $W_I = -26.8$ MeV for all four energies investigated. The results of the calculations are shown by the dashed curves in fig. 2, together with the experimental data. These optical model parameters (potential set A, table 1)

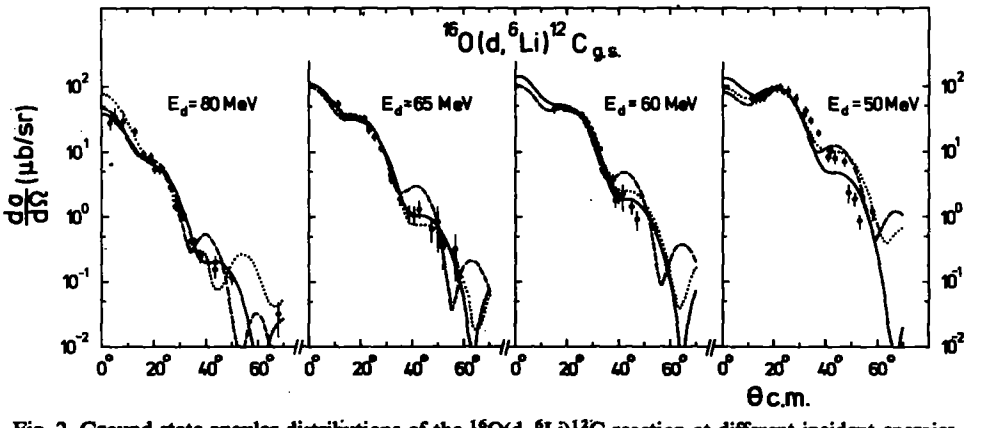

Fig. 2. Ground state angular distributions of the ^{16}O(d, ^{6}Li)^{12}C reaction at different incident energies. The theoretical DWBA curves were performed with the following ^{6}Li potentials: dashed lines: Potential set A in table 1. solid lines: Potential set B in table 1. dotted lines: Potential set D in table 1.

were used in an earlier publication [2]) for the reaction with 80 MeV deuteron beam and described the angular distributions rather well. We now employ a different bound state parametrization, following a more extensive study on the bound state radius parameter for sd shell nuclei [3]). The present calculations show more structure relative to the earlier analysis and too much structure relative to the data, as can be seen in fig. 2, dashed curve.

The potential depths V_R and W_I were then varied to obtain better fits to the angular distributions of the different ground state transitions. It was found that the 80, 65 and 60 MeV data could be fitted well with one constant potential set with $V_R = -179$ MeV and $W_I = -17.4$ MeV (potential set B). Results of FR DWBA calculations are shown by the solid curves in fig. 2. Only the 50 MeV data deviate significantly from the theoretical angular distribution shape for angles larger than 30° c.m. Even varying other ^{6}Li and deuteron optical-model parameters within reasonable limits gives no better fit to the ground state angular distribution of the 50 MeV data. As will be discussed later, it seems that DWBA calculations can not reproduce the experimental angular distribution shape for the $^{16}O(d, {}^6Li)^{12}C_{g.s.}$ reaction for low incident energies, ($E_d \lesssim 55$ MeV) as long as an angular range of up to $\sim 60°$ c.m. is

TABLE 1

The α-spectroscopic factors for the ground state transition at E_d = 80, 65, 60 and 50 MeV

^{6}Li potential	Incident deuteron energies				N_1S_α 80 MeV
	80 MeV	65 MeV	60 MeV	50 MeV	
A	1.0	1.31	1.46	1.38	1.30
B	1.0	1.69	2.08	2.00	0.36
C	1.0	5.13	7.33	9.65	0.11
D	1.0	0.98	0.99	0.97	0.67
E	1.0	1.83	2.49	3.65	0.39
B′	1.0	1.58	1.83	1.83	0.12
D′	1.0	0.92	0.93	0.98	0.23

^{6}Li optical potentials:

