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Configuration mixing effect in the $^{12}C(^6Li,d)^{16}O^*$ α-transfer reaction

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Differential cross section of the α-particle transfer to the five lowest lying states of the ^{16}O is calculated in the zero-range distorted-wave Born approximation. The use of microscopic form factors in which mixing of various p-h configurations is taken into account has a considerable effect on the calculated results and improves the fit to the experimental data compared with the case when a phenomenological form factor is used.

[NUCLEAR REACTION $^{12}C(^6Li, d_{i=0-4})^{16}O^*$, E=18, 20, 28 MeV, ZR DWBA, CCBA, configuration mixing effect.]

In the past decade a considerable amount of attention has been devoted to the α-transfer reactions,[1-9] since the study of the direct α-transfer process offers a new source of the spectroscopic information concerning the α clusterization of nuclear states. For this purpose, the $(^6Li,d)$ reaction seems to be the best one because the measured angular distributions at energies well above the Coulomb barrier suggest a direct α transfer[2,3] and the α-d clusterization in the ^6Li is high. The spectroscopic information extracted is reliable only if the reaction is described with sufficient accuracy. The main assumptions are usually the single-step α-cluster transfer and the applicability of the distorted-wave Born approximation (DWBA). The single-step assumption can be accepted because of the good properties of the α particle. The crucial points of the DWBA description are the optical potentials used for the calculation of the distorted waves and the approximations made in the determination of the (complete) form factor, which also involves the selection of the potential inducing the transfer. The optical potentials are deduced generally from the optical-model analyses of the elastic scattering in the entrance and exit channels. The exact finite range (EFR) DWBA calculations are often replaced by less time-consuming approaches as the no-recoil[4] or the zero-range (ZR) approximations. One may expect that the ZR approximation works reasonably well in the $(^6Li,d)$ reaction since the α-d clusters move dominantly[10] in a relative S state in ^6Li and the momentum matching condition in the forward direction is fulfilled. Applying the ZR approximation, the complete form factor[4] of the $^{12}C(^6Li,d)^{16}O$ reaction can be written as

$$F_L(\vec{r}) = D_0 S_0^{1/2} (L - ML M | 00) Y_L^{-M}(\hat{r}) G_L(r), \quad (1)$$

where D_0 and S_0 denote the ZR constant and the α-spectroscopic factor of ^6Li, respectively. The radial shape of the form factor is determined by $G_L(r)$ which is called hereafter phenomenological form factor (PFF) or microscopic form factor (MFF), depending on the method by which G_L is calculated. The PFF is calculated from a pure configuration assumption as an eigenfunction of a real potential. The determination of the MFF requires, in principle, a microscopic model both for $^{16}O^*$ and for ^{12}C. The various configurations mixed in the microscopic model may result in differences in the calculated cross sections compared to the phenomenological case. Suggestions for studying this effect in the reaction $^{12}C(^6Li,d)^{16}O^*$ are given in previous works.[9,11,12] Preliminary results have been reported elsewhere.[13]

In this note the importance of the configuration mixing effect is studied in the five transitions of the α-transfer reaction $^{12}C(^6Li,d)^{16}O^*[J_i^\pi(E^*)]$ which lead to all levels of the ^{16}O lying below the α threshold, namely, to $0_1^+(0.0)$, $0_2^+(6.05)$, $3_1^-(6.13)$, $2_1^+(6.92)$, and $1_1^-(7.12)$, respectively. This reaction has been studied experimentally by several authors[1,5,9,14,15] and it has been concluded[5,14,15] that at bombarding energies around 18 MeV a direct α-stripping mechanism plays an important role. We compare, therefore, the results of the ZR DWBA calculations obtained with PFF and MFF to each other and to the experimental data of Bethge *et al.*[5] and Meier-Ewert *et al.*[1] We assume that in the energy region considered, the characteristics of the angular distributions at forward scattering angles are mainly determined by the direct mechanism. Nevertheless, two-step and compound processes may influence the magnitude of the experimental cross sections especially for the weak transitions (e.g., for 0_1^+ and 0_2^+).

TABLE I. Parameters of the potentials used in the DWBA calculations.

