Resonant Effects in the Reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$

M. Paul, S. J. Sanders, J. Cseh,[a] D. F. Geesaman, W. Henning, D. G. Kovar, C. Olmer, and J. P. Schiffer[b]
Argonne National Laboratory, Argonne, Illinois 60439
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Excitation functions were measured at forward angles for the reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$ to the ground and first excited states of ^{28}Si. Resonancelike structures were found in both excitation functions with pronounced maxima at center-of-mass energies of ~28, ~31, and ~34 MeV. Angular distributions obtained at these three energies are fitted rather well with $P_L^2(\cos\theta)$ with $L = 21$, 23, and 25, respectively.

Both elastic and inelastic scattering of ^{12}C and ^{16}O on ^{28}Si have recently been found to exhibit remarkable bahavior.[1,2] The elastic cross section at 180° rises to several percent of the Rutherford cross section and exhibits resonancelike structures as a function of incident energy. Such behavior has previously been seen mostly in considerably lighter systems, usually with ^{12}C or ^{16}O as both target and projectile.[3] At present the nature of this resonance behavior is not understood. The angular momenta extracted from the backward-angle angular distributions at the resonance energies are close to those for the grazing partial waves. If these phenomena indeed occur in the grazing partial waves then similar resonancelike behavior might be expected, even at forward angles, in direct reactions that are strongly surface peaked. We report here measurements of the reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$; the exit channel is one in which several clear backward-angle resonances have been observed.[1,2] Some evidence[4] for backward-angle resonances has also been seen, in particular at $E_{c.m.} = 25.2$ MeV, in the inelastic scattering of ^{16}O to the 2^+ first excited state of ^{24}Mg and in the reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$ to the first 0^+ and 2^+ states of ^{28}Si. We have measured excitation functions for the 0^+ ground state and 2^+ first excited state of ^{28}Si at two forward angles (0° and ≈11°) and found strong resonant behavior as a function of bombarding energy.

The experiment was carried out with ^{16}O beams from the recently upgraded Argonne *FN* tandem Van de Graaff accelerator. Self-supporting Mg targets (>99.9% enriched in ^{24}Mg) of ~150 $\mu g/cm^2$ were used. The reaction products were momentum analyzed in an Enge split-pole magnetic spectograph and detected in an ionization-chamber, focal-plane detector.[5] For measurements at and near 0°, a gold foil was placed in front of the detector to stop the ^{16}O beam. The ^{12}C particles still had sufficient energy to be readily detectable and to yield ΔE-E signals for Z identification. The gold foils were typically ~10–20 mg/cm^2 thick, depending on the incident energy. The small-angle scattering in the foil caused a loss of ~15% in the detected ^{12}C yield. This loss was measured by comparing the observed yield at a small angle (~6°) with and without the foils. Corrections for the charge-state distribution of the ^{12}C ions were also made. The relative normalization of the cross sections was obtained from the yield of elastically scattered ^{16}O ions detected in a Si surface-barrier monitor counter at ~12°; optical-model calculations were used to determine the energy dependence of the elastic scattering. The yield of elastically scattered ^{16}O ions detected at small angles in the spectrograph was used to establish the absolute cross sections.

Excitation functions, shown in Fig. 1, were obtained at 0° and also at a larger scattering angle near $\theta_{lab} = 11°$. Since the ground-state angular distribution is known to be sharply oscillatory,[6] this excitation function was determined at the second maximum after 0° in the angular distribution, by measuring the yield at each energy at three or four angles, between 8° and 14°, and interpolating the corresponding maximum cross section. The excitation function to the 2^+ state in ^{28}Si was also measured in this region of scattering angle, using a similar procedure. The estimated errors in the interpolation process are included in Fig. 1. Pronounced resonant effects are clearly evident in the 0° yield; the other two excitation functions show similar, correlated structures. The 180° elastic excitation function of Ref. 1 for the $^{12}C + ^{28}Si$ channel is shown for comparison in Fig. 1; the structures are qualitatively similar to but not clearly correlated with those found in the reaction data.

Angular distributions for the reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si(g.s.)$ are shown in Fig. 2 at the three resonance energies, $E_{lab} = 47$, 52, and 57 MeV. The solid lines are the squares of Legendre poly-

