main width.

We wish to thank Professor V. Jaccarino for many helpful discussions and suggestions.

†Work supported in part by the National Science Foundation.

[1]D. S. McClure, in *Optical Properties of Ions in Crystals*, edited by H. M. Crosswhite and H. W. Moos (Interscience, New York, 1967), p. 257.

[2]M. F. Kharchenko and V. V. Eremenko, Fiz. Tverd. Tela 9, 1655 (1967), and 10, 1402 (1968) [Sov. Phys. Solid State 9, 1302 (1967), and 10, 1112 (1968)].

[3]K. L. Dudko, V. V. Eremenko, and V. M. Fridman, Zh. Eksp. Teor. Fiz. 61, 678, 1553 (1971) [Sov. Phys. JETP 34, 362, 828 (1972)].

[4]S. Foner, in *Magnetism*, edited by G. T. Rado and H. Suhl (Academic, New York, 1963), Vol. 1, Chap. 9.

[5]T. Nagamiya, K. Yosida, and R. Kubo, Advan. Phys. 4, 1 (1955) (or p. 38 for formula).

[6]S. Chikazumi, *Physics of Magnetism* (Wiley, New York, 1964), Chaps. 9–11.

(^{16}O, ^{12}C) and (^{6}Li, d) as α-Transfer Reactions

R. M. DeVries*

Département de Physique Nucléaire, Centre d'Etudes Nucleaires de Saclay, 91190–Gif sur Yvette, France

(Received 6 December 1972)

By means of a finite-range distorted-wave Born-approximation program which exactly includes recoil, α spectroscopic factors are extracted from the (^{6}Li, d) and (^{16}O, ^{12}C) reactions on ^{40}Ca. The production of ^{12}C*(2^{+}) is correctly predicted to be suppressed. The results are consistent with the assumption of an α-particle transfer as dominant in the two reactions.

The nature of the (^{16}O, ^{12}C) reaction is not well understood[1]; in particular, the internal state of the transferred four nucleons is not known although the reaction is usually referred to as an "α"-transfer reaction. In this paper the (^{16}O, ^{12}C) and the direct component of the (^{6}Li, d) reactions are assumed to proceed via the one-step transfer of an α particle, an assumption which seems fairly well established for the Li-induced reactions.[2] Two questions are answered: (a) Is the (^{16}O, ^{12}C) reaction quantitatively consistent with the (^{6}Li, d) reaction? (b) Why is the (^{16}O, ^{12}C*) reaction not observed on medium-mass targets?

Recent measurements of the (^{6}Li, d) reaction on ^{40}Ca[3] and ^{58}Ni[4] allow comparison with the spectra seen in the (^{16}O, ^{12}C)[5,6] reaction on the same targets. There appears to be an overall correlation between the strong levels produced in the two reactions. In this paper, finite-range distorted-wave Born-approximation (DWBA) calculations for the (^{6}Li, d) and (^{16}O, ^{12}C) reactions on ^{40}Ca are compared, this target being chosen because angular distributions exist for both reactions. It should be noted that zero-range DWBA calculations were made for the (^{6}Li, d) reactions, which reproduced the shapes of the angular distributions, but no absolute spectroscopic factors could be obtained. The (^{16}O, ^{12}C) reaction is not expected to be meaningfully treated with the zero-range or more sophisticated approximations unless they include recoil effects.[7] In this paper a DWBA formalism[8] is used which exactly includes recoil effects.

For a stripping reaction $A(a,b)B$, where $a=b+x$ and $B=A+x$, a transition amplitude may be written[8]

$$T \propto S_a^{1/2} S_B^{1/2} \int d^3r_a\, d^3r_b\, \chi_{aA}^{(+)}(\vec{r}_a) \langle \Psi_B(\vec{r}_{xA}) | V_{xb}(\vec{r}_{xb}) | \Psi_a(\vec{r}_{xb}) \rangle \chi_{bB}^{(-)}(\vec{r}_b). \quad (1)$$

In this expression χ is a distorted wave and the bracketed term is a form factor containing a final bound state Ψ_B and the potential V_{bx} used to generate the bound state Ψ_b.