Channel A_1+A_2	Parameter set	Energy range (MeV)	V (MeV)	r_v (fm)	a_v (fm)	W_D (MeV)	r_w (fm)	a_w (fm)	r_c (fm)	Ref.
^{6}Li+ ^{12}C	$L1$	28	250.0	1.354	0.65	30.0	1.354	0.65	2.0	9
	$L2$	18–20	35.0	1.420	1.04	8.5	2.170	0.49	2.5	16
d+ ^{16}O	$D1$	19–27	95.0	1.127	0.80	10.0	1.332	0.8	2.0	9
	$D2$	13–21	92.9	1.036	0.79	6.0	1.355	0.73	1.3	17
^{4}He+ ^{12}C	WSI	<0	a	1.3	0.65				1.3	present work
	WSII	<0	a	1.2[b]	0.65				1.2[b]	present work
	WSIII	<0	a	1.25[b]	0.65				1.25[b]	9

$V(r)=-V(1+e_v)^{-1}-4iW_De_w(1+e_w)^{-2}+V_C(r,R_c)\quad e_x\equiv\exp[(r-R_x)/a_x]\quad R_x=r_xA_2^{1/3}$

[a] Adjusted to reproduce the α-separation energy.
[b] $R_x=r_x(A_1^{1/3}+A_2^{1/3})$.

The PFF is taken to be

$$G_L(r)=S_\alpha^{1/2}u_L(r)\,, \tag{2}$$

where S_α is the α-spectroscopic factor of ^{16}O* and $u_L(r)$ is a normalized single-α-particle bound state wave function of a Woods-Saxon (WS) well with the depth adjusted to reproduce the α-separation energy. The geometry of the wells used in generating the PFF's is specified in Table I. In order to trace the geometry dependence of the cross section, we have calculated and plotted in Fig. 1 the PFF's with different radius parameters. The number of nodes N in the radial wave function may also affect the cross section if the internal region contributes to the radial integrals. The N values are found from the relation $2N+L=\sum_{i=1}^{4}(2n_i+l_i)$, where n_i and l_i are the quantum numbers of the orbit into which the ith nucleon is transferred (the lowest value $n=0$).

The MFF is calculated from the overlap integral[18]

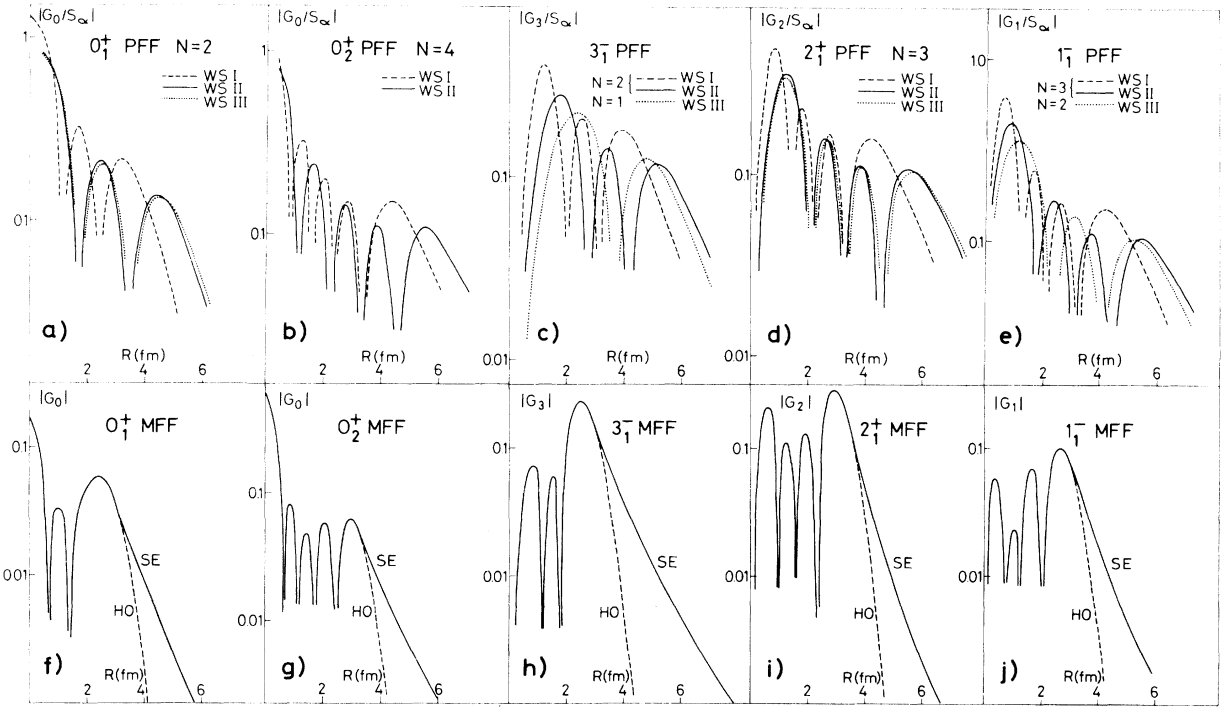

FIG. 1. Form factors used in the DWBA calculations. Phenomenological form factors calculated using potentials WSI, WSII, WSIII of Table I are shown in (a)–(e). Microscopic form factors with corrected tail (SE) and without correction (HO) are displayed in (f)–(i), respectively.

