$^{16,18}O(\alpha, {}^6He)^{14,16}O$ reactions*

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The $(\alpha, {}^6He)$ reaction on ^{16}O and ^{18}O has been studied at $E_\alpha = 58$ MeV. Although the cross sections are much smaller than the corresponding (p, t) cross sections by about a factor of 20, the angular distributions are characteristic of a direct transfer mechanism and are reproduced satisfactorily by distorted-wave theory assuming LS coupling in ^6He.

[NUCLEAR REACTIONS: $^{16}O(\alpha, {}^6He)$ and $^{18}O(\alpha, {}^6He)$, $E=58$ MeV; measured $\sigma(E_{^6He}, \theta)$; ^{16}O deduced transition strengths and DWBA normalization.]

I. INTRODUCTION

α-particle induced multinucleon transfers have not been investigated extensively and hence relatively little is known about the characteristics of these reactions. We have studied[1] the two-neutron pickup reactions $^{16,18}O(\alpha, {}^6He)^{14,16}O$ at $E_\alpha = 58$ MeV to provide additional information. Several shell-model calculations are available for $^{14,16,18}O$. A comparison with data from $^{16,18}O(p, t)$ is also possible and facilitates analysis. Earlier studies[2] of the $^{26}Mg(\alpha, {}^6He)$ reaction at lower bombarding energies (35–40 MeV) indicated a sizeable nondirect component.

II. EXPERIMENT

The experiments were performed using a 58 MeV α-particle beam from the University of Michigan 2 m variable energy cyclotron. Targets consisted of oxidized nickel foils[3] (140 $\mu g/cm^2$ of ^{18}O and 450 $\mu g/cm^2$ of Ni). Reaction products were detected at large angles ($\theta \geq 21°$ lab) with a ΔE-E solid-state counter telescope system[4] ($\Delta\theta \sim 0.5°$). At small angles ($\theta \leq 21°$ lab) data were obtained using a magnetic spectrometer ($\Delta\theta \sim 6°$) with a solid-state or gas-proportional position-sensitive counter in the focal plane. The spectrometer allowed measurements at $\theta = 0°$. The energy resolution full width at half-maximum (FWHM) was 100 to 200 keV for the telescope data and 50 to 100 keV for the spectrometer data and was limited by target thickness and kinematic effects. At some angles certain groups were obscured by reactions from the nickel contaminants.

A ^6He spectrum from $^{18}O(\alpha, {}^6He)^{16}O$ is shown in Fig. 1 (oxide target with ΔE-E telescope) and compared with recent $^{18}O(p, t)^{16}O$ data.[5] The ^{16}O ground state (0^+) is populated about four times more intensely than any other group at the angle shown, which corresponds to an $L=0$ maximum. Next in strength are the known doublets[5] at $E_x = 6.05$ and 6.13 MeV (0^+ and 3^-) and $E_x = 6.92$ and 7.12 MeV (2^+ and 1^-). The 2^+-1^- doublet was partially resolved at large angles and cross sections could be extracted. Also observed were groups at $E_x \approx 10.4$, 13.3, and 16.3 MeV.

Unlike (α, t), $(\alpha, {}^3He)$, or (α, d) at $E_\alpha \approx 60$ MeV, the $(\alpha, {}^6He)$ reaction does not necessarily favor high spin states. In $^{18}O(\alpha, {}^6He)^{16}O$ g.s. the favored l-transfer is about two, while for $E_x \approx 7$ MeV it is zero, and at $E_x \approx 16$ MeV it is again about two.

The correspondence with levels seen[5] in $^{18}O(p, t)^{16}O$ is close except that the $^{18}O(\alpha, {}^6He)^{16}O$ cross sections are only about 5% of the (p, t) cross sections. This difference is even more dramatic for the reaction on the ^{16}O target. We obtained an upper limit for the $^{16}O(\alpha, {}^6He)^{14}O$ g.s. cross section of 0.4 μb/sr for $\theta \gtrsim 18°$. This is to be compared with cross sections of about 100 μb/sr observed in $^{16}O(p, t)^{14}O$, i.e. (p, t) is about 200 times stronger.