	V_R		W_I	dV_R/dE
A	−214		−26.8	0.00
B	−179		−17.4	0.00
C	−214	for $E_{^6Li}^{lab}$ = 50.6 MeV	−26.8	−3.00
D	−177	for $E_{^6Li}^{lab}$ = 78.0 MeV	−16.5	−0.86
E	−177	for $E_{^6Li}^{lab}$ = 98.0 MeV	−17.4	−0.86

In the last column the absolute extracted N_1S_α values are given. Radius and diffuseness parameters were used as given in ref. [8]), the depths of the real V_R and imaginary W_I potentials and the energy dependence dV_R/dE are listed. Potential sets B′ and D′ are the same as potential sets B and D, respectively, but using the Brown and Green wave function [15]) for ^{16}O.

regarded. It is interesting to note, that even though differing quality of fits to the experimental angular distributions is observed among the four energies investigated (see fig. 2), no significant difference can be observed in the spectroscopic factors extracted. The relative spectroscopic factors (normalized to 1.0 for the 80 MeV reaction) are listed in table 1 along with the "absolute spectroscopic factor" $N_1 S_\alpha$ for the 80 MeV case. For either of potential sets A and B the alpha-transfer spectroscopic factors extracted at different deuteron incident energies agree to within a factor of two. Taking into consideration the uncertainties involved in both the DWBA calculations and the data normalization, the agreement is acceptable; and there is no strong evidence for an energy dependence in the extracted spectroscopic factors.

Next, a possible energy dependence of the potential depths of the ^{6}Li optical-model potential is investigated. On the basis of elastic scattering cross sections energy dependences of "$dV_R/dE \leqq -4$" and "$dV_R/dE \sim -2$" have been suggested in refs. [8,9]). Spectroscopic factors extracted from FR DWBA calculations employing $dV_R/dE = -3$ (with $V_R = -214$ MeV and $W_I = -26.8$ MeV for $E_{^6\mathrm{Li}} = -50.6$ MeV [ref. [8])] are listed in table 1 (potential set C). This energy dependence results in a relative spectroscopic factor variation from 1 to $\sim$ 10, which is rather unphysical.

Finally we searched for a possible energy dependence of the real potential depth V_R, assuming a constant α-spectroscopic factor S_α for the ground state reaction at the four different incident energies. The potential depth V_R is taken to decrease with increasing energy, as is usual for optical-model parameters. An energy dependence of $dV_R/dE = -0.86$ seems to fulfill this aim, as can be seen in table 1, potential set D. For these DWBA calculations a potential depth of $V_R = -177$ MeV was used for the case of 65 MeV incident deuteron energy (i.e. a ^{6}Li equivalent laboratory energy of 78.1 MeV). The theoretical angular distributions are shown in fig. 2 by the dotted lines. However, it should be mentioned that, in the neighbourhood of the real well depth specified by this energy dependence, the shape of the $E_d = 80$ MeV DWBA angular distribution is much more sensitive to changes of the depth of the real potential than was otherwise observed. Using the same energy dependence but $V_R = -177$ MeV for the case of 80 MeV incident deuteron energy (potential set E in table 1) results in (i) a good fit to the 80 MeV data, (ii) poor fits to the other experimental angular distributions, and (iii) a relative spectroscopic factor, which increases significantly with decreasing incident energy.

A search on the imaginary potential depth was inconclusive. If there is an energy dependence of W_I it seems that $|dW_I/dE| \leqq 0.1$.

3.1.2. The case of $E_d = 50$ MeV. The ^{16}O(d, ^{6}Li)^{12}C reaction has been analyzed recently by two other groups [10,11]). One contribution [10]) is based on $E_d = 54.25$ MeV data and performs in principle the same kind of DWBA analysis as presented here. The other [11]) is based on $E_d = 35$ MeV data from the University of Michigan [12]) and involves both finite-range distorted wave and finite-range coupled-channel Born approximation calculations. Both of the investigations fail to describe the experi-

mental angular distribution shape. As mentioned above we cannot get a good fit to the present E_d = 50 MeV data either, at least not for reaction angles larger than 30° c.m. Possibly mechanisms other than the assumed direct cluster transfer mechanism become more important with decreasing energy.

