$L = 1$ single-proton pickup reactions on ^{40}Ca

P. D. Bond, M. J. LeVine, D. J. Pisano,* and C. E. Thorn
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

L. L. Lee, Jr.
Department of Physics, State University of New York, Stony Brook, New York 11794
(Received 19 December 1978)

In an attempt to determine the cause of the out-of-phase behavior of the angular distributions for the (^{13}C,^{14}N) $L = 1$ transfer reactions on Ca isotopes measured at 68 MeV bombarding energy, several projectiles have been used which change specific parameters in the experiment. In contrast to the 68 MeV ^{40}Ca(^{13}C,^{14}N) data, the results for 50 MeV (^{13}C,^{14}N), 70 MeV (^{14}N,^{15}O), and 70 MeV (^{15}N,^{16}O) reactions to the $s_{1/2}$ state in ^{39}K are in excellent agreement with distorted-wave Born-approximation calculations. A phasing problem between data and theory for the $d_{3/2}$ state in ^{39}K is present for two of these reactions, but is not as severe as with the earlier (^{13}C,^{14}N) measurement.

[NUCLEAR REACTIONS ^{40}Ca(^{13}C, ^{14}N), E=50 MeV; ^{40}Ca(^{14}N, ^{15}O), (^{15}N, ^{16}O), E=70 MeV; measured $\sigma(\theta)$. DWBA analysis.]

I. INTRODUCTION

With the availability of high energy heavy-ion beams having good energy resolution, it has been hoped that transfer reactions induced by heavy ions would provide new spectroscopic information complementing that already obtained in light-ion reactions. Experiments at a number of laboratories have shown that, at energies about twice the Coulomb barrier, pronounced oscillations may appear in the forward angular distributions of heavy-ion induced reactions which, as with light ions, are characteristic of the angular momentum transfer.[1-3] These results are generally analyzed using full recoil distorted-wave Born approximation (DWBA) calculations which have produced quantitative fits to a number of experiments.

It is important at this stage to critically assess the successes and possible failures of this approach since one must have a full understanding of the mechanism of the reactions before meaningful spectroscopic factors can be extracted from these experiments. A recent Letter[4] pointed out a systematic failure of DWBA calculation to reproduce the results of several proton pickup experiments on the Ca isotopes, which involved a transferred angular momentum of $L=1$. In that work (^{13}C, ^{14}N), reactions on several Ca isotopes leading to the ground and first excited states of K isotopes having spin $\frac{3}{2}^+$ and $\frac{1}{2}^+$ respectively were studied at bombarding energies of 60 and 68 MeV. These states are well-established single-hole states, so one would expect the DWBA calculations to fit both the magnitude and angular dependence of the transfer cross sections. However, the angular distributions for both of these transitions (Fig. 1) were found to be consistently out of phase with the DWBA calculations, although the magnitudes of the cross sections were in good agreement. Because of the simplicity of the DWBA transition amplitude for $L=1$ reactions and the out-of-phase behavior at forward angles, it was concluded that there was a puzzling lack of understanding of the reaction mechanism. Several other $L=1$ failures have been observed for much lighter targets,[5-7] where the interpretation is less clear.

In an attempt to ascertain the causes of the out-of-phase behavior of the (^{13}C, ^{14}N) angular distributions, other reactions on ^{40}Ca leading to the same $\frac{3}{2}^+$ ground state and 2.53 MeV, $\frac{1}{2}^+$ state in ^{39}K have been studied. The reactions, chosen to independently change crucial parameters in the experiment, were (^{14}N, ^{15}O), which changes the projectile but does not significantly change the Q values of the reactions, (^{15}N, ^{16}O), which optimizes the Q value of the reactions, and (^{13}C, ^{14}N) at a lower energy, which investigates the energy dependence of the phasing problem. As will be shown below, DWBA calculations reproduce the present experimental results far better than those of the earlier work, but several difficulties still remain. The present data also provide additional tests for some proposed solutions[8-10] for the phasing problem (Fig. 1) and should be a determining factor in deciding whether coupled channels effects or some other mechanism is responsible for the failure of the DWBA.

