state cross sections should be calculated using better wave functions. Further studies are needed on the importance of the approximations being made and on cross-section sensitivity to pion wave functions. Experimentally it would be useful to improve pion resolution and to obtain angular distributions. To this end, a new pion spectrometer is being built for use in the new experimental hall under construction at Bates.

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Structure in the $^{24}Mg(^{18}O,^{14}C)^{28}Si$ Ground-State Excitation Function

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The excitation function of the reaction $^{24}Mg(^{18}O,^{14}C)^{28}Si$(g.s.) has been measured at the second maximum of the angular distributions ($\theta_{lab} \simeq 5°$) from 39- to 65-MeV incident energies. Oscillatory structure in the excitation function is observed with peak-to-valley ratios equal to ~1.5. The angular distributions measured near the maxima of the excitation function decrease more rapidly toward large angles than squares of Legendre polynomials, suggesting a direct reaction process to be important. Standard distorted-wave Born-approximation calculations do fit the angular distributions quite well, but fail to reproduce the structure in the excitation function.

Much recent experimental effort has focused on the resonancelike phenomena observed in the interaction of ^{12}C and ^{16}O with ^{24}Mg, ^{28}Si, and ^{40}Ca nuclei.[1-5] Elastic- and inelastic-scattering excitation functions measured at back angles contain resonances with angular distributions characterized by the squares of single Legendre polynomials. The scattering cross sections at back angles are found to be anomalously large with values several orders of magnitude greater than the predictions of optical models which fit forward-angle scattering data. In the α-particle transfer reactions, where both the entrance and exit channels exhibit resonance behavior, structure is observed at both forward and back angles.[6-10] The structure is quite strong in the case of $^{24}Mg(^{16}O,^{12}C)^{28}Si$ excitation functions, but less pronounced for $^{28}Si(^{16}O,^{12}C)^{32}S$. In both cases the back-angle excitation functions show resonance structure which is correlated only weakly, if at all, with the resonances observed by scattering in the entrance and exit channels. Thus far there are too few data to

determine whether the structure in the (^{16}O, ^{12}C) reaction is related to the structure in the entrance and exit channels, or whether another mechanism, perhaps related to α transfer, is responsible for the (^{16}O, ^{12}C) structure.

In the case of anomalous back-angle elastic scattering, the effect has been observed only with α-particle-type targets and projectiles. Back-angle elastic scattering cross sections for ^{12}C + ^{29}Si, and ^{12}C + ^{28}Si,[4] for example, are two orders of magnitude smaller than the cross section for ^{12}C + ^{28}Si. Similarly, ^{18}O + ^{28}Si back-angle scattering is about 250 times smaller than in the ^{16}O + ^{28}Si system.[11]

In this Letter we report measurements of the ^{24}Mg(^{18}O, ^{14}C)^{28}Si ground-state reaction in the energy range 40 MeV $\leq E_{1ab}(^{18}\text{O}) \leq$ 65 MeV. One purpose of the present study is to determine whether the structure observed in ^{24}Mg(^{16}O, ^{12}C) excitation functions persists in α transfer reactions involving non-α projectiles. The present study may also shed some light on the (^{18}O, ^{14}C) reaction mechanism, for which very few data exist.

The ^{18}O beam from the Los Alamos Scientific Laboratory tandem Van de Graaff accelerator was used to bombard a ^{24}Mg self-supporting target of approximately 80-μg/cm^2 thickness. A helical cathode proportional chamber,[12] designed for heavy-ion detection, was placed in the quadrupole–triple-dipole spectrometer to provide clear identification of the ^{14}C reaction products. Excitation functions of the ^{24}Mg(^{18}O, ^{14}C)^{28}Si(g.s.) transition are shown in Fig. 1. Three procedures were used to establish the energy dependence of the cross sections. First, several measurements were made at each energy, at various angles around the position of the second maximum ($\theta_{1ab} \simeq 5°$), in the angular distribution. The peak cross section was extracted at each energy and is shown by the open circles in Fig. 1. Using the energy dependence of the angular position of the second maximum obtained in the first method above, a second excitation function, given by the filled circles, was generated from cross sections measured at the peak angle at each energy. Finally, also shown in Fig. 1 is the excitation function measured at a fixed angle ($\theta_{1ab} = 7.5°$, $\Delta\theta_{1ab} = \pm 2.3°$).