The observed deterioration of the quality of DWBA fits with decreasing energy could lead to the assumption of compound nucleus contributions being of increasing significance relative to the direct transfer process. In the present case, however, there is no indication for this type of reaction mechanism: (i) The cross sections of the ^{16}O(d, ^{6}Li)$^{12}C_{g.s.}$ experiments presented here at different energies vary smoothly with the incident energy (even though closer energy steps might be desirable for this argument), and this is a typical indication in favour of a direct mechanism as opposed to a compound mechanism. (ii) Both deuteron and ^{6}Li energies are much larger than the nucleon binding energy. (iii) Large angle ^{16}O(d, ^{6}Li)^{12}C data [2]) for 80 MeV deuteron energy gave no indication for significant compound nucleus contributions. (iv) Even through, with respect to absolute magnitude, no reliable compound nucleus reaction calculations are feasible up to date (because of the strong negative reaction Q-value numerous reaction channels are open before the ^{6}Li emission), no reasonable shape of a compound nuclear angular distribution was obtained, which would improve the fit of the theoretical curves to the experimental data, when adding direct and compound part incoherently.

The analysis as performed was based on a simple 1s configuration for the relative motion of α-particle and deuteron in the ^{6}Li ion. Taking a $\sim$ 25 % 0D contribution of the spectroscopic amplitude for the ^{6}Li into account [13]), does not influence

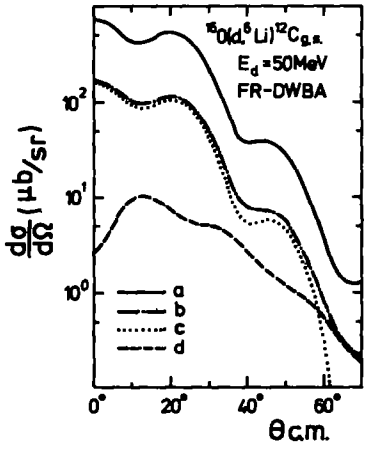

Fig. 3. Finite-range DWBA calculations performed with: *curve (a)* (solid line): ^{16}O ground state wave function according to Brown and Green [15]); 1S and 0D contributions to the relative α-d = ^{6}Li motion according to ref. [13]); *curve (b)* (dashed dotted line): ^{16}O ground state wave function assumed in the closed p-shell limit; 1S and 0D contributions to the relative α-d = ^{6}Li motion according to ref. [13]); *curve (c)* (dotted line): as curve b, but only the 1S contribution to the relative α-d motion; *curve (d)* (dashed line): as curve b, but only the 0D contribution to the relative α-d motion.

either the shape or the amplitude of the FR DWBA angular distribution drastically, as can be seen in fig. 3. The calculations in this figure were performed with the FR code DWUCK5 [14]), which gives essentially the same angular distribution shape as the FR code LOLA [ref. [6])], but differs in absolute magnitude by about 20 %. The dotted curve in fig. 3 is the result for a pure 1S, the dashed curve for a pure 0D ^{6}Li configuration, with spectroscopic amplitudes of 0.97 and −0.23, respectively. The dashed-dotted curve results from a coherently summed calculation of both contributions. Comparison of this curve with the E_d = 50 MeV angular distribution in fig. 2 (not shown here, but note that the solid curve of fig. 2 is the same as the dotted curve in fig. 3) shows that the neglect of the 0D state of ^{6}Li seems not to be responsible for the poor fit obtained for the E_d = 50 MeV case.