Despite the small cross sections, the $(\alpha, {}^6He)$ angular distributions appear to be characteristic for a direct dineutron transfer. They are displayed in Fig. 2. The curves are distorted-wave calculations (see Sec. III). The spins indicated are those assigned[5] in (p, t) or other work.

III. ANALYSIS

We have analyzed the $(\alpha, {}^6He)$ data with zero-range distorted-wave Born approximation (DWBA). The two neutrons are assumed to be transferred as an LS coupled pair in a relative $1S$ state in ^6He. One has[6]

$$\frac{d\sigma^{\rm exp}}{d\Omega} = N \frac{C^2}{(2J+1)} \frac{d\sigma^{\rm DW}}{d\Omega_{LSJ}}, \qquad (1)$$

where C^2 is an isospin Clebsch-Gordan coefficient; L, S, and J are the orbital, spin, and total angular momenta transfers, respectively; and $d\sigma/d\Omega^{DW}$ is the DWBA cross section calculated with a microscopic two-nucleon transfer form factor.[6] The normalization N can, in principle, be calculated if the range and strength of the projectile-nucleon effective force and the projectile size are known. Often, however, N is determined empirically and only relative strengths between different transitions are compared.

The results of the DWBA calculation are shown in Fig. 2 and compiled in Table I. The results were obtained with ^{18}O and ^{16}O wave functions based on the Zuker interaction.[5,7] Other wave functions were tried and gave similar results. The α-particle optical parameters were fixed at values taken from the literature[8] ($E_\alpha = 56$ MeV). Similarly, the ^6He optical parameters were those published by Schumaker *et al.*[9] for $^6Li + {}^{16}O$ at $E(^6Li) = 36$ MeV. Other published parameter sets gave poorer fits to the data, but better fits could also be obtained by adjusting one or more parameters. The radius of the target potential binding the transferred nucleons also affected the shapes of the angular distributions. Using fixed parameters, however, the DWBA calculations satisfactorily reproduce the observed angular distributions (Fig. 2), although they are relatively structureless and lack distinct l signatures except for the $l = 0$ g.s. transition.

The values of N obtained [Eq. (1)] are listed in Table I (absolute and relative) and are compared with values[5] deduced from an analysis of $^{18}O(p, t)$-^{16}O. Again the close correspondence between the $(\alpha, {}^6He)$ and (p, t) results is observed: the relative N values are within a factor of about 2 of each other except for the transitions to the 2^+ state at $E_x = 6.92$ MeV, which is populated more strongly in $(\alpha, {}^6He)$ than in (p, t). It should be noted, however, that the observed cross sections for the transitions to the 2^+ state are significantly larger than the calculated ones for both $(\alpha, {}^6He)$ and (p, t). This may indicate a substantial inadequacy in the wave function for this state.

In addition to giving reasonable predictions for the relative cross sections for $^{18}O(\alpha, {}^6He)^{16}O$, DWBA correctly predicts the sharply reduced cross sec-

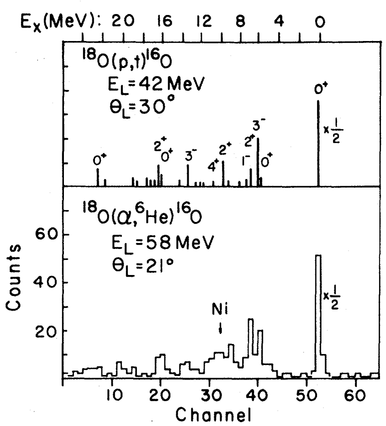

FIG. 1. Bottom: A ^6He spectrum from $^{18}O(\alpha, {}^6He)^{16}O$ taken with a nickel-oxide target and a ΔE-E counter telescope. The group labeled Ni is due to reactions from the nickel backing. Top: A schematic representation of an $^{18}O(p,t)^{16}O$ spectrum (Ref. 5). Both the $(\alpha, {}^6He)$ and (p,t) spectra were taken at $L = 0$ maxima ($\theta > 0°$).