The equation[9]

$$2N + L = \sum_{i=1}^{4} (2n_i + l_i) \quad (2)$$

determines the number of nodes N and the L value from the shell model n_i and l_i of each particle. The four nucleons are assumed to be in an internal 0s state with the known α binding energy. Table I lists the assumed shell-model configurations and resulting N and L values. Multi-particle-hole configurations in the ^{16}O(g.s.) are ignored, a procedure which is justified from analysis[12] of the reactions ^{12}C(^{6}Li, d)^{16}O and ^{16}O(d,

^{6}Li)^{12}C. All the bound states were calculated in Woods-Saxon potentials with $R = 1.25(A^{1/2} + 4^{1/3})$ and diffuseness $a_0 = 0.65$. Small changes in these parameters affected the predicted shapes very little. As would be expected, the predicted magnitudes in both reactions increased with larger bound-state radii. Thus the relative cross sections and, therefore, relative spectroscopic factors are fairly independent of these bound-state parameters.

The optical potentials used for the (^{6}Li, d) reaction were the same as those used in Ref. 3. The use of other values from the literature changed the predicted cross section little; in particular, "breakup" potentials for the ^{6}Li channel calculated by Watson[13] from a superposition of deuteron and α optical potentials produced very similar results. The optical potential used for the ^{16}O and ^{12}C channels was taken from an analysis of the reaction ^{48}Ca(^{16}O, ^{14}C)^{50}Ti[14] [$V = 100$, $R = 1.22(A^{1/3} + a^{1/3})$, $a_0 = a_I = 0.7$, $W_{\rm vol} = 40$] except for a change of a_0[16] from 0.7 to 0.8 which increased the predicted peak width slightly. These parameters were found from fitting the 48-MeV ^{16}O + ^{48}Ca elastic scattering[5] except that $a = 0.5$ in that study.

The α-cluster spectroscopic factors for ^{16}O and ^{6}Li were taken from the literature. They are listed in Table I.

Calculations were made for all states cleanly resolved in the (^{16}O, ^{12}C) reaction. Although complete angular distributions were not available for the (^{16}O, ^{12}C) reaction, at this incident energy the angular distributions are sufficiently well defined by their peak values. Compound nucleus contributions to the (^{6}Li, d) reaction are ignored, as is probably justified at such high incident energy[2].

The finite-range DWBA cross sections were calculated with the program described earlier[15] and are compared with the experimental data in Fig. 1. Comparison of the DWBA and the experimental cross section yields spectroscopic factors for the ^{44}Ti states which are quite similar in absolute value for the (^{6}Li, d) and (^{16}O, ^{12}C) reactions. This suggests that the mechanisms of the two reactions are similar and consistent with the assumption of a simple α-particle transfer.

TABLE I. Bound-state configuration.

Nucleus	Assumed configuration	nl	S_α
^{44}Ti	^{40}Ca$\otimes(fp)^4$	$6s, 5d, 4g$	See Fig. 1
^{16}O	^{12}C$\otimes p^4$	$2s, 1d$	0.23, 1.26[a]
^{6}Li	s^4p^2	$1s$	1.12[b]

[a]Ref. 10. [b]Ref. 11.

As shown in Table I, the spectroscopic factor for ^{16}O(g.s.) = ^{12}C*(2$^+$) + α is about 5 times bigger than for ^{12}C in its ground state. It has been noted,[16] therefore, that experimentally the ^{12}C* state should be strongly seen in (^{16}O, ^{12}C) reactions if they proceed via α transfer. This argument neglects the DWBA dynamics; and, in fact, as shown in Fig. 1, the predicted DWBA cross section for the production of ^{12}C*, using the same ^{44}Ti spectroscopic factors, is small at the experimentally measured angles. The experimental spectrum of Ref. 1 shows no evidence of ^{12}C*-^{44}Ti(g.s.) excitation, and ^{12}C*-^{44}Ti* states would be hidden in (or may compose) the background in this excitation region.