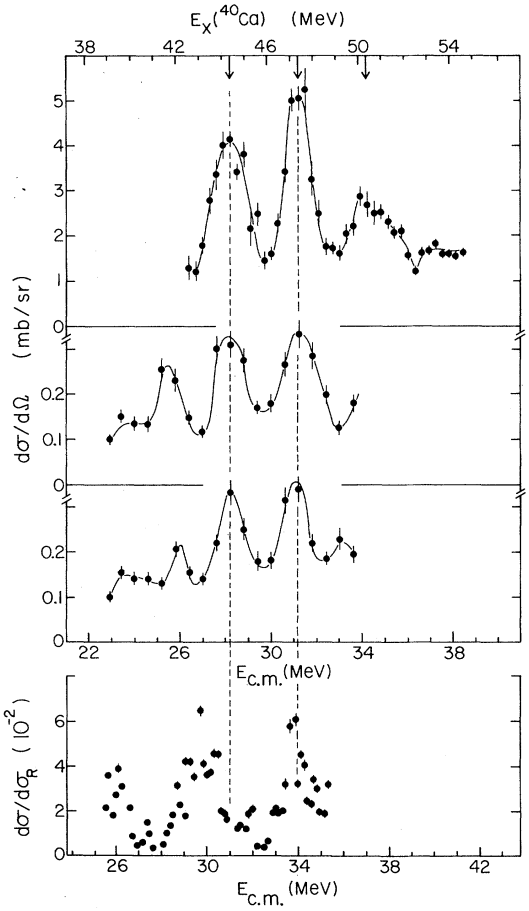

FIG. 1. Excitation functions for the reaction $^{24}Mg(^{16}O, ^{12}C)^{28}Si$. The top curve is the $\theta_{lab} = 0°$ ground-state yield; the second and third curves from the top are excitation functions for the yields to the ground 0^+ and 2^+ first excited states of ^{28}Si at the maximum near the laboratory angle of 11°. The $^{28}Si + ^{12}C$ elastic-scattering excitation function measured at 180° from Ref. 1 is included at the bottom, with the ratio to Rutherford-scattering cross section plotted; the energy scale is adjusted to give the same excitation energy in ^{40}Ca as the top three curves. The solid lines connecting the points are guides to the eye; dashed vertical lines are used to indicate the observed resonance positions. Angular distributions were obtained at the energies indicated by arrows. The errors shown are relative; absolute errors in the cross section are ~25%.

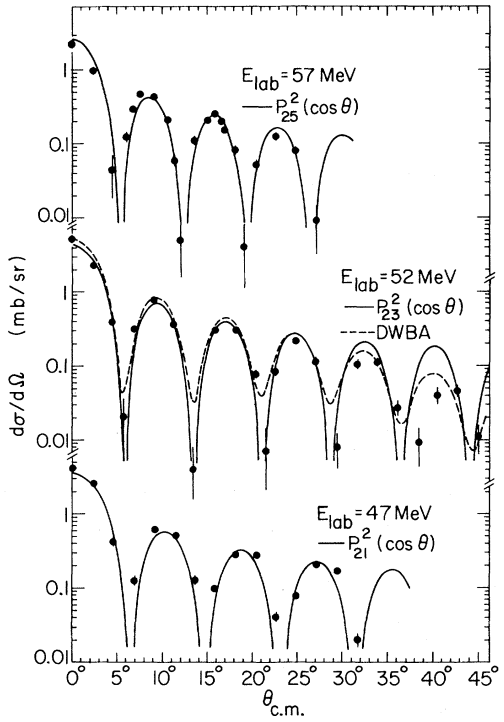

FIG. 2. Angular distributions for the reaction $^{24}Mg(^{16}O, ^{12}C)^{28}Si(0^+)$. The solid lines are calculations of $P_L^2(\cos\theta)$ with the indicated value of L and with the absolute magnitude adjusted to give a best fit to the data. The dashed line on the middle curve is a DWBA calculation mentioned in the text. The errors shown are relative; absolute errors in the cross section are ~25%.

nomials, $P_L^2(\cos\theta)$ with $L = 21$, 23, and 25, which have been adjusted to fit the data. At each energy, a change in the assigned L value by one unit doubles the value of χ^2. The values of L are near those of the grazing partial waves, as were the ones observed in the elastic scattering data. As previously shown,[6] distorted-wave Born-approximation (DWBA) calculations are capable of reproducing the observed shapes of the angular distributions for this reaction. Shown in Fig. 2 is a calculated[7] DWBA angular distribution for the transition to the ^{28}Si ground state at $E_{lab} = 52$ MeV using the "conventional" optical-model and bound-state parameters of Erskine *et al.*[6] Since the reaction $^{24}Mg(^{16}O, ^{12}C)^{28}Si$ is well matched kinematically, only few partial waves contribute. The calculated distribution of reaction amplitudes in L space is approximately Gaussian around the grazing partial wave, with a width of $\sim 5\hbar$. Comparison of the shape predicted by DWBA and by a pure Legendre polynomial shows the difficulty in establishing whether a *single* resonant angular momentum is responsible for the resonance. The *dominant* L in the angular distribution is apparently well established by the shape of the angular distribution.

The correlated structure seen at $E_{c.m.} = 25.2$ MeV in Ref. 4 also appears in the present 11° excitation function. It is interesting to note that

Peng *et al.*[6] have measured an angular distribution at this energy and that the location of the minima in the angular distribution seems to be consistent with $L = 19$.

The origin of these resonant structures is still not understood. They seem to be similar to those seen in the $^{12}C + ^{28}Si$ elastic channel but not identical with them in energy or partial wave. A number of questions may be asked.

(1) Are such resonances readily generated as "shape resonances" by simple surface-transparent optical potentials, or are they evidence for more subtle effects in the structure of ^{40}Ca at high angular momenta?

(2) If they are shape resonances, how is one to understand the relationship between the resonances in the entrance and the exit channels? One might expect the reaction channel to exhibit more complex structure in its excitation function and less sharp localization in L than either elastic channel. Neither expectation seems to be borne out.

(3) Does the α-transfer reaction play a special role in these resonances and is the symmetry of α-particle nuclei an essential ingredient? Will resonances be seen in α transfer to states other than the 0^+ and 2^+ states, or in transfer reactions other than α transfer? Is it the good momentum matching and surface localization of the α transfer that matters, or are sturctural symmetries important?

(4) What happens in heavier systems? There is some evidence for backward-angle oscillations in $^{12}C + ^{40}Ca$ elastic scattering, though the cross sections is $\sim 10^{-4}$ times the Rutherford cross section,[8] but will effects similar to those seen here appear in transfer reactions on ^{40}Ca?

Strong resonancelike structures, well defined in angular momentum, are seen at forward angles, where the reaction was assumed to be purely direct and smoothly varying in energy. The ramifications of such resonances in nuclear structure —the implied simplicity of high-angular-momentum configurations at high excitation—will become apparent only with considerably more experimental effort.

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[a]Visitor from Institute of Nuclear Research of the Hungarian Academy of Sciences, Debrecen, Hungary.
[b]Also at the University of Chicago.

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