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# ($O^{16}$, $C^{12}$) Studies in the 2*s*-1*d* Shell*

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Angular distributions were measured for the ($O^{16}$, $C^{12}$) reactions on $Mg^{24,26}$, $Al^{27}$, and $Si^{28}$ at 42 MeV. States in the "α-particle" nuclei $Si^{28}$ and $S^{32}$ were populated strongly for $0 \le E_x \le 11$ MeV, while cross sections for transitions to states in $Si^{30}$ and $P^{31}$ were small. The $Si^{28}$ and $S^{32}$ ground-state angular distributions are sharply oscillatory in nature. The 4.43-MeV state of $C^{12}$ is strongly excited in the reaction $Mg^{24}(O^{16}, C^{12})Si^{28}$, but not in the others.

The ($Li^6$, *d*) and ($Li^7$, *t*) reactions have been shown to be useful in studying four-nucleon-transfer reactions on 1*p* shell and 2*s*-1*d* shell nuclei, and much attention has been focused on interpreting the results of such studies in terms of α-clustering models.[1] However, lithium-induced reaction cross sections decrease with increasing target mass (probably as a result of breakup competition), and it has been impractical to use this reaction to study 1*f*-2*p* shell nuclei. Since the ($O^{16}$, $C^{12}$) reaction provides a possible alternative probe for direct four-nucleon-transfer effects, Faraggi *et al.*[2,3] have studied the ($O^{16}$, $C^{12}$) reaction on a variety of even-mass targets in the 1*f*-2*p* shell and have seen strong population of highly excited states of several residual nuclei. They have interpreted these as quartet states of the sort predicted by Danos and Gillet.[4] Although such an interpretation is attractive in many respects, there are several difficulties which must be considered. It is not clear that the ($O^{16}$, $C^{12}$) reaction is a good "α-transfer" reaction. This reaction has received much less attention than the lithium-induced reactions and interpretation even of results of lithium studies is very difficult. The ($O^{16}$, $C^{12}$) angular-distribution studies[5] available for tandem beam energies and targets of mass $20 \lesssim A \lesssim 60$ are not sufficient to indicate whether or not these reactions are direct; most ($O^{16}$, $C^{12}$) experiments[2,3] have not involved measurements of angular distributions.

There is at least one indication that the ($O^{16}$, $C^{12}$) reaction may not involve as pure a direct four-nucleon-transfer mechanism as do lithium-induced reactions. $O^{16}(d, Li^6)C^{12}$ studies[6] have indicated that $O^{16}$ has about 4 times more α

$+C^{12*}$(4.43 MeV) parentage than it has $\alpha + C^{12}$(g.s.) parentage. Since none of the $1f$-$2p$ shell ($O^{16}$, $C^{12}$) studies have yielded any indication of residual population of the 4.43-MeV $2^+$ state of $C^{12}$, Robson has suggested[7] that this reaction must not be a good "$\alpha$-transfer" reaction.

Additionally, recent studies of ($O^{16}$, $N^{15}$) reactions have indicated that this reaction is direct and that angular-momentum matching effects are so important as to obscure nuclear-structure effects.[8,9] Thus, even if the ($O^{16}$, $C^{12}$) reaction were clearly a direct $\alpha$ transfer, there would be the possibility that a strong population of states at high excitation energy merely indicated favorable angular-momentum matching. This possibility clearly makes the already formidable task of identifying quartet states even more difficult.

In an effort to extend the present knowledge of the ($O^{16}$, $C^{12}$) reaction mechanism, we have measured angular distributions for this reaction on several $2s$-$1d$ shell targets. Two of the target nuclides ($Mg^{24}$ and $Si^{28}$) allow transitions to nuclei whose ground states should have strong $\alpha$ + target parentage. One ($Mg^{26}$) might be expected to show blocking effects of the sort noted in $1f$-$2p$ shell studies,[2,3] and one ($Al^{27}$) might be expected to show either blocking effects or a population of (weakly coupled) $S^{32}$ + hole states analogous to effects seen in the reaction $N^{15}$($Li^7$, $t$)$F^{19}$.[10]