It has been suggested that the ^{12}C* states might be suppressed because the higher binding energy and loss of one node ($2S \rightarrow 1D$) would give a smaller tail on the ^{16}O bound state.[17] As shown in Fig. 2, the difference is not sufficient to give the predicted reduction in cross section.

Perhaps the strong reduction of the ^{12}C*(2$^+$) state may be understood with a simple semiclassical argument in the approximation that, at the time of transfer, the incident projectile has a small velocity, which is ignored. It is also as-

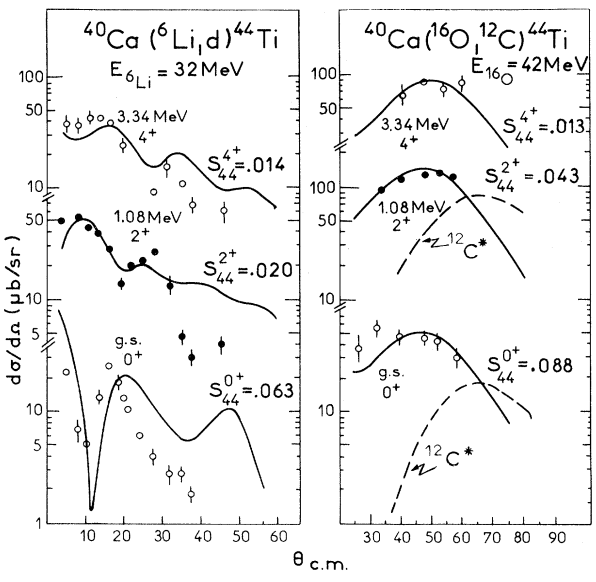

FIG. 1. Comparison of the theoretical and experimental angular distributions as discussed in the text. The ^{12}C* curves refer to predictions for the reactions ^{40}Ca(^{16}O, ^{12}C*(2$^+$))^{44}Ti using the same S_{44} as was obtained from fitting the reactions ^{40}Ca(^{16}O, ^{12}C(g.s.))^{44}Ti.

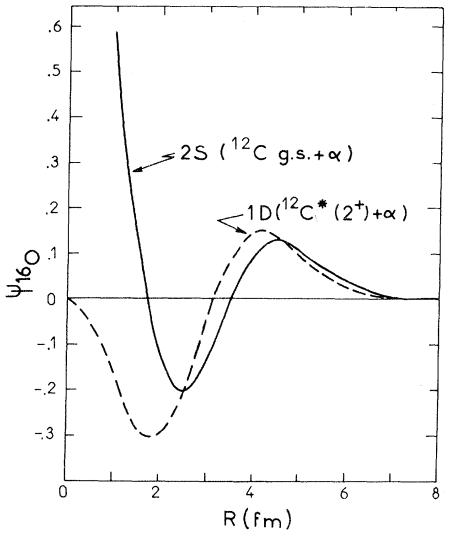

FIG. 2. Comparison of the bound-state wave functions for $^{16}O(g.s.)=^{12}C(g.s.)+\alpha$ and $^{16}O(g.s.)=^{12}C^*(2^+)+\alpha$.

sumed that the transfer takes place in the plane defined by the motion of the two cores, and therefore angular momentum pR must be conserved in this plane. In this picture an α particle in an $l=2$ state around a $^{12}C^*(2^+)$ will find it difficult to settle into an $l=0$ orbit around ^{40}Ca, particularly since the ^{40}Ca radius is bigger than the ^{12}C radius. However we would expect that the likelihood of higher l-value orbits around ^{40}Ca world be reduced less, in agreement with the DWBA prediction for the $^{12}C^*(2^+)$-$^{44}Ti^*(2^+)$ final state shown in Fig. 1. Calculations for the $^{12}C^*(2^+)$-$^{44}Ti^*(4^+)$ final state were prohibited by program space limitations. If this argument is valid, $^{12}C^*(2^+)$ peaks should appear in (^{16}O, ^{12}C) spectra on lighter (smaller radii) targets and, in fact, are seen in reactions on ^{24}Mg [18] and ^{12}C.[19] Thus it is suggested that the nonobservation of $^{12}C^*(2^+)$ peaks in (^{16}O, ^{12}C) reactions on medium and heavy targets is due to a combination of angular-momentum mismatch and size effects.