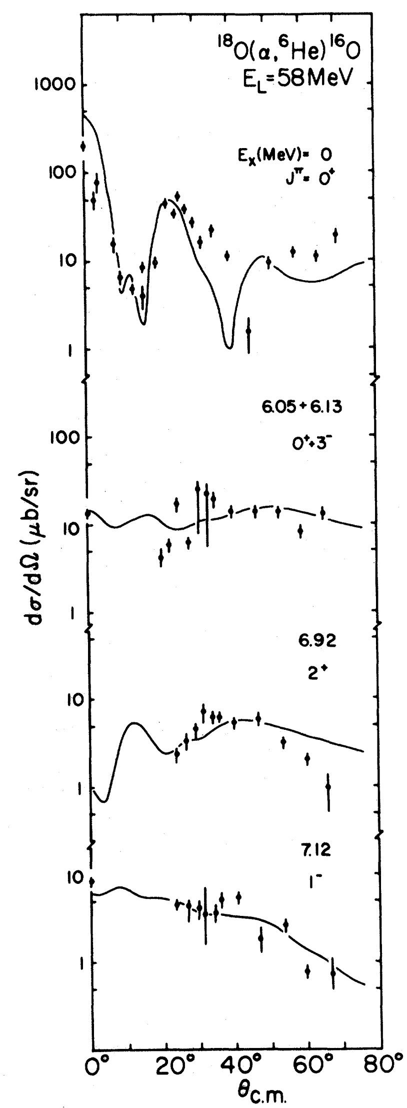

FIG. 2. Angular distributions for $^{18}O(\alpha, {}^6He)^{16}O$. The spin assignments are from other sources (see Ref. 5). The curves are DWBA calculations assuming a dineutron transfer (see text). The error bars include statistical errors and uncertainties in background corrections or peak unfolding.

TABLE I. Comparison of experiment and theory.

E_x [b] (MeV)	J^π, T [c]	This work $^{18}O(\alpha, {}^6He)^{16}O$ N_{abs} [d]	N_{rel} [e]	Other work $^{18}O(p,t)^{16}O$ [a] N_{abs} [f]	N_{rel} [e]
g.s.	0^+, 0	5.3	1.0	3.7	1.0
6.05	0^+, 0	(5) [g]	(1.0) [g]	4.2	1.1
6.13	3^-, 0	10.0 [g]	1.9	8.8	2.4
6.92	2^+, 0	172	32.5	15.0	4.1
7.12	1^-, 0	7.8	1.5	2.7	0.7
13.3 [b]	3^-, 1	3.4	0.6	6.1	1.7
16.3 [b]	(0^+, 0) [h]	10.7	2.07	10.0	2.7

[a] Reference 5, $E_p = 41.8$ MeV.

[b] Taken from Ref. 5 except $E_x = 13.3$ and 16.3, which are from this experiment, ± 100 keV.

[c] Spin, parity and isospin of levels in ^{16}O as assigned from other sources (see Ref. 5).