A 42-MeV $O^{16}$ beam from the Pittsburgh three-stage tandem accelerator was used in this experiment. This beam energy was chosen because excitation-function studies on $Al^{27}$ indicated that peak cross sections for the ($O^{16}$, $N^{15}$) reaction[8] are not very sensitive to beam energy above $E_{O^{16}} \simeq 35$ MeV, but that the angle of the peak cross section decreases with increasing beam energy. Thus, the beam energy was selected to maximize dynamic range, yet keep the peak cross section [assuming that ($O^{16}$, $N^{15}$) angular distributions are typical] at a conveniently measurable laboratory angle. An array of three telescopes (each consisting of an ~9-$\mu$m $\Delta E$ surface-barrier detector in front of a ~50-$\mu$m $E$ surface-barrier detector) was used to detect emerging ions and analyze them as to energy and species. Signals from these detectors were processed by a Tennelec PACE-4 ADC plus PDP-15/40 on-line computer system. The resulting data were stored event-by-event on magnetic tape and further analyzed off line.

Figure 1 shows a spectrum for the reaction $Mg^{24}$($O^{16}$, $C^{12}$)$Si^{28}$. Although the ground-state

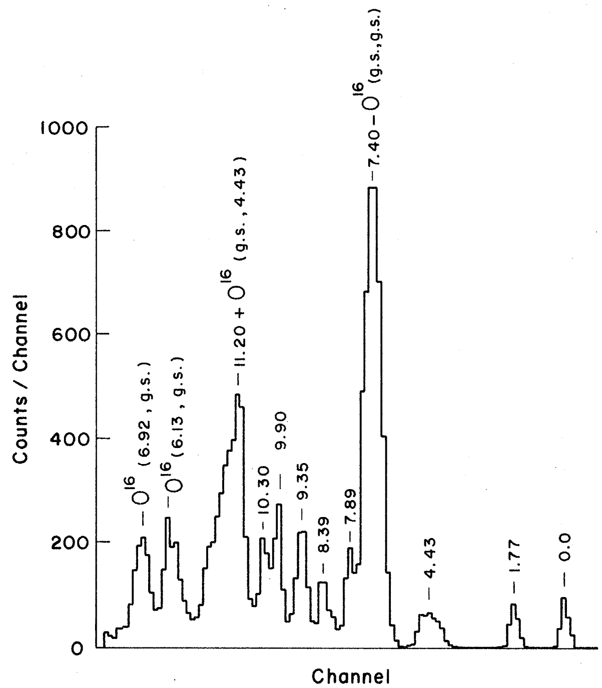


FIG. 1. $Mg^{24}$($O^{16}$, $C^{12}$)$Si^{28}$ spectrum measured at $\theta_{lab}=26°$.

transition is severely angular-momentum mismatched ($\Delta l_{favored}=5$), the ground state can be seen to be appreciably populated. The (Doppler-broadened) peak corresponding to a transition to $Si^{28}$(g.s.) + $C^{12}$(4.43 MeV) has ~3 times the yield of the ground-state peak. Above ~6 MeV the level density of $Si^{28}$ is sufficiently high that with present resolution (~250 keV) it is not possible to associate peaks with previously known $Si^{28}$ states,[11] but it is clear that approximately seven of the many $Si^{28}$ states between 6 and 11 MeV excitation energy are selectively populated. Table I lists the states (of all four residual nuclei) which are populated in this study along with their peak cross sections and the c.m. angles at which these peak cross sections occur. Except for the $Mg^{24} + O^{16} \rightarrow C^{12*}$(4.43 MeV) + $Si^{28}$(g.s.) transition, no (Doppler-broadening) evidence was seen for excitation of the 4.43-MeV $2^+$ state of $C^{12}$ in this study. No states were appreciably populated in $P^{31}$ and very few were populated in $Si^{30}$.