Finally, fig. 3 presents a coherent FR DWBA calculation (DWUCK5), which takes into account the ^{16}O ground state wave function according to Brown and Green [15]) and the 1S and 0D components of ^{6}Li according to Werby *et al.* [13]). No significant change is seen in the angular distribution shape, but a large increase of the absolute magnitude can be observed.

The question of the deterioration of DWBA fits with decreasing energy remains open. Other effects than described by the cluster approach, or more complicated reaction processes, might be responsible.

3.1.3. Influence of the ^{16}O ground state wave function. In fig. 3 it is shown that DWBA calculations including 2p-2h and 4p-4h components of the ^{16}O ground state wave function [15]) (solid line) have essentially the same angular distribution shape as DWBA calculations based on a closed shell assumption (dotted line).

Extracted spectroscopic factors obtained from FR DWBA calculations (code LOLA) including sd shell contributions in the ^{16}O ground state [15]) are given in table 1, using potential sets B′ and D′, which are the same as the optical-model potential sets B and D, respectively. Quite reasonably, inclusion of the more sophisticated ^{16}O wave function, has no significant influence on the relative spectroscopic factors for the ground state transitions. The absolute spectroscopic factors decrease by a factor of about three.

In an earlier publication [3]), based on the same kind of parametrization of the FR DWBA analysis presented here, good agreement between "absolute" experimental and shell-model predicted spectroscopic factors in the sd shell was found with the normalization factor, N_1, being close to unity.

The theoretical α-spectroscopic factor for the ground state transition ^{16}O → ^{12}C has been predicted [16]) (in the limit of the full 0p shell-model space) to be 0.235. The extracted "absolute" experimental spectrosopic factors, $N_1 S_\alpha$, are given in the last column in table 1. Since the theoretical absolute spectroscopic factor increases slightly [17]) whereas the experimental one decreases when including sd shell contributions to the ground state of ^{16}O, the spectroscopic factor obtained from the analysis using potential set D (table 1) seems to be quite realistic. Furthermore, this potential set resulted in a constant relative experimental spectroscopic factor for the different incident energies.

3.2. THE TRANSITION TO THE 2^+ STATE AT 4.44 MeV

Using the ground-state-transition results of the previous sections as a guide, the transition to the 2^+ state at 4.44 MeV in ^{12}C has been investigated. Five different ^6Li optical potentials were tried for the FR DWBA calculations: (i) Potential set B with constant $V_R = -179$ MeV and $W_I = -17.4$ MeV (see table 1). (ii) Potential set C with $V_R = -214$ MeV for $E^{lab}_{^6Li} = 50.6$ MeV, $dV_R/dE = -3.0$, and a constant $W_I = -26.8$ (see table 1), which resulted in a strong variation of the ground state spectroscopic factor at the different incident energies. (iii) Potential set D with $V_R = -177$ MeV for 78.1 MeV ^6Li laboratory energy, $dV_R/dE = -0.86$ and $W_I = -16.5$ MeV (see table 1). (iv) Potential set F with $V_R = -177$ MeV and $W_I = -17.4$ MeV for the ground state transition at all energies and $V_R = -182.8$ MeV and $W_I = -17.4$ MeV for all of the transitions to the 2^+ state. (v) Potential set G with the energy dependence of set B of table 1 but employing the same potential strength for both the transition to the ground state and to the 2^+ state at 4.44 MeV at the individual incident energies. In fig. 4 the experimental angular distributions for the transition to the 2^+ state are compared to FR-DWBA calculations which use potential set B (solid lines) and potential set D (dashed lines). In table 2 the relative spectroscopic factors ($S_\alpha(L = 2)/S_\alpha(L = 0)$) are listed, using the normalization between experimental data and theoretical curves shown in fig. 4. It is understood that (especially in cases where the agreement between the theoretical DWBA curves

TABLE 2

Relative alpha spectroscopic factors ($S_\alpha(L = 2)/S_\alpha(L = 0)$) for the transition to the 2^+ state at 4.44 MeV in ^{12}C extracted for the measurements at $E_d = 80$, 65, 60, and 50 MeV