[d] DWBA normalization as defined by Eq. (1). Zuker interaction wave functions used for ^{16}O and ^{18}O (Refs. 5 and 7). α optical potential (Woods-Saxon well): $V_R = -160.8$ MeV, $R_R = 1.5 A_t^{1/3}$ fm, $a_R = 0.535$ fm, $W_I = -27.6$ MeV, $R_I = 1.5 A_t^{1/3}$ fm, $a_I = 0.39$ fm (Ref. 8). ^6He optical potential ($^6Li + {}^{16}O$, 36 MeV): $V_R = -222.3$ MeV, $R_R = 1.21 A_t^{1/3}$ fm, $a_R = 0.80$ fm, $W_I = -11.8$ MeV, $R_I = 2.017 A_t^{1/3}$ fm, and $a_I = 1.035$ fm (Ref. 9); bound state potential ($n + {}^{16}O$): $R_R = 1.25 A_t^{1/3}$, $a_R = 0.63$ fm, $\lambda_{so} = 25$, and V_R adjusted to fit binding energy ($= \frac{1}{2} S_{2n}$).

[e] DWBA normalization relative to transition to ^{16}O g.s.

[f] DWBA normalization defined by Eq. (1) (Ref. 5).

[g] Unresolved doublet. We have deduced the 3^- strength listed by assuming unity for the relative 0^+ strength; the latter is calculated to contribute ~15% of the observed cross section.

[h] Assignment is uncertain (see Ref. 5). The $(\alpha, {}^6He)$ and (p,t) calculations assume $J^\pi = 0^+$ and $T = 0$.

tion of the $^{16}O(\alpha, {}^6He)^{14}O$ g.s. transition. We observed a cross section of $\lesssim 0.4$ μb/sr at 21° (lab) whereas the calculations, based on the ^{18}O normalization, predict ~0.2 μb/sr at this angle. The reduced cross section for $^{16}O(\alpha, {}^6He)^{14}O$ is a consequence of the increased neutron binding in ^{16}O and the strong absorption of the projectile which confines the reaction to the nuclear surface and introduces kinematic constraints (momentum matching, etc.). The latter effects account for most of the over-all reduction in the $(\alpha, {}^6He)$ cross sections compared with (p, t).

Perhaps surprisingly, the calculations also reproduce (to within a factor of 2) the absolute $(\alpha, {}^6He)$ cross sections, i.e., the g.s. N value deduced from our analysis ($N = 5.3$) is close to the value obtained[5] in $^{18}O(p,t)^{16}O$ g.s. ($N = 3.7$). The factor N should not necessarily be the same for the two reactions. If the α-neutron and proton-neutron forces had the same range, one would expect[6] $N(\alpha, {}^6He)/N(p,t) = |V_{\alpha n}|^2 (\Delta_{^6He})^3 / |V_{pn}|^2 \times (\Delta_t)^3$ where $V_{\alpha n}$ and V_{pn} are the strengths of the effective α-neutron and proton-neutron interaction and Δ is the projectile r.m.s. matter radius. Since $\Delta_{^6He} \approx 2.5$ fm and $\Delta_t \approx 1.7$ fm if one has $V_{\alpha n} = 4 V_{pn}$, then $N(\alpha, {}^6He)/N(p,t) \approx 51$; whereas if $V_{\alpha n} = V_{pn}$, then $N(\alpha, {}^6He)/N(p,t)$ would be ≈3.2. The experimentally observed ratio 1.44 is more consistent with the latter assumption. A more meaningful analysis of the relative cross sections will require a complete finite range treatment, however.

IV. CONCLUSIONS

The study of the $^{16,18}O(\alpha, {}^6He)^{14,16}O$ reactions at $E_\alpha = 58$ MeV indicates that the reactions are direct. The correspondence with (p,t) data for the same nuclei is close except that the $(\alpha, {}^6He)$ cross sections are much smaller and the angular distributions lack distinct features for high l transfers. Similar results have recently been reported[10] for $^{154}Sm(\alpha, {}^6He)^{152}Sm$. As in (p,t), our $(\alpha, {}^6He)$ data, with a few exceptions, can be successfully interpreted using DWBA theory, assuming transfer of a dineutron cluster in a relative s state. Thus, in $(\alpha, {}^6He)$ the ^6He may be considered as an α-particle core with two predominantly LS-coupled valence neutrons. This is consistent with shell-model calculations in this mass region.[11]

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