In conclusion, it appears that the (^6Li, d) and (^{16}O, ^{12}C) reactions on ^{40}Ca quantitatively proceed via the same reaction mechanism. The DWBA correctly predicts the suppression of $^{12}C^*(2^+)$ formation; these results, therefore, are consistent with the idea that the (^{16}O, ^{12}C) reaction proceeds via the transfer of an α particle.

The author would like to thank George Morrison for many enlightening conversations and C. Detraz and M. C. Mermaz for critically reading this paper.

*Address after 31 December 1972: Nuclear Physics Laboratory, University of Washington, Seattle, Wash. 98195.

[1]G. C. Morrison, in Proceedings of the European Conference on Nuclear Physics, Aix-en-Provence, France, 1972 (to be published).

[2]K. Bethge, Annu. Rev. Nucl. Sci. 20, 255 (1970).

[3]U. Strohbusch, C. L. Fink, B. Zeidman, R. N. Horoshko, H. W. Fulbright, and R. Markham, Phys. Rev. Lett. 29, 735 (1972).

[4]H. H. Gutbrod and R. G. Markham, Phys. Rev. Lett. 29, 808 (1972).

[5]G. C. Morrison, J. Phys. (Paris), Suppl. 32, C6-69 (1971).

[6]H. Faraggi, M. C. Lemaire, J. M. Loiseaux, M. C. Mermaz, and A. Papineau, Phys. Rev. C 4, 1375 (1971).

[7]F. Schmittroth, W. Tobocman, and A. A. Golestaneh, Phys. Rev. C 1, 377 (1970); R. M. DeVries, to be published.

[8]N. Austern, R. M. Drisko, E. C. Halbert, and G. R. Satchler, Phys. Rev. 133, B3 (1964).

[9]L. J. Denes, W. W. Daehnick, and R. M. Drisko, Phys. Rev. 148, 1097 (1966).

[10]I. Rotter, Fortschr. Phys. 16, 195 (1968), Table 9b.

[11]W. J. Klages, H. H. Duhm, H. Yoshida, P. E. Schumacher, and C. Detraz, Nucl. Phys. A156, 65 (1970).

[12]H. H. Gutbrod, H. Yoshida, and R. Bock, Nucl. Phys. A165, 240 (1971); G. Bassani, R. M. DeVries, N. Saunier, B. M. Traore, A. Foti, and G. Pappalardo, to be published.

[13]J. W. Watson, to be published.

[14]R. M. DeVries and G. C. Morrison, to be published.

[15]R. M. DeVries, Ph. D. thesis, University of California at Los Angeles, 1971 (unpublished); J. L. Perrenoud and R. M. DeVries, Phys. Lett. 36B, 18 (1971).

[16]D. Robson, Comments Nucl. Particle Phys. 5, 18 (1972).

[17]A. Arima, in *Proceedings of a Symposium on Two Nucleon Transfer and Pairing Excitations, Argonne, Illinois, 1972,* CONF-700801 (U. S. AEC Division of Technical Information, Springfield, Va., 1972).

[18]J. V. Maher, C. A. Erb, G. H. Wedberg, J. L. Ricci, and R. W. Miller, Phys. Rev. Lett. 29, 291 (1972).

[19]B. G. Harvey, J. Mahoney, J. R. Meriwether, and D. L. Hendrie, UCRL Annual Report No. UCRL-20426, 1970 (unpublished), p. 85.