While the $L=1$ transitions are particularly sensitive to details of the reaction mechanism, larger L transfers seem to be much less sensitive

 © 1979 The American Physical Society

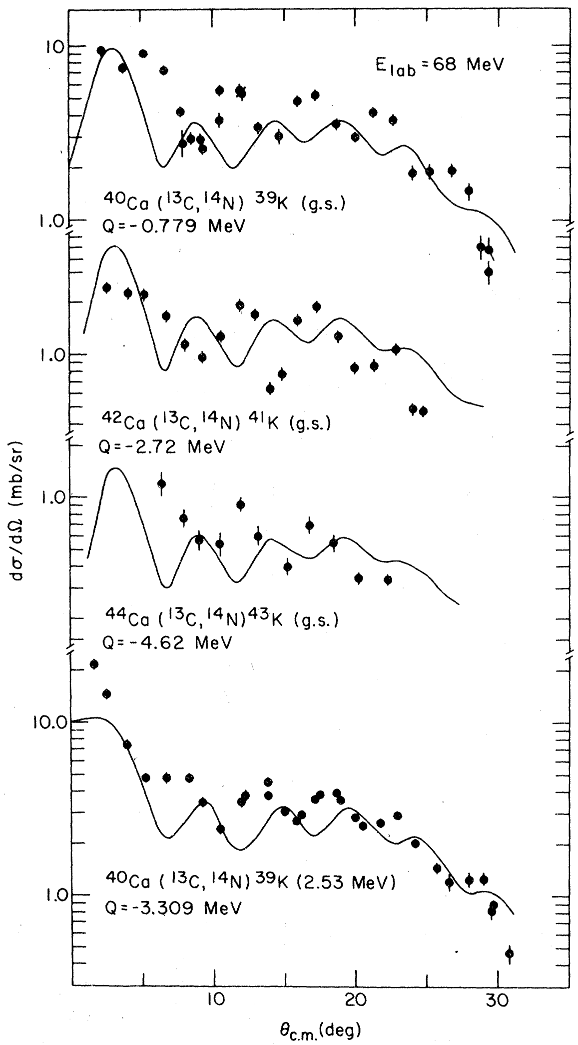

FIG. 1. The Ca(^{13}C, ^{14}N) K reactions measured at 68 MeV bombarding energy, leading to the ground state and $s_{1/2}$ state. Data are from Ref. 4.

and hence may result in the extraction of reliable spectroscopic information. In particular it is shown that $L=4$ transitions need not be so well matched to be insensitive to parameter changes which influence the $L=1$ reactions.

II. EXPERIMENTAL PROCEDURE

Measurements were made using 50-MeV ^{13}C and 70-MeV ^{14,15}N beams from the Brookhaven National Laboratory Tandem Van de Graaff facility. Transfer reaction products were detected in two 10 cm long position-sensitive silicon detectors placed in the focal plane of the Brookhaven quadrupole-dipole-dipole-dipole (QDDD) spectrometer. Simultaneous measurement of position along the focal plane and the energy of the ions gave unambiguous identification of the ^{14}N, ^{15}O, and ^{16}O reaction products. The position-sensitive detectors were positioned such that the particle groups leading to the $d_{3/2}$ ground state of ^{39}K and the $s_{1/2}$ excited state were each centered on a counter.

Targets were ~100 μg/cm^2 natural calcium (97% ^{40}Ca) evaporated on thin carbon foils such that the calcium was restricted to a small (2 mm × 5 mm) spot in the center of the target frame. This ensured that the reaction products were always centered vertically on the 1.3 cm high focal-plane detectors. The optical system of the beam line and spectrometer made it possible to make measurements at laboratory angles as small as two degrees. This ability to make measurements to very small angles is extremely important since the positions of the most forward diffraction peaks