Figure 2 shows angular distributions for transitions to the low-lying levels of $Si^{28}$ and $S^{32}$ along with those to the high-lying levels of $Si^{28}$. Not only are the absolute cross sections large (~100 $\mu$b/sr) for angular-momentum-mismatched transitions to low-lying states, but the strongly

TABLE I. Peak cross sections and center-of-mass angles. States seen in the reaction $Al^{27}(O^{16}, C^{12})P^{31}$ are not included. (Several states having cross sections in the 1–25-μb/sr range were seen at high excitation energies, but could not be associated with known levels in $P^{31}$.)

| $Mg^{24}(O^{16},C^{12})Si^{28}$ | | | $Si^{28}(O^{16},C^{12})S^{32}$ | | |
|---|---|---|---|---|---|
| $E_x$ (MeV) | $\sigma_{max}$ (mb/sr) | $\theta_{max}$ (cm) | $E_x$ (MeV) | $\sigma_{max}$ (mb/sr) | $\theta_{max}$ (cm) |
| 0.00 | .07 | 39 | 0.00 | .40 | 32 |
| 1.77 | .07 | 39 | 2.24 | .34 | 32 |
| 4.43[a] | .13 | 34 | 4.29 | .88 | 33 |
| 7.40 | .68 | 35 | 4.70 | 2.67 | 37 |
| 7.89 | .22 | 35 | 5.50 | .60 | 37 |
| 8.39 | .32 | 35 | 6.40 | .36 | 34 |
| 9.35 | .32 | 36 | 6.90 | 1.33 | 37 |
| 9.90 | .28 | 48 | 8.00 | .88 | 38 |
| 10.30 | .39 | 36 | 9.80[b] | .05 | - |
| 11.20[b] | ∿.30 | - | | | |

| $Mg^{26}(O^{16},C^{12})Si^{30}$ | | |
|---|---|---|
| $E_x$(MeV) | $\sigma_{max}$(mb/sr) | $\theta_{max}$(cm) |
| 0.00 | .002 | 40 |
| 2.23 | .018 | 36 |
| 3.51 | .018 | 33 |

[a]The excited nucleus in this case is $C^{12}$.
[b]Obscured by impurities at most angles.

oscillatory structure of the ground-state angular distributions has not been observed for any other heavy-ion–induced transfer reaction in this region of target mass and beam energy. The angular distributions for transitions populating excited states show some oscillations, but have shapes more typical of other heavy-ion transfer reactions. The angular distributions shown for the strong transitions (~1 mb/sr) to high-lying states in $Si^{28}$ are similar to those populating high-lying states in $S^{32}$. It has not been feasible in this study to measure cross sections smaller than ~1–5 μb/sr, and it would be even more difficult to make very large-angle measurements (since the laboratory energy of the emerging ions would be too low for telescope measurements), but the angular distributions of Fig. 2 indicate a steep falloff of cross section with increasing angle and argue against interpreting the reaction in terms of compound nuclear processes.

It is difficult to make meaningful distorted-wave Born-approximation (DWBA) calculations because of, among other factors, the required complexity of the form factor, the expected importance of recoil effects, and, as for any multinucleon transfer reaction, the inability to separate structure and kinematic factors in the DWBA cross section. Extensions of this study are planned which will attempt such calculations, but even without realistic DWBA calculations it is interesting to consider the results of applying $Q$-value and angular-momentum matching considerations to the experimental results discussed above. The ground-state $Q$ values for the reac-