Two features of the excitation function in Fig. 1 are readily noted: (1) The cross section increases as the beam energy rises above the Coulomb barrier, reaching a peak value at about 50-MeV incident energy; the cross section then decreases as the beam energy increases further. (2) Oscillatory structure with peak-to-valley ratios of

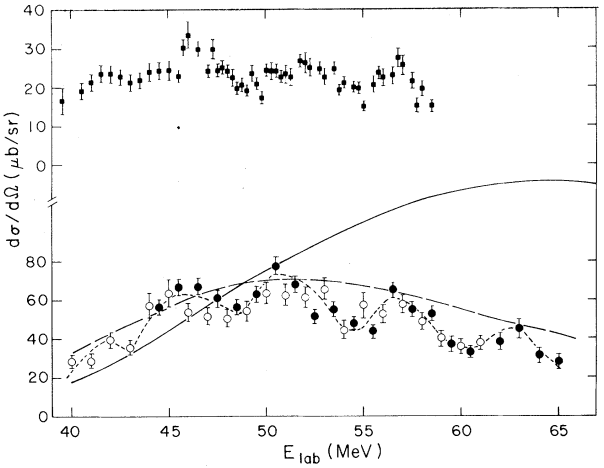

FIG. 1. Excitation functions for the ^{24}Mg(^{18}O, ^{14}C)^{28}Si (g.s.) transitions. The upper excitation function was measured at a fixed angle ($\theta_{1ab} = 7.50$, $\Delta\theta_{1ab} = \pm 2.3°$). The lower excitation function corresponds to the peak cross section at the second maximum ($\theta_{1ab} \simeq 5°$) of the angular distribution. Solid circles indicate the peak cross section extracted from measurements at several angles around the second maximum. Open circles indicate measurements at the estimated peak angle. (See text.) The short-dashed curve is to guide the eye. The solid and long-dashed curves are predictions of DWBA calculations using, respectively, an energy-independent and an energy-dependent optical potential.

~ 1.5 is present in the excitation function. Though not very sharply defined in energy, the peak cross sections occur at approximately $E_{1ab}(^{18}\text{O})$ = 42, 46, 51, 57, and 63 MeV.

Figure 2 shows the angular distribution of the reaction ^{24}Mg(^{18}O, ^{14}C)^{28}Si measured at $E_{1ab}(^{18}\text{O})$ = 46, 51.5, 57, and 48.75 MeV. The first three energies are near maxima in the excitation function while the last energy lies near a minimum. Also shown in Fig. 2 are curves of squares of the Legendre polynomials [$P_J^2(\cos\theta)$] which best describe the period of oscillation of the data at the most forward angles. It is apparent that the experimental cross sections decrease much faster with increasing angle than the P_J^2 curves, and that the data gradually oscillate out of phase with the P_J^2 curves at the larger angles. There is little qualitative change between the angular distributions measured at maxima and minima in the excitation functions. These features strongly indicate that several angular momenta contribute to the cross section at each energy, and that direct processes may be dominant in the reaction.

It is interesting to compare the present measurements of the reaction (^{18}O, ^{14}C) with the reac-

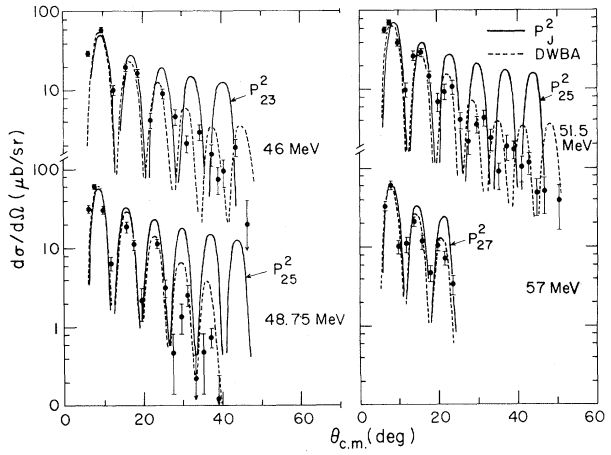

FIG. 2. Angular distribution for the ^{24}Mg(^{18}O, ^{14}C)^{28}Si (g.s.) transition at several energies. The squared-Legendre-polynomial fits are shown as solid curves and the DWBA calculations are dashed curves. The angular acceptance is $\Delta\theta_{lab} = \pm 1.2°$.

tion ^{24}Mg(^{16}O, ^{12}C)^{28}Si. In both cases the structure in the cross sections is smooth and regularly spaced, although for (^{18}O, ^{14}C) the amplitude is only about half that observed for (^{16}O, ^{12}C). The maxima in the ^{24}Mg(^{18}O, ^{14}C)^{18}Si excitation function are located at very similar laboratory beam energies as those in the ^{24}Mg(^{16}O, ^{12}C)^{28}Si excitation function [$E_{lab}(^{16}O) = 42$, 47, 52, 57 MeV]. This agreement is probably accidental since it disappears when the excitation functions are compared in the center-of-mass systems of the different reactions. Furthermore, the angular distributions of corresponding peaks in the two reactions differ in their period of oscillations, with the shorter period belonging to the reaction (^{18}O, ^{14}C). A difference in J values of two units of angular momentum is implied by these angular distributions.[6,13] This is consistent with the difference in the dominant partial waves for the two reactions that is indicated by distorted-wave Born-approximation (DWBA) calculations. It is nevertheless significant that, as in the reaction ^{24}Mg(^{16}O, ^{12}C)^{28}Si, odd J values appear to be dominant partial waves near the maxima of the (^{18}O, ^{14}C) excitation function.