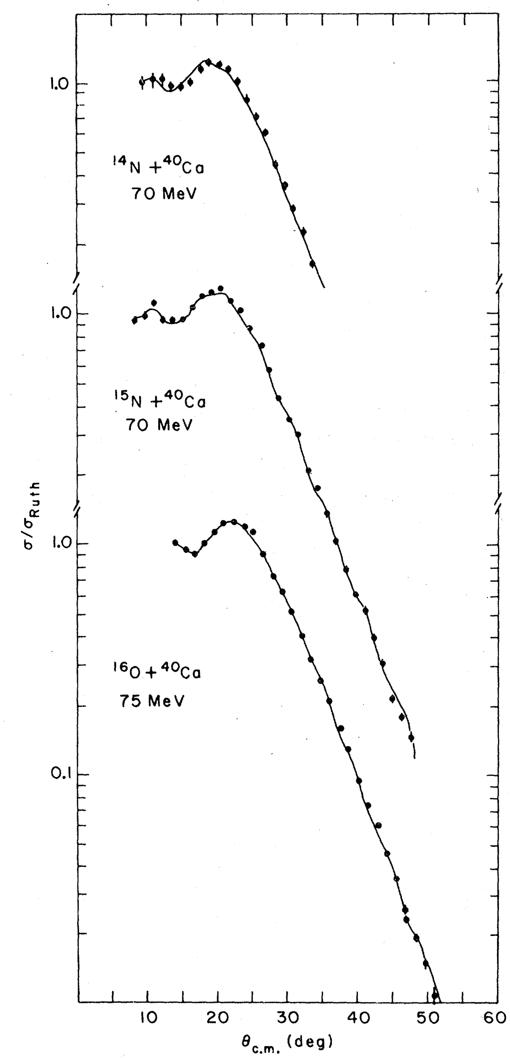

FIG. 2. Elastic scattering of ^{14}N, ^{15}N, and ^{16}O from ^{40}Ca. The solid lines are calculations described in the text.

TABLE I. Optical model parameters for incoming and outgoing channels which were used in the calculation of reaction cross sections. V, W are given in MeV, r_0 and a in fm and $R_0 = r_0\ (A_1^{1/3} + A_2^{1/3})$.

Reaction	E_{lab} (MeV)	Incoming channel V	W	r_0	a	Outgoing channel V	W	r_0	a
$^{40}Ca(^{13}C,^{14}N)\,^{39}K$	68	33.4	18	1.27	0.55	34.2	12	1.27	0.55
	50	33.4	10	1.27	0.55	34.2	10	1.27	0.55
$^{40}Ca(^{14}N,^{15}O)\,^{39}K$	70	34.2	15	1.27	0.55	34.2	15	1.27	0.55
$^{40}Ca(^{15}N,^{16}O)\,^{39}K$	70	28.1	11.1	1.27	0.55	34.4[a]	15.6	1.27	0.55

[a] Determined from a fit to $^{16}O + ^{40}Ca$ at 75 MeV.

are the most sensitive tests of the DWBA calculations.

Absolute cross sections for transfer were obtained to ±15% by correcting for measured charge state fractions and normalizing the reaction data to elastic scattering measurements in the QDDD which were assumed to be Rutherford at forward angles. Elastic scattering angular distributions, measured to ensure that the optical potentials satisfactorily reproduced the elastic scattering, were obtained for the most part in a scattering chamber with surface barrier detector telescopes.

