Experimental evidence of multistep processes in the $^{74}Ge(^{18}O,^{16}O)^{76}Ge$ and $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ reactions*

P. D. Bond, H. J. Korner,† M.-C. Lemaire,‡ D. J. Pisano,§ and C. E. Thorn
Brookhaven National Laboratory, Upton, New York 11973
(Received 9 March 1977)

Angular distributions of the $^{74}Ge(^{18}O,^{16}O)^{76}Ge$ and $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ reactions have been measured at incident energies of 75 and 77.6 MeV, respectively. The time-reversed reaction cross sections leading to the Ge ground states are nearly identical bell shaped curves. Stripping and pickup angular distributions to the Ge 2^+ states show a strong shape difference suggesting interference between direct and two-step transfer. Angular distributions for which ^{18}O is in its first 2^+ state are similar in shape to those with ^{18}O in its ground state. Data are also presented for elastic and inelastic scattering in both entrance and exit channels as well as for single-neutron transfer.

[NUCLEAR REACTIONS $^{74}Ge(^{18}O,^{16}O)$, $(^{18}O,^{17}O)$, $(^{18}O,^{18}O)$ $E=75$ MeV; $^{76}Ge(^{16}O,^{18}O)$, $(^{16}O,^{16}O)$ $E=77.6$ MeV; measured $\sigma(\theta)$.]

I. INTRODUCTION

The importance of multistep processes in heavy-ion induced two-nucleon transfer reactions has been discussed by several authors.[1-3] Specifically, it has been predicted for incident energies moderately above the Coulomb barrier that two-step processes involving inelastic scattering and transfer can strongly change the shape of the angular distributions for 2^+ states from the "normal" bell shape of the ground state transition. Several experiments on deformed[4] and vibrational[5-7] nuclei have shown shape changes in 2^+ angular distributions which have been attributed to pure two-step transitions or to interference between the direct and indirect transitions. A particularly striking prediction[1,2] for transfer to 2^+ *vibrational* states is that the sign of this interference is opposite for stripping and pickup reactions; hence quite different shapes could be expected for "inverse" reactions.

This paper reports data on the $^{74}Ge(^{18}O,^{16}O)^{76}Ge$ and $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ transfer reactions which demonstrate a *dramatic* difference in the shape of the angular distributions of the 2^+ states in stripping and pickup. A similar experiment by the Berkeley group[8] on the Sn isotopes investigated the magnitude dependence of the 2^+ states in stripping and pickup near the grazing peak, but the lack of data both forward and backward of the grazing peak precludes any conclusion about the influence of the interference between direct and indirect routes on the shapes of the angular distributions. The results reported here are thus the first which conclusively demonstrate a shape change in the angular distributions for stripping and pickup reactions on vibrational nuclei.

This paper also reports data for elastic and inelastic scattering in both entrance and exit channels as well as for single-neutron transfer. These results should serve to constrain optical model parameters and the data taken as a whole should provide an extremely sensitive test of our understanding of both the reaction mechanisms and the structure of the nuclear states. The following paper will discuss a coupled-channel analysis of the data presented here.

II. EXPERIMENTAL TECHNIQUE

The experiments were performed with 6^+ ^{18}O and ^{16}O beams from the Brookhaven tandem Van de Graaff accelerator. Incident energies of 75 MeV for ^{18}O and 77.6 MeV for ^{16}O were chosen so the $(^{16}O,^{18}O)$ reaction to the ^{74}Ge ground state (g.s.) was the time reverse of the $(^{18}O,^{16}O)$ reaction to the ^{76}Ge g.s. The targets were small spots (2×5 mm) of isotopically enriched ^{74}Ge or ^{76}Ge, 50 $\mu g/cm^2$ thick, supported on 20 $\mu g/cm^2$ carbon backings and overcoated with ~6 $\mu g/cm^2$ of carbon. It was observed that these Ge targets could withstand beam currents of 1 μA only if they were overcoated and oriented with the beam incident on the thicker carbon backing. Reaction products were momentum analyzed in the BNL quadrupole-dipole-dipole-dipole (QDDD) spectrometer and detected by a 70 cm long proportional counter in the focal plane. This counter consists of two proportional counters separated by a thin cathode plane. The front counter measures energy loss and the rear, thicker counter measures the residual energy of the ions. Position is determined at the front wire by the