^6Li potential	Incident deuteron energies				a)
	80 MeV	65 MeV	60 MeV	50 MeV	
B	6.06	4.85	3.68	3.54	2.52
C	5.19	4.09	3.65	4.12	1.54
D	3.61	3.90	3.67	3.37	0.53
F	5.51	3.06	3.78	3.42	2.09
G	3.49	4.65	3.88	3.18	1.47
B′	4.25	3.28	2.68	2.77	1.57
D′	2.53	2.91	2.62	2.55	0.38

^6Li optical potential depths:

B, C, and D as given in table 1.

F: $V_R = -177.0$ MeV for all ground state transitions and $V_R = -182.5$ MeV for all transitions to the 2^+ state at 4.44 MeV in ^{12}C; $W_I = -17.4$ MeV.

G: for both the ground state transition and the transition to the 2^+ state at 4.44 MeV in ^{12}C the same potential strength at one incident energy: $V_R = -177.0$ MeV for $E^{lab}_{^6Li} = 78$ MeV, $W_I = -16.5$ MeV, and $dV_R/dE = -0.86$; same as potential set D in table 1. Potential sets B′ and D′ in table 1.

a) Difference of the maximum and minimum relative spectroscopic factors for one kind of potential.

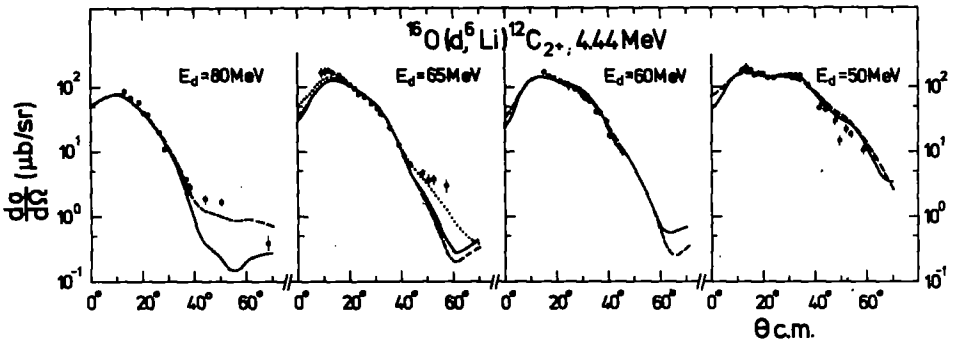

Fig. 4. Angular distributions for the transition to the 2^+ state at 4.44 MeV in ^{12}C for different incident energies. The theoretical DWBA curves were performed with ^{6}Li potentials: solid lines: Potential set B in table 2 and table 1; dashed lines: Potential set D in table 2 and table 1; the dotted line for the case of E_d = 65 MeV includes the ^{16}O ground state wave function according to Brown and Green [15]) and 1S plus 0D contributions to the relative α-d = ^{6}Li motion according to ref. [13]), else potential set D in table 1.

and the experimental angular distribution shapes is rather poor) the determination of both the relative and the absolute spectroscopic factors have a fairly large uncertainty. But only a variation within a factor of two is observed among the relative spectroscopic factors ($S_\alpha(L = 2)/S_\alpha(L = 0)$) extracted by employing the ^{6}Li optical potential sets B, C, D, F, and G (see table 2). Note, for example, that the relative ground state spectroscopic factors extracted with potential set C (table 1) varied by almost a factor of ten. As was observed in the case of the ground state transition, again the relative spectroscopic factors extracted using potential sets D and D′ lead to the most consistent results with respect to a constant relative alpha spectroscopic factor (see table 2 last column).