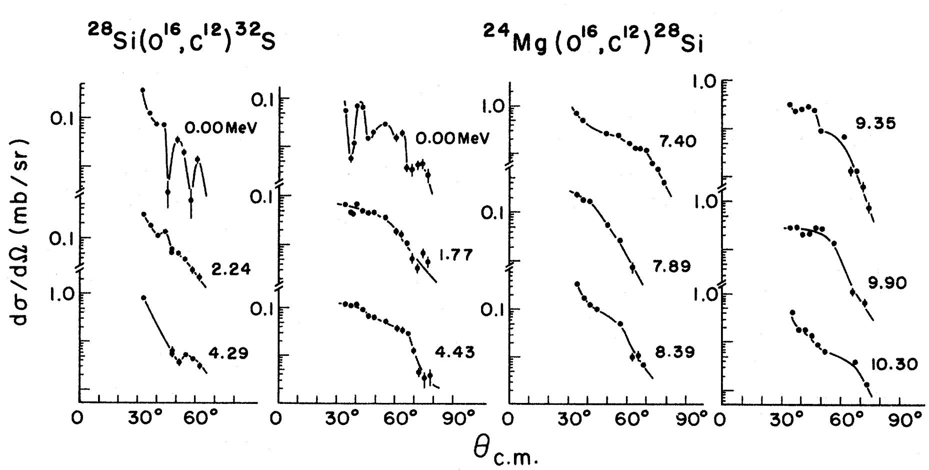


FIG. 2. Angular distributions for all strong $Mg^{24}(O^{16}, C^{12})Si^{28}$ transitions and for several $Si^{28}(O^{16}, C^{12})S^{32}$ transitions. Measurements were attempted at several angles larger than are shown, but the cross sections are so small at large angles that no meaningful data points could be added to the figure. Curves have been drawn to guide the eye and indicate that the cross sections do, in fact, decrease at larger angles.

tions $Mg^{24}(O^{16}, C^{12})Si^{28}$ and $Si^{28}(O^{16}, C^{12})S^{32}$ (2.82 and −0.23 MeV, respectively) span the range of ground-state $Q$ values for this study and for targets studied[2,3] in the $1f$-$2p$ shell. Also angular-momentum matching conditions, as a function of $Q$ value, are very similar for $A \sim 26$ targets studied at 42 MeV and $A \sim 54$ targets studied at 48 MeV. The favored angular-momentum transfer, $\lambda_f$, for the transition populating the $Si^{28}$ ground state is 3 units, while $\lambda_f = 1$ for the transition populating the $S^{32}$ ground state. For a state at $E_x = 4.5$ MeV in $Si^{28}$ $\lambda_f = 0$, and $\lambda_f = 3$ for the same excitation energy in $S^{32}$. Unless recoil effects blur the strong selectivity arising from the angular-momentum matching conditions, which is characteristic of the $(O^{16}, N^{15})$ reaction,[8,9] strong transitions involving mismatches of 2 or more units of angular momentum should indicate very enhanced form factors. Several interesting qualitative conclusions can be drawn from these considerations and the data presented above.

First, the strong $\lambda = 0$ transitions to the $Si^{28}$ and $S^{32}$ ground states, despite poor angular-momentum matching in the case of $Si^{28}$, probably indicate a real structure effect—*viz.*, a strong enhancement of the form factors for these states. This conclusion is strengthened by the observation that the $(O^{16}, C^{12})$ ground-state reactions on $Mg^{24}$ and $Mg^{26}$ have nearly identical $Q$ values and favored $\lambda$'s, yet the $Si^{28}$ ground-state cross section is about 35 times larger than that of the $Si^{30}$ ground state. The weak ($\lambda = 0$) ground-state transitions observed for the even-even $1f$-$2p$ shell nuclei—where the angular-momentum matching is no worse and is in some cases better than for $Si^{28}$—would then very reasonably indicate that the $1f$-$2p$ shell residual nuclei have smaller target-plus-$\alpha$ parentages than do $Si^{28}$ and $S^{32}$.

Second, the nature of the reaction mechanism remains in doubt, but the shapes of the angular distribution for the strong transitions certainly argue for noncompound nuclear processes. [It is unfortunate that the only energy dependences measured in this study were measured for the reactions $Al^{27}(O^{16}, C^{12})P^{31}$ where no states were populated strongly. An expansion of this work to look for energy dependences in the reaction $Mg^{24}(O^{16}, C^{12})Si^{28}$ is in progress.] The appearance of the 4.43-MeV state of $C^{12}$ in the reaction $Mg^{24}(O^{16}, C^{12})Si^{28}$ study provides at least one case where this state appears (and exceeds the ground state in cross section), but the failure to populate this state in other reactions—even though the angular-momentum matching conditions are either similar or more favorable in the other cases studied—may indicate a complication in the reaction mechanism in accordance with Robson's suggestions.[7] However, it is interesting to note that Siemssen *et al.*[12] have reported systematic and unexpected differences in angular distributions for apparently direct heavy-ion–induced one- and two-proton transfer reactions depending on which of the final nuclei is in an excited state.