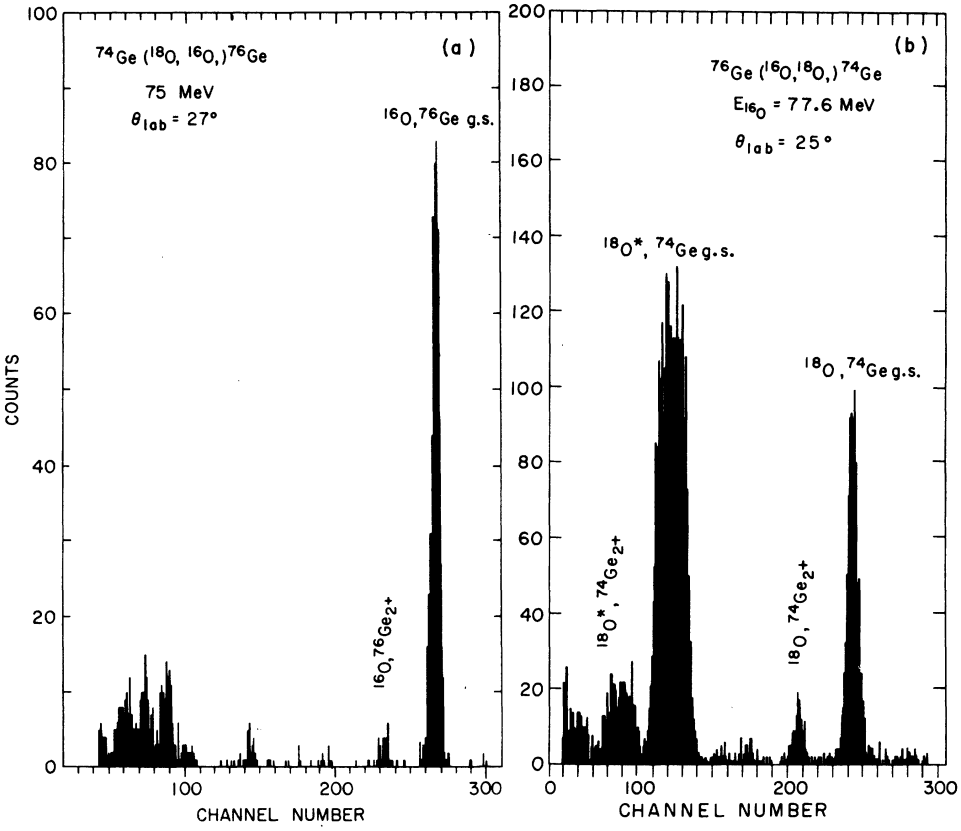

FIG. 1. (a) Position spectrum of outgoing ^{16}O ions taken at $\theta_{lab}=27°$ in the reaction ^{74}Ge(^{18}O, ^{16}O)^{76}Ge. (b) Position spectrum of outgoing ^{18}O ions in the reaction ^{76}Ge(^{16}O, ^{18}O)^{74}Ge taken at $\theta_{lab}=25°$.

charge division method using an analog divider circuit. The position resolution of this detector (about 1.5 mm) makes a negligible contribution to the observed energy resolution of 80 keV. It was found that all particles incident on the focal plane could be distinguished by using only the two dimensional map of residual energy vs position. For the (^{16}O, ^{18}O) reaction the yield of ^{15}N (7^+) ions tended to obscure the ^{18}O (8^+) ions at some angles if both ions were stopped in the detector. This difficulty was avoided by adjusting the gas pressure to just stop the ^{18}O (8^+) ions but not the ^{15}N (7^+) ions. Charge state ratios were measured at several angles and found to be consistent with those previously tabulated.[9] Yields were normalized to a monitor counter and then corrected for charge state fraction according to the curves in Ref. 9. This correction amounted to an overall increase in yield of about 30% and a relative correction between forward and backward angles of 3%. Most of the data were taken with a solid angle of 4 msr and an angular aperture of 2.3° in the reaction plane. Absolute cross sections were determined by measuring elastic scattering which was assumed to be Rutherford at forward angles.