In fig. 4 it can be seen that for the 80 MeV deuteron incident energy the quality of the fit using the ^{6}Li potential set D is somewhat better than the one using potential set B, whereas no clear distinction can be made in the other cases. The shape of the 2^+ state angular distribution for the 50 MeV deuteron data is in fairly good agreement to the theoretical curves, in contrast to the equivalent ground state transition. The two previously cited investigations [10,11]) on the $^{16}O(d, {}^{6}Li)^{12}C$ reaction at 54.25 MeV and at 35 MeV deuteron energy fail to describe the experimental angular distribution for the population of this 2^+ state.

The experimental angular distribution for the 65 MeV deuteron data (fig. 4) is only described reasonably well in the angular range from 20° to 45° c.m. by the DWBA calculations. At the lower and the higher angular range the data show cross sections which are relatively too large. Inclusion of 1S and 0D contributions in the relative α-d motion of ^{6}Li allows the 2^+ state in ^{12}C to be populated by $L = 0$ to $L = 4$ transfer. FR DWBA calculations using the computer code DWUCK5 [ref. [14])] were performed to test whether $L = 0$ or $L = 4$ transition strength might be responsible for the observed enhancement of the cross section at the lower and

at the higher angular range, respectively. The result of the calculations (using spectroscopic amplitudes [13]) $A^{^6Li}_{\alpha,d}(1S) = 0.97$; $A^{^6Li}_{\alpha,d}(0D) = -0.23$) is shown in fig. 4 (for the case of $E_d = 65$ MeV) by the dotted line, and gives some improvement in the quality of the fit to the data.

Finally using potential sets B and D FR DWBA calculations were performed for the transition to the 2^+ state in ^{12}C including the Brown and Green wave function [15]) for the ^{16}O ground state. The shape of the angular distribution did not change significantly relative to the one calculated for the closed p-shell assumption for the ^{16}O ground state. However, the relative spectroscopic factors ($S_\alpha(L = 2)/S_\alpha(L = 0)$) decrease by about 40 %, as can be seen in table 2, when comparing the results obtained with potential set B(D) to the ones with potential set B'(D'), respectively.

3.3. THE TRANSITION TO THE 4^+ STATE AT 14.08 MeV

The yield of the 4^+ state at 14.08 MeV excitation energy is comparable to the yield of the underlying broad structure and background, as can be seen in fig. 1 and as has been discussed in ref. [2]). Therefore, the statistical uncertainties of the data points are rather large. Angular distributions are shown in fig. 5 for the four

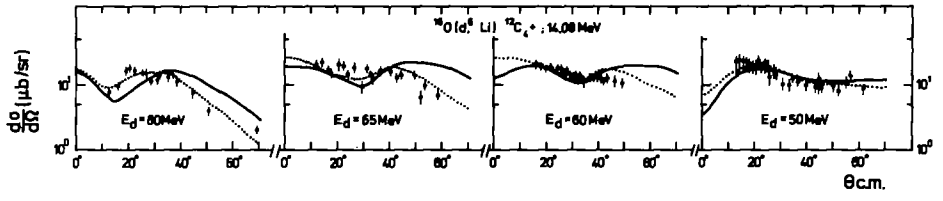

Fig. 5. Angular distributions for the transition to the 4^+ state at 14.08 MeV in ^{12}C for different incident energies. The theoretical DWBA curves were perfomed with ^6Li potentials: solid lines: Potential set B in table 1; dotted lines: ^{16}O ground-state wave function according to Brown and Green [15]) and 1S plus 0D contributions to the relative α-d = ^6Li motion according to ref. [13]), else potential set D in table 1.

incident energies. The solid curves shown in the figure result from DWBA calculations, performed with the ^6Li optical potential B (see table 1). The shapes of the theoretical angular distributions did not change significantly when other reasonable potential depths were employed for the real and/or imaginary part of the ^6Li optical-model potential. The quality of the fits (solid lines in fig. 5) is rather bad, and consequently a factor of about two uncertainty is introduced into the spectroscopic factor, depending on how to normalize experimental to theoretical angular distributions. Using a normalization of theoretical to experimental cross sections as given in fig. 5, spectroscopic factors for the 4^+ state in ^{12}C relative to the ground state transitions at the same incident energy varied between 2.5 and 1.0 for ^6Li potential sets as given in table 1. Again using ^6Li potential set D of table 1 resulted in the most constant relative spectroscopic factor of 1.7 ± 0.3.