In order to examine the role of direct processes in the reaction ^{24}Mg(^{18}O, ^{14}C), we have made finite-range DWBA calculations using the code LOLA.[14] In Fig. 2 the dashed curves show the angular distributions calculated with the six-parameter Woods-Saxon potential used by Berg *et al.*[15] to fit the ^{28}Si(^{18}O, ^{14}C)^{32}S angular distributions at 60 MeV. These curves fit the present data appreciably better than do the squared Legendre polynomials, as they reproduce both the oscillations and the falloff with angle reasonably well. This good agreement indicates the importance of a direct process in the present reaction, and also emphasizes that the angular distributions are characteristic of the dominant partial waves rather than of intermediate-spin assignments.

Despite the good agreement with the angular distributions, the DWBA calculations using the potential described above fail to reproduce either the general shape or the structure of the excitation function as shown by the solid curve in Fig. 1. It is perhaps not surprising that the general shape is not reproduced, since the same optical potential is used over a wide energy range (~ 25 MeV), and global fits to the ^{12}C + ^{28}Si elastic scattering over a wide energy range suggest the preference of energy-dependent potentials.[16] In fact, better agreement with the present excitation function is achieved by use of an energy-dependent imaginary potential ($W = 259 - 3.72E$), as shown by the long-dashed curve in Fig. 1. The angular distribution shapes with this potential are similar to those obtained using a constant W.

The failure of DWBA calculations to fit the structure in the excitation function indicates the likelihood that some resonancelike process that cannot be described by present direct-reaction theories contributes to the reaction ^{24}Mg(^{18}O, ^{14}C)^{28}Si. The relationship between this structure and that of the reaction ^{24}Mg(^{16}O, ^{12}C) is not clear, although several obvious similarities have been noted. The mild and quite regularly spaced oscillations observed in the present excitation function suggest the presence of shape resonances similar to those found in the ^{16}O + ^{16}O scattering. The ^{16}O resonances are described by surface-transparent optical potentials,[17] but the present DWBA calculations, which utilize a surface-transparent potential ($r_v > r_w$, $a_v > a_w$), do not produce any oscillations in the excitation function. Furthermore, even if one succeeds in producing oscillations by using an extremely surface-transparent potential, one would still need to introduce parity dependence in the potential to inhibit the even partial waves, as was done by Dehnhard *et al.*[18] to describe the back-angle-scattering excitation function in the ^{16}O + ^{28}Si system. We have performed DWBA calculations in which the effect of parity dependence was simulated crudely by the modification $\beta_L \rightarrow \beta_L[1 + a(-1)^L]$. No structure in the excitation function at forward angles is obtained

even for such unreasonably large values of a as 0.3, although the back-angle excitation function does become strongly structured.

In summary, resonancelike structure is observed in the excitation function of the reaction $^{24}Mg(^{18}O, ^{14}C)^{28}Si$, where resonant behavior in the entrance and exit channels is not expected. While the angular distributions are well described by direct-reaction calculations, the resonant structure cannot be reproduced by such calculations at present. The relationship with the resonances in the reaction $^{24}Mg(^{16}O, ^{12}C)$ as well as the origin of the structure in both reactions remain unexplained.

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Energy Dependence of Pion Production by Protons on Nuclei

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The reactions $^{10}B(p,\pi^+)^{11}B$(g.s.) and $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) have been studied with proton beams in the energy range 140 to 200 MeV. Angular distributions at several energies, supplemented with fixed-angle cross-section data at several other energies, establish for the first time the energy dependence of these reactions in the near-threshold region.

The proton-induced pion production reaction, leaving a nucleus in a discrete final state, is known to exhibit distinct variations in character for different targets and residual nuclear states. If the production process can be sufficiently well understood, the reaction might constitute a useful spectroscopic tool for investigation of the high-momentum components of nuclear wave functions. The momentum transfer to the nucleus in this reaction is 2 or 3 times larger than the nuclear Fermi momentum. The reaction also may provide interesting new information about the production and propagation of pions in strong nuclear fields.

The experiments of Dahlgren *et al.*[1] and Höistad, Johansson, and Jonsson,[2] in particular, and more recent investigations[3-6] have stimulated a significant theoretical effort[7-14] to unravel the basic features of the production process. None of the interpretations so far can be regarded as entirely satisfactory because interrelated questions regarding the reaction mechanism, pion rescattering, and nuclear structure have so far allowed too much theoretical freedom with respect to the limited experimental data available.

The present work was motivated by the expectation that a thorough investigation of the energy dependence of the cross sections for a few final states as the threshold energy is approached would be of substantial benefit in determining a proper description for the production process. The energy dependence of the (p,π^+) reaction as