III. RESULTS

Figure 1(a) shows a position spectrum of outgoing ^{16}O ions from the (^{18}O, ^{16}O) reaction. Of the ^{76}Ge levels observed in the two-neutron stripping reaction, the ground state is the strongest transition in the 3.5 MeV excitation energy range studied here. In contrast, the spectra obtained in the pickup reaction [see Fig. 1(b)] are dominated by the population of the ^{18}O 2^+ state at 1.98 MeV (^{18}O*) leaving ^{74}Ge in its ground state. This peak is about 400 keV wide due to the in-flight γ decay of the ^{18}O*, but it conveniently falls in a gap in the energy level spectrum of ^{74}Ge. The mutual excitation of ^{18}O* and the ^{74}Ge 2^+ state at 0.597 MeV (^{74}Ge*) is also Doppler broadened and cannot be separated from transitions to ^{74}Ge states near 2.5 MeV in excitation (with ^{18}O in its ground state).

The differential cross sections of the ^{74}Ge-(^{18}O, ^{16}O)^{74}Ge (g.s.) and the ^{76}Ge(^{16}O, ^{18}O)^{74}Ge (g.s.) are displayed in Fig. 2. Within the experimental uncertainties, the stripping and pickup bell-shaped angular distributions are identical, as expected for time-reversed reactions. There is an expected 3% difference in magnitude due to the ratio $(k_f/k_i)^2$

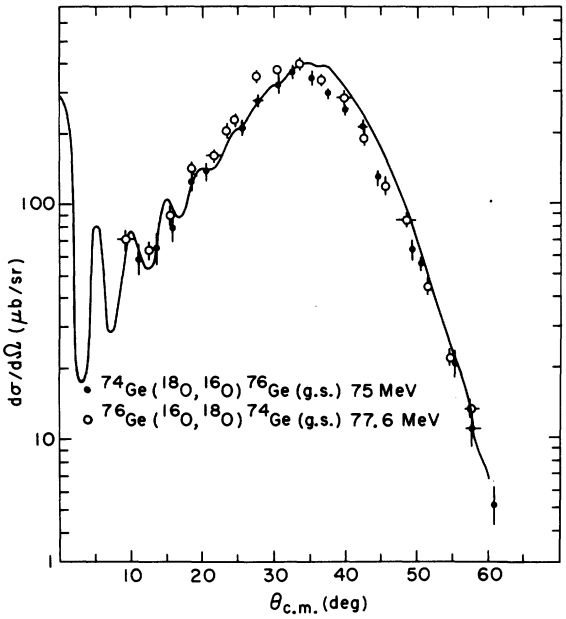

FIG. 2. Angular distributions of the reactions $^{74}Ge(^{18}O, ^{16}O)^{76}Ge$ (g.s.) and $^{76}Ge(^{16}O, ^{18}O)^{74}Ge$ (g.s.) The horizontal uncertainties indicate the opening angle of the QDDD. The solid curve is a calculation, arbitrarily normalized, using the code LOLA.

between the two reactions, but such a factor is smaller than the experimental uncertainty.

The angular distributions for reactions to the 2^+ vibrational states of ^{74}Ge and ^{76}Ge, shown in Fig. 3, are very different from those observed for

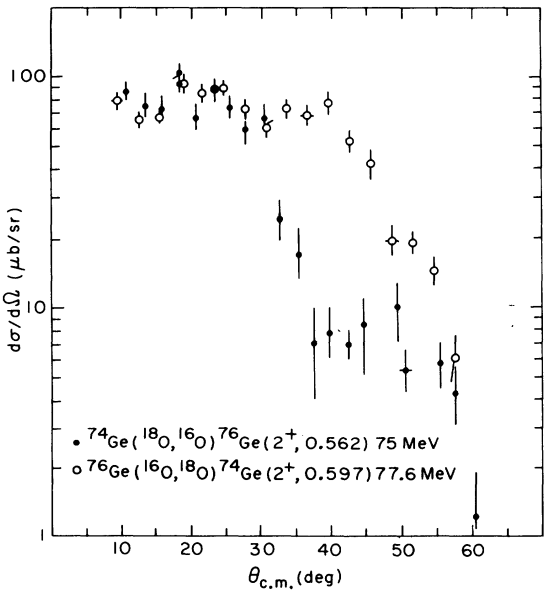

FIG. 3. Angular distributions of the $^{74}Ge(^{18}O, ^{16}O)^{76}Ge$ (2^+) and $^{76}Ge(^{16}O, ^{18}O)^{74}Ge$ (2^+) reactions.