In an earlier publication [2]) of the ^{16}O(d, ^{6}Li)^{12}C reaction at $E_d = 80$ MeV a fair fit between experimental data and theoretical DWBA curves for the 4^+ state was achieved, employing a different parametrization for the DWBA calculations. As can be seen by the dotted lines in fig. 5 the fits of the theoretical curves to the experimental angular distributions improve in the present parametrization, if 1S and 0D contributions [again with spectroscopic amplitudes [13]) as 0.97 and -0.23, respectively] are summed up coherently for the relative α-d motion of ^{6}Li. From the point of view of the quality of the fits it seems that in fact some more 0D strength should be used relative to the 1S strength.

DWBA calculations which use the ^{16}O ground state wave function of Brown and Green [15]) result in a relative spectroscopic factor $(S_\alpha(L = 4)/S_\alpha(L = 0))$ half as large as the value obtained under the closed shell assumption. The 4^+ α-spectroscopic factor relative to the ground state spectroscopic factor is 0.9 ± 0.2 using potential set D′ of table 1.

4. Summary

When extracting systematics of α-spectroscopic factors over a range of nuclei and for population of various final states, one has to ensure a consistent choice of parameters for the DWBA calculations. In an earlier publication [3]) the choice of the bound state parameters involved in the calculations was selected by fitting experimental ground state to ground-state angular distributions for nuclei of the sd shell. On the basis of this parametrization we present a search on the energy dependence of the rather poorly known ^{6}Li optical-model potential using the ^{16}O(d, ^{6}Li)^{12}C reaction at deuteron energies as $E_d = 80$, 65, 60 and 50 MeV. It is understood that a direct reaction mechanism process is the basic assumption for the present analysis. The search included only variations of the depths for the real (V_R) and imaginary (W_I) optical potential volume parts and was done under the condition of $dV_R/dE \leqq 0$. It was found that an energy dependence $dV_R/dE = -0.86$ with $V_R = -177$ MeV for $E_{^6\mathrm{Li}}^{\mathrm{lab}} = 78.0$ MeV is best for producing an energy independent spectroscopic factor. However, no energy dependence of the ^{6}Li optical-model potential is necessary for finding a best fit to the experimental angular distribution shapes.

It remains puzzling that the shape of the ground-state transition for the $E_d = 50$ MeV data could not be reproduced by DWBA calculations for angles larger than 30° c.m., suggesting a reaction mechanism not describable in the framework of a direct process and/or an oversimplified use of the cluster approach. A reasonable fit, however, was obtained for the transition to the 2^+ state at 4.44 MeV in ^{12}C.

It was found earlier [2]) that the optimum choice of the bound state radius parameter for fitting angular distributions appears to be dependent on the final state excited by the reaction. Here, in the case of the population of the 2^+ state in ^{12}C at $E_d = 80$ MeV use of the energy dependent well depth (see fig. 4 dashed line) seems to resolve this unpleasant requirement.

In fig. 3 it was shown that (relative to a pure 1S calculation) a coherent superposition of 1S and 0D contributions [13]) for the relative motion of the α-d $\simeq$ ^{6}Li system, has a minor influence on the DWBA angular distribution shape for the ground state transition. In the case of the 4^+ final state in ^{12}C an influence is definitely observed (see fig. 5) suggesting that even more 0D strength than was used in the analysis would further improve the fits to the data without having a significant influence on the extracted spectroscopic factors. Further investigations on other target nuclei are required to study this question in more detail.

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