$$G_L(r)=\langle \psi_{^{12}C}\psi_\alpha\, Y_L^M(\hat{r})\,|\,\psi_{^{16}O}\rangle\,, \tag{3}$$

where ψ_x denotes the internal wave function of the nucleus x. It is expressed as a superposition of the eigenfunctions $\varphi_{NL}^{HO}(r)$ of a harmonic oscillator potential weighted by the α-spectroscopic amplitudes A_{NL} (Ref. 12) as follows:

$$G_L(r)=\sum_N (-)^N A_{NL}\varphi_{NL}^{HO}(r)\,. \tag{4}$$

Here the phase factor takes care of the difference in the sign convention of φ_{NL}^{HO} in the code DWUCK[19] and in the calculation of the A_{NL} values.[11,20]

In the calculation of the A_{NL} values, shell model wave functions of Zuker *et al.*[21] were used in which the ground state of the ^{12}C is approximated by an inert closed $p_{3/2}$ core.[22] The MFF of Eq. (4) has more than one term, mainly due to the different np-nh configuration in the final states and partly[12] due to the different extension of the nuclei ^{16}O and ^4He.

The values of the size parameter $\nu=m\omega/\hbar$ for the ^{16}O and the ^4He denoted by ν_0 and $\nu_{0\alpha}$, respectively, have been determined from the mean square radii of the proton distributions which were derived from the measured rms charge radii[24] of the corresponding nuclei. The amplitudes A_{NL} depend on the ratio $\nu_0/\nu_{0\alpha}$, the radial extent of $\varphi_{NL}(r)$ is characterized by the parameter $b=1/(4\nu_0)^{1/2}$. In the present case, $b=0.86$ fm and $\nu_0/\nu_{0\alpha}=0.463$. The MFF's of Eq. (4) are displayed in the lower part of Fig. 1 (HO). In order to correct the asymptote, the tail of a WS eigenfunction with proper asymptote is matched smoothly to the MFF beyond its last peak and the new MFF shown in Fig. 1 (SE) has been renormalized to preserve the norm. This procedure is essentially the same as the "connecting potential" method of Arima *et al.*[4] From the comparison of the MFF and PFF of Fig. 1, one can recognize that the surface part is generally enhanced while the internal region is suppressed in the MFF, which reflects clearly the known fact that the α clusterization is relatively strong on the nuclear surface.

The differential cross section is calculated by using the DWBA code DWUCK.[19] In order to test the accuracy of the ZR approximation we recalculate the cross sections at 28 MeV which have already been calculated by Cunsolo *et al.*[9] in EFR. A comparison of the full (EFR) and the dashed (ZR) curves of Fig. 2 shows that the finite range of the interaction has little effect on the angular distributions at forward angles and the magnitude of the ZR cross sections agrees within 30% with that of the EFR results. Therefore, the use of the ZR approximation seems to be justified. The optical potential parameters and the geometry of the bound state potential used in this calculation are denoted in Table I by $L1$, $D1$, and WSIII, respectively. The corresponding PFF's are the dotted curves (WSIII) of Figs. 1(a) and 1(c)–1(e), respectively. In the case of the 3_1^- and 1_1^- final states the node number N differs by 1 from the "effective" N value given by the microscopic model (which is used, however, in calculating the PFF's denoted by WSII and WSI). Owing to the strong absorptive part of the potential $L1$, the use of the WSII PFF results in similar angular distributions