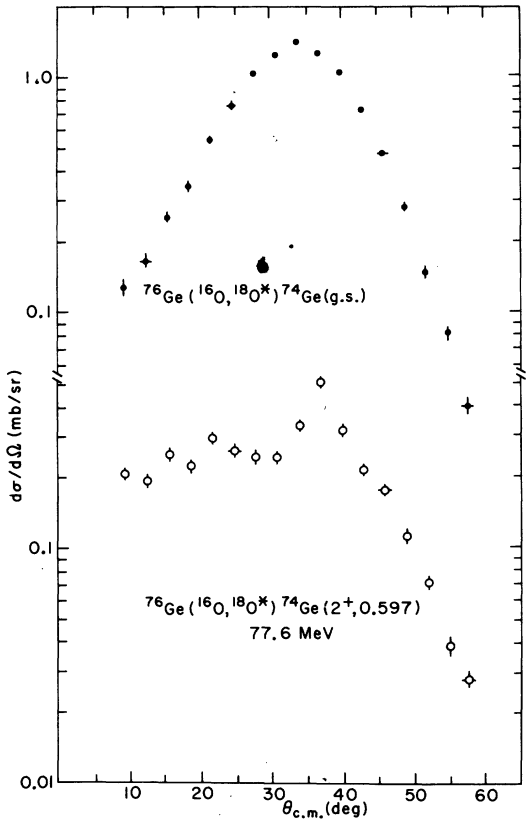

FIG. 4. Angular distributions of the $^{76}Ge(^{16}O, ^{18}O)^{74}Ge$ reactions in which ^{18}O is in its 1.98 MeV, 2^+ state and ^{74}Ge is in its g.s. or first 2^+ state.

the ground state transitions. Both 2^+ cross sections are flat forward of 30°, in contrast to the g.s. angular distributions which drop sharply. Any oscillations in the forward angle cross section would be reduced substantially by the rather large opening angle (2.3°) which was used to take the data. The $(^{16}O, ^{18}O)$ pickup reaction continues to be flat to about 40°, somewhat past the grazing angle, but the $(^{18}O, ^{16}O)$ stripping cross section shows a steep drop forward of the grazing angle followed by a "plateau" between 40° and 55°. The difference in shape of the 2^+ cross sections clearly shows that these are not both single-step nor both pure two-step reactions and strongly implies that destructive interference with the direct transfer is occurring in the $(^{18}O, ^{16}O)$ stripping reaction.

The cross sections for ^{18}O produced in its 1.98 MeV 2^+ excited state ($^{18}O^*$) in the $^{76}Ge(^{16}O, ^{18}O)^{74}Ge$ experiment are large (Fig. 4). The shape of the ^{74}Ge g.s. $+ ^{18}O^*$ cross section is almost identical to the ground state angular distributions shown in Fig. 2, but its magnitude is about a factor of 3.5 larger than the cross section with ^{18}O in its g.s. The angular distribution for the exit channel ^{74}Ge

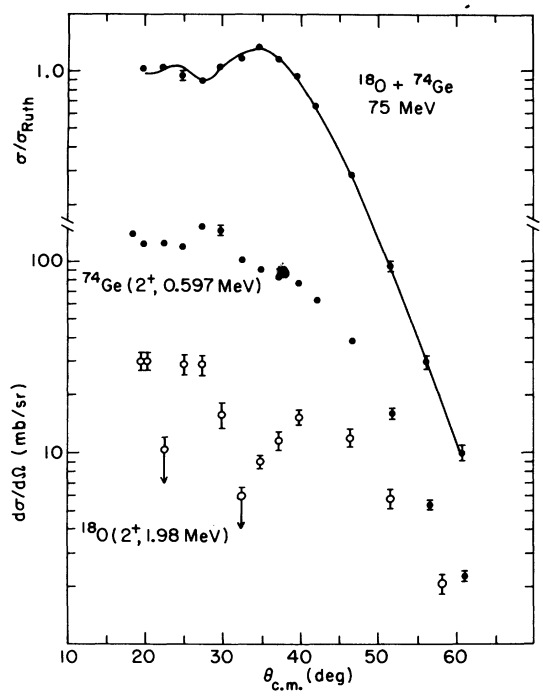

FIG. 5. Elastic and inelastic scattering angular distributions of $^{18}O+^{74}Ge$ at 75 MeV. The solid line was calculated with the code A-THREE.