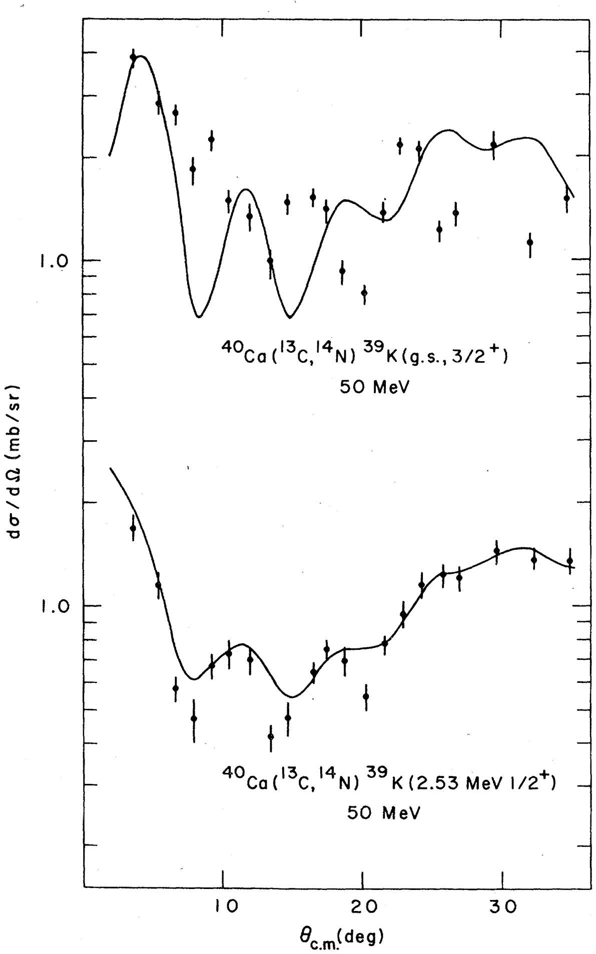

FIG. 3. The $^{40}Ca(^{13}C, ^{14}N)\,^{39}K$ reactions, measured at 50 MeV bombarding energy, leading to the $d_{3/2}$ ground state and $s_{1/2}$ excited state in ^{39}K. The solid lines are DWBA calculations described in the text.

III. RESULTS

The results of elastic scattering of ^{14}N, ^{15}N, and ^{16}O from ^{40}Ca are shown in Fig. 2. The solid lines in Fig. 2 are the results of optical model fits[11] to the elastic scattering in which the radius parameter and diffusivity were held constant. Optical parameters used for the entrance and exit channel

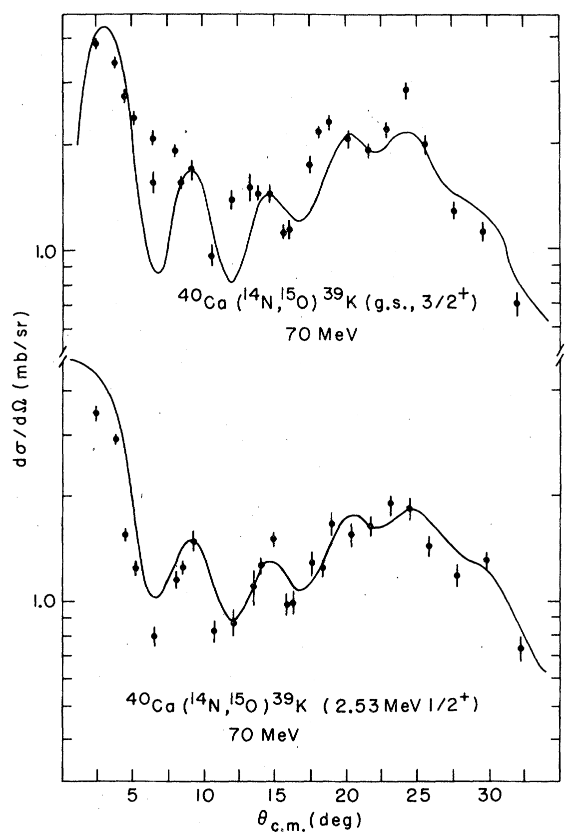

FIG. 4. The $^{40}Ca\,(^{14}N, ^{15}O)\,^{39}K$ reactions to the g.s. and and $s_{1/2}$ excited state, measured at 70 MeV bombarding energy. The solid lines are DWBA calculations described in the text.

elastic scattering are listed in Table I. Since the shapes of the calculated transfer reaction cross sections are more sensitive to the optical model parameters than is the elastic scattering,[12] the parameters in some cases (discussed below) were changed slightly to better reproduce the magnitude of the forward angle transfer cross section. In the discussion of the transfer angular distributions the calculated *positions* of the *forward angle* oscillations will be emphasized, since they are more invariant to parameter changes than either the large angle oscillations or the magnitude of the cross section.