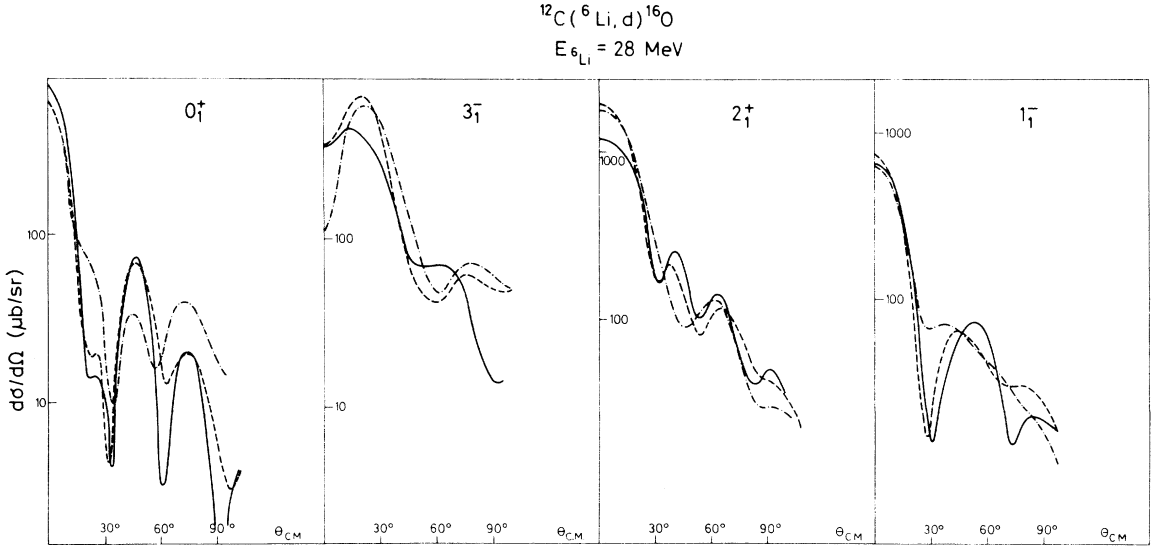

FIG. 2. Differential cross sections for different transitions of the $^{12}C(^6Li,d)^{16}O$ reaction at 28 MeV bombarding energy in different approaches of the DWBA. EFR calculations of Cunsolo *et al.* (Ref. 9) are denoted by full lines. The dashed and dot-dashed curves represent ZR results with PFF (WSIII) and MFF (SE) of Fig. 1, respectively.

in spite of the differences in N. Even the use of the (SE) MFF causes no drastic change in the angular distribution (see the dot-dashed curve of Fig. 2). Therefore, at this energy the configuration mixing has little effect on the shape of the theoretical cross section.

At lower energies, the less absorptive potential $L2$ of Table I gives a good account of the ^{6}Li elastic scattering on ^{12}C.[16] In the exit channel we use the deuteron potential $D2$ of Table I, in which the imaginary strength has been reduced by about 30% compared to the potential given by Newman *et al.*[17] because the energy is lower in our case. We expect that the contribution of the internal region to the reaction cross section is more important in this case. Indeed, the use of PFF's with different radial extent WSI and WSII produces angular distributions with quite different shapes in each transition displayed in the upper part of Fig. 3. The results with MFF's are shown in the lower part of Fig. 3. They reproduce the measured angular distributions reasonably well. The agreement is much better than could be achieved by using PFF's with several radius parameters between WSI and WSII. The results corresponding to the HO and SE MFF's do not differ from each other seriously. It seems to be justified that the contribution of the internal region plays an important role; therefore, the large effect of the configuration mixing on the calculated cross sections is understood. As far as the magnitude of the cross sections is concerned, the results of our DWBA calculations highly underestimate the measured cross sections for the weak 0^+ transitions if we use $D_0^2 = 10^4$ MeV^2 fm^3 (derived from the range function $V_{\alpha d}\,\phi_{\alpha d}$ used by Cunsolo *et al.*[9]) and $S_0 = 0.69$ of Werby *et al.*[25] Contributions of two-step and compound processes might be responsible for this difference, but a detailed investigation of this question is beyond the scope of this note. We illustrate here only that the angular distribution of the 0_1^+ transition will not change drastically if we take into account the two-step process via inelastic excitation of the 2_1^+ (4.439 MeV) state in ^{12}C. The full curve on Fig. 3(a) is the result of the CCBA calculation made by using code CHUCK.[26] The 2_1^+ state in ^{12}C is assumed to be excited by rotational excitation of a permanent-