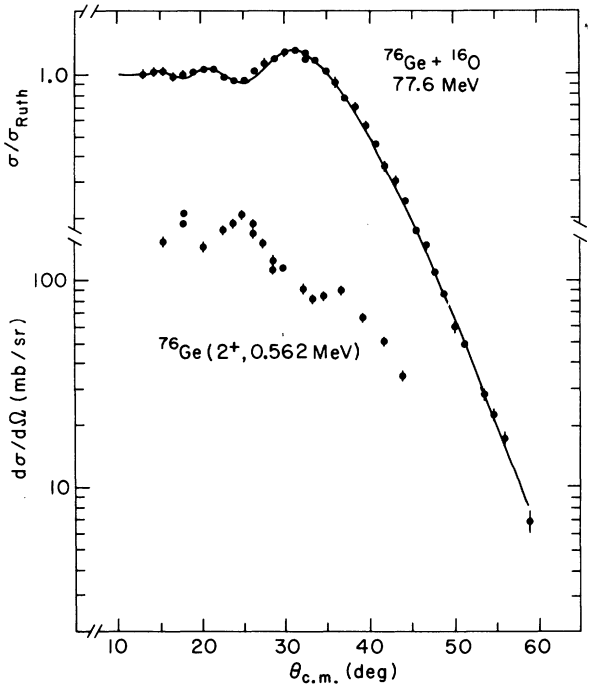

FIG. 6. Elastic and inelastic scattering angular distributions of $^{16}O+^{76}Ge$ at 77.6 MeV. The solid line was calculated with the code A-THREE.

$+^{18}O^*$ is very similar to that for $^{74}Ge^* + ^{18}O$ and the ratio of the magnitudes of the cross sections $(^{74}Ge^* + ^{18}O^*)/(^{74}Ge^* + ^{18}O) = 3$ is close to the ratio for the final states with ^{74}Ge in its g.s., viz. $(^{74}Ge + ^{18}O^*)/(^{74}Ge + ^{18}O)$. The peak in the $^{74}Ge^* + ^{18}O^*$ cross section at about $\theta_{c.m.} = 37°$ is perhaps overemphasized since a contaminant reaction appears to be passing through this excitation region at this angle.

Elastic scattering for both the incoming and outgoing channels, shown in Figs. 5 and 6, have been measured with the QDDD and with silicon surface barrier counters in a scattering chamber. Also shown are the angular distributions for the inelastic channels which are expected to contribute most to multistep processes. An example of single-neutron transfer, viz., $^{74}Ge(^{18}O, ^{17}O)^{75}Ge$ (g.s.), also measured in the QDDD, is shown in Fig. 7. The angular distribution is a smooth bell-shaped curve peaking at roughly $\theta_{c.m.} = 37°$.

IV. DISCUSSION

Fits to elastic scattering with the code A-THREE[10] are shown as solid lines in Figs. 5 and 6. The derived optical model parameters are given in Table I. With no changes in parameters the solid curve shown in Fig. 7 for the one-neutron transfer is ob-

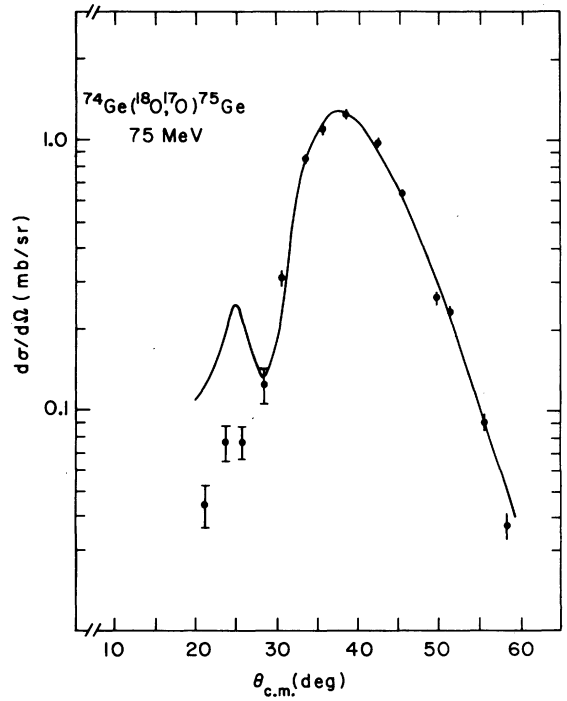

FIG. 7. Angular distribution of the reaction $^{74}Ge(^{18}O, ^{17}O)^{75}Ge$ (g.s.). The solid line is a curve, arbitrarily normalized, calculated with the code LOLA.