The cross sections for the (^{13}C, ^{14}N) reactions at 50 MeV to both the g.s. ($d_{3/2}$) and 2.53 MeV ($s_{1/2}$) states of ^{39}K are shown in Fig. 3. The solid curves represent the results of exact finite range DWBA calculations using the code LOLA, including the Coulomb correction terms.[13] The same optical potential parameters as those used in Ref. 4 and Fig. 1 were used except that the depth of the imaginary potential was reduced (see Table I). The agreement between data and theory for the $s_{1/2}$ state is very good while the calculated angular distribution for the $d_{3/2}$ state is still out of phase with the data. Data at an even lower bombarding energy, 40 MeV, for the ground state of ^{39}K have been reported elsewhere[12] and much better agreement between calculation and experiment is obtained. Thus, the out-of-phase behavior between the DWBA and the data for the (^{13}C, ^{14}N) reactions is strongly energy dependent.

Results for the ^{40}Ca(^{14}N, ^{15}O)^{39}K reactions are shown in Fig. 4. The calculations reproduce the data for the $s_{1/2}$ state extremely well, while there is a slight shift in phase between the data and calculations for the ground state angular distribution. The Q values for the (^{14}N, ^{15}O) reactions are almost identical to the (^{13}C, ^{14}N) reactions (see Table II), so it is tempting to attribute the out-of-phase behavior in the (^{13}C, ^{14}N) 68 MeV reactions to the projectile-ejectile system. However, the situation is complicated by the higher Coulomb barriers in both channels of the (^{14}N, ^{15}O) reaction, so that the energy above the barrier for the (^{14}N, ^{15}O) reactions at 70 MeV is closer to the (^{13}C, ^{14}N) reactions at 60 MeV. The similarity of the 70 MeV (^{14}N, ^{15}O) and 50 MeV (^{13}C, ^{14}N) results would indicate that the origin of the phase problem may not be projectile related, but a study of the (^{14}N, ^{15}O) reaction at other energies needs to be made.

To extend the range of Q values covered in these studies, especially toward the optimum (positive) value (see Table II), measurements were also made on the (^{15}N, ^{16}O) reaction to the same two final states in ^{39}K (also see Ref. 16). These results are shown in Fig. 5 where the solid lines again represent the results of exact finite range DWBA calculations using parameters listed in Table I. Calculations with a more weakly absorbing potential are shown as dashed lines in Fig. 5. Again one notes that the agreement with the data is quite acceptable, especially for the $\frac{1}{2}^+$ state. The positions of the oscillations at forward angles, the crucial data to fit, are reproduced very well by DWBA calculations using either optical model set. Unfortunately, the ground state here provides little test of the reaction mechanism, since the angular distribution is so flat. The slight shift in phase at large angles for the $s_{1/2}$ state is easily cured by very slight adjustments in optical parameters. It should be noted that this is qualitatively a very different phasing problem from that seen in Fig. 1 where the forward angle oscillations are out of phase.

Parenthetically, it is interesting to note the oscillatory behavior of the $s_{1/2}$ data and the smooth behavior of the $d_{3/2}$ data for the (^{15}N, ^{16}O) reaction, which indicate that the incoming and outgoing grazing partial waves are matched much closer to

TABLE II. Q values, bound state parameters and calculation normalizations for the reactions (^{13}C, ^{14}N), (^{14}N, ^{15}O), and (^{15}N, ^{16}O) on ^{40}Ca to states in ^{39}K. The bound state geometry in the calculations was chosen as $r_0 = 1.25$ fm and $a = 0.65$ fm.

Reaction	Final state (E_{ex}, J^π)	Q (MeV)	C^2S_i [a]	C^2S_f [b]	N
(^{13}C, ^{14}N)	(0, $\frac{3}{2}^+$)	−0.779	0.7	4.0	1.19
	(2.53 MeV, $\frac{1}{2}^+$)	−3.31	0.7	1.53	1.13
(^{14}N, ^{15}O)	(0, $\frac{3}{2}^+$)	−1.04	1.43	4.0	1.0
	(2.53 MeV, $\frac{1}{2}^+$)	−3.53	1.43	1.53	1.0
(^{15}N, ^{16}O)	(0, $\frac{3}{2}^+$)	+3.798	2.0	4.0	1.25
	(2.53 MeV, $\frac{1}{2}^+$)	+1.268	2.0	1.53	1.25

[a] Reference 14.
[b] Reference 15.