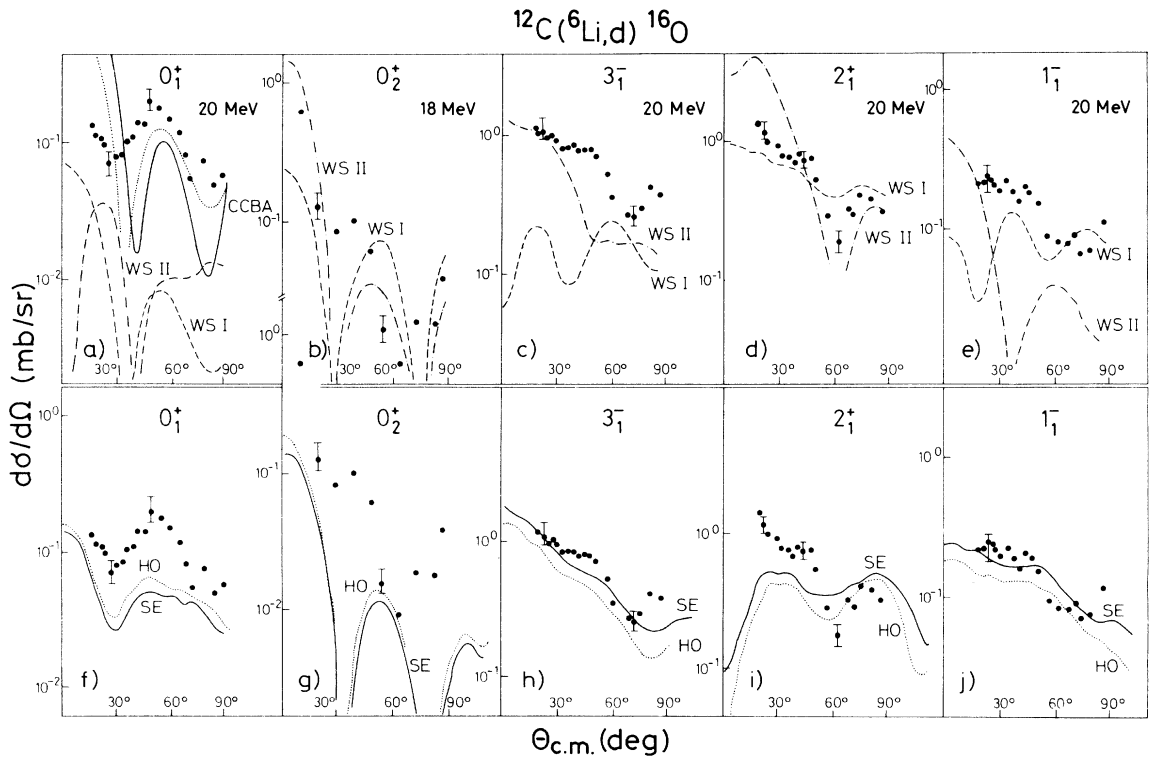

FIG. 3. Differential cross sections of the ^{12}C(^{6}Li, d)^{16}O reaction calculated in ZR DWBA using PFF of Figs. 1(a)–1(e) and MFF of Figs. 1(f)–1(i), respectively. The full and the dotted lines in (a) are CCBA and DWBA results with A_{NL}'s of Kurath (Ref. 28). In the other cases A_{NL}'s calculated by Apagyi (Ref. 11) at $\nu_0/\nu_{0\alpha} = 0.46$ are used. Dots are the experimental results measured at 18 MeV for the 0_2^+ final state by Bethge *et al.* (Ref. 5) and at 20 MeV for the other transitions by Meier-Ewert *et al.* (Ref. 1).

ly deformed shape with $\beta_2 = -0.5$.[27] A_{NL}'s for the direct and indirect transition are taken from Kurath[28] ($A_{20} = -0.48$, $A_{12} = -1.14$)[29] and WSI geometry is used. Dotted curves on Fig. 3(a) represent the DWBA result using the spectroscopic factor of Kurath[28] (other parameter values are unchanged). Comparing the full and the dotted curves one can estimate the effect of the two-step process.[30] Although some enhancement due to the constructive interference between the two routes appears in the forward direction, the change in the shape is much less than that caused by the use of the MFF. This remains valid even if the relative phase of the two routes is reversed.

Therefore, we can conclude that in certain cases the configuration mixing has a large effect on the form factor of the α-transfer reactions. Depending on the degree of the absorption in the entrance and exit channels, this may or may not influence the shape of the calculated cross sections considerably, which shows the importance of a good knowledge of the absorption. If the absorption is not too strong, the configuration mixing should be taken into account in order to give a reasonably good description of the angular distributions measured. Since the magnitude of the cross section calculated is always influenced by the shape of the form factor in the internal region as well, the configuration mixing also influences the value of the α-spectroscopic factors determined by the DWBA analyses of the measured cross sections in the case of the strong absorption.

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