TABLE I. Optical model parameters from a fit to the elastic scattering. A standard Woods-Saxon geometry was assumed.

		V_0	W_0	r_0	a
$^{16}O+^{76}Ge$	77.6 MeV	−40	−15	1.250	0.587
$^{18}O+^{74}Ge$	75 MeV	−40	−15	1.204	0.664

tained with the code LOLA.[11] The peak position of the cross section is reproduced very well but the forward angle data indicate the absorption should be somewhat stronger. Since the primary concern here is with shapes of the angular distributions the curve has been arbitrarily normalized. The angular distribution for the two-neutron transfer calculated with the code LOLA using the cluster approximation is shown in Fig. 2. The excellent agreement of the shape of the experimental and theoretical cross sections indicates that the g.s. to g.s. transfer is predominantly single step. A calculation of the (^{16}O, $^{18}O^*$) reaction, using structure factors for ^{18}O given in Ref. 12 and assuming pure $(g_{9/2})^2$ for the Ge g.s., gives an expected enhancement of the $^{18}O^*$ cross section over the ^{18}O g.s. cross section of ~2.9, whereas the observed cross section is increased by a factor of 3.5. It has been predicted[13] that strong population of the ^{18}O excited state should be associated with an enhancement of the forward angle ^{18}O g.s. cross section. The data do not indicate a large enhancement.

Distorted-wave Born-approximation calculations for the Ge 2^+ states are nearly identical in shape to the g.s. This complete lack of agreement between data and calculations clearly indicates that two-step processes must be important for transfer to those 2^+ states. A thorough discussion of coupled-channel calculations for these reactions is presented in the following paper. However, to indicate that coupling to the inelastic scattering can produce the observed shape changes in the two-neutron transfer, a simplified coupled-channels calculation has been performed using the code FRIMP.[14] For this *schematic* calculation several simplifying assumptions have been made: the two neutrons were transferred as an $S=0$ cluster; $J=0$ transfers between the two ground states and between the two 2^+ states were assigned unit spectroscopic amplitudes; the amplitudes of the $J=2$ transfers between the ground states and 2^+ states were varied arbitrarily to reproduce the observed shapes; all other direct transfer routes were omitted; deformation parameters for inelastic scattering were taken from Coulomb excitation results; optical model parameters were taken from Table I with W changed to 12 MeV, and therefore are not those that would be obtained from a coupled channels fit to elastic and inelastic scattering. It was found that a value of −0.32 (the sign is taken relative to the nuclear inelastic excitation) for the spectroscopic amplitude of the $J=2$ transfer in the stripping reaction gave an angular distribution with roughly the shape of the data (Fig. 8). Also shown in Fig. 8 is the pickup angular distribution with a $J=2$ route spectroscopic amplitude of +0.32. Values of this amplitude as small as 0 produce very little change in the shape of the pickup cross section. Thus the destructive interference of the direct and indirect routes in stripping can produce the large reduction in cross section at the grazing angle shown by the data, while the constructive interference of the direct and indirect routes in pickup is *not* clearly demonstrated in this simple calculation, nor in the data. It should again be emphasized that these calculations are not meant to be definitive. Properly a calculation should include the coupling to the $^{18}O^*$ state and should treat the wave functions of the transferred nucleons in a microscopic way. The calculations presented here rather provide a *qualitative* understanding of the observed angular distributions.

V. SUMMARY

In summary, the present data provide dramatic evidence of the importance of two-step processes in two-nucleon transfer reactions on vibrational

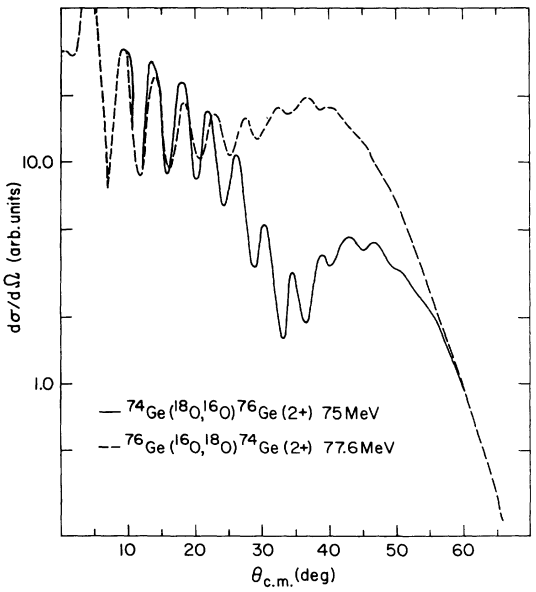

FIG. 8. Calculations, with an arbitrary normalization, of the reactions $^{74}Ge(^{18}O,^{16}O)^{76}Ge$ (2^+) and $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ (2^+) using the code FRIMP.