Third, it is interesting to compare the systematics of the data presented above with those seen in Li-induced $\alpha$-transfer studies. In each case the most strongly populated states lie at high excitation energies. Low excited states of "$\alpha$-particle" nuclei are appreciably populated, but have distinctly smaller cross sections than do states in the range 6 MeV $\leq E_x \leq$ 11 MeV. Low excited states of the non-$\alpha$-particle nuclei $Si^{30}$ and $P^{31}$ are extremely weakly excited. One difference between lithium- and oxygen-induced reactions is the failure of the $(O^{16}, C^{12})$ reaction to populate states at high excitation in $Si^{30}$ with strong cross section. Additionally, despite the success of the weak-coupling model in relating the results of an $N^{15}(Li^7, t)F^{19}$ study[10] to those of an $O^{16}(Li^7, t)Ne^{20}$ study,[10] it is apparent that no such parallel can be drawn between the above $Al^{27}(O^{16}, C^{12})P^{31}$ and $Si^{28}(O^{16}, C^{12})S^{32}$ data.

Finally, the varying shapes of the measured angular distributions strongly suggest that discussions of target-to-target "blocking" effects based on absolute cross sections at one angle[2] may be oversimplified.

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# $^{58}$Ni($\alpha$, $\alpha'$)$^{58}$Ni and the Nature of High-Lying States in $^{58}$Ni

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We have studied levels in $^{58}$Ni up to 10 MeV excitation energy through the ($\alpha$,$\alpha'$) reaction at 30 MeV and found surprising overall agreement between the observed spectra and those from $\alpha$-transfer reactions.

There has been considerable interest recently in higher excited states seen in the ($^{16}$O,$^{12}$C) reaction in $f$-$p$-shell target nuclei[1,2] and their interpretation in terms of quartet structure.[3] Although it is now reasonably well established that the ($^{16}$O,$^{12}$C) reaction is direct, the nature of such heavy-ion reactions makes it difficult to obtain spectroscopic information, or even to establish

TABLE I. Comparison of levels in $^{58}$Ni above the first 3$^-$ state at 4472 keV strongly excited in the ($\alpha$,$\alpha'$) reaction and in the ($^{16}$O,$^{12}$C) and ($^7$Li,$t$) reactions.

| | ($\alpha$,$\alpha'$) | | ($^{16}$O,$^{12}$C)$^b$ | ($^7$Li,$t$)$^c$ |
|---|---|---|---|---|
| $E$ $^a$ (keV) | $J^\pi$ (This work) | $\beta_L$ (This work) | $E$ (±0.05) (MeV) | $E$ (±0.03) (MeV) |
| 4472 | 3$^-$ | 0.17 | 4.50 | 4.47 |
| 4750 | 4$^+$ | 0.076 | ··· | ··· |
| 5122 | Multiplet ($M$) | ··· | 5.22(?) | 5.03(?) |
| 5408 | $M$ | ··· | ··· | ··· |
| 5582 | 2$^{+\,d}$ | 0.067 | 5.59 | (Impurity) |
| 6024 | 3$^-$ | 0.059 | 6.03 | 5.98 |
| 6318 | $M$ | ··· | ··· | ··· |
| 6463 | $M$ | ··· | 6.45 | 6.42 |
| 6742 | 3$^-$ | 0.061 | 6.80 | 6.78 |
| 6847 | 3$^-$ | 0.073 | | |
| 7056 | $M$ | ··· | ··· | 7.03 |
| 7212 | 4$^+$ | 0.082 | 7.2 (±0.1)$^e$ | 7.13 |
| 7521 | 3$^-$ | 0.063 | 7.56 | 7.53 |
| 7734 | $M$ | ··· | 7.80 | 7.72 |
| 8108 | $M$ | ··· | 8.06 | |
| 8493 | (3,1)$^-$ | 0.052(3$^-$) | | |
| 8662 | (3,1)$^-$ | 0.057(3$^-$) | | |
| 9290 | $M$ | ··· | | |

$^a$The uncertainty, $\Delta E$, is ±8 keV for the levels up to 6742 keV, increasing to, at most, ±15 keV for the higher levels.
$^b$See Ref. 9.
$^c$See Ref. 4.
$^d$Given as 4$^+$ in Ref. 6; 4$^+$+5$^-$ in Ref. 7.
$^e$Taken from Ref. 1.