nuclei. The differential cross sections of reactions to the ^{74}Ge and ^{76}Ge first 2^+ vibrational states clearly indicate that two-step processes are important for describing the shapes observed in the stripping and pickup reactions to these states. Unfortunately no codes which can simultaneously treat coupled channels, recoil, a microscopic form factor, and sequential transfer exist, and thus a definitive test of whether theory can quantitatively reproduce the data cannot presently be made. In spite of this limitation the authors would like to emphasize the fact that data exist not only for the two-neutron transfer reaction but also for the elastic and inelastic scattering and for single-neutron transfer. With such data the parameters describing the generalized optical waves in the entrance and exit channels can be fixed. Therefore, a coupled-channel analysis, which is discussed in the following paper, will be strongly tested as to whether it can adequately describe the reaction mechanism as well as the structure of the different states contributing to the transfer.

One of us (M.-C. L.) would like to thank the Tandem group for their hospitality during her stay at Brookhaven and Dr. Low for helpful discussions.

---

*Work supported by the U. S. Energy Research and Development Administration.

†Permanent address: Physik Department, Technische Universitaet, Muenchen, Germany.

‡Permanent address: DPh-N/BE, CEN Saclay, B. P. 2, 91190 Gif-sur-Yvette, France.

§Present address: EMI Medical, Inc., 3605 Woodhead Drive, Northbrook, Illinois 60062.

[1]R. J. Ascuitto and N. K. Glendenning, Argonne National Laboratory Physics Division Informal Report PHY-1973B (unpublished), Vol. 1, p. 513; Phys. Lett. 47B, 322 (1973).

[2]R. J. Ascuitto and J. S. Vaagen, in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, 1974,* edited by R. L. Robinson, F. K. McGowan, J. B. Ball, and J. H. Hamilton (North-Holland, Amsterdam/American Elsevier, New York, 1974), Vol. 2, p. 257.

[3]T. Tamura, K. S. Low, and T. Udagawa, in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, 1974* (see Ref. 2), Vol. 1, p. 70; Phys. Lett. 51B, 116 (1974).

[4]K. A. Erb, D. L. Hanson, R. J. Ascuitto, B. Sorenson, J. S. Vaagen, and J. J. Kolata, Phys. Rev. Lett. 33, 1102 (1974).

[5]K. Yagi, D. L. Hendrie, L. Kraus, C. F. Maguire, J. Mahoney, D. K. Scott, Y. Terrien, T. Udagawa, K. S. Low, and T. Tamura, Phys. Rev. Lett. 34, 96 (1975).

[6]M. E. Cobern, M.-C. Lemaire, K. S. Low, M. C. Mermaz, H. Sztark, T. Udagawa, and T. Tamura, Phys. Rev. C 13, 1200 (1976).

[7]R. J. Ascuitto, J. S. Vaagen, D. J. Pisano, C. E. Thorn, J. Lien, and G. Løvhøiden, Nucl. Phys. A273, 230 (1976).

[8]D. K. Scott, B. G. Harvey, D. L. Hendrie, U. Jahnke, L. Kraus, C. F. Maguire, J. Mahoney, Y. Terrien, K. Yagi, and N. K. Glendenning, Phys. Rev. Lett. 34, 895 (1975).

[9]J. B. Marion and F. C. Young, *Nuclear Reaction Analysis* (North-Holland, Amsterdam, 1968).

[10]E. H. Auerbach (unpublished).

[11]R. M. DeVries, Phys. Rev. C 8, 951 (1973).

[12]S. Kahana and E. Tomusiak, Nucl. Phys. 71, 402 (1965). The amplitude for the $d_{3/2}s_{1/2}$ component in the 2^+ wave function in Table I should read -0.245.

[13]N. K. Glendenning and G. Wolschin, Phys. Rev. Lett. 34, 1642 (1975).

[14]D. J. Pisano, Phys. Rev. C 14, 468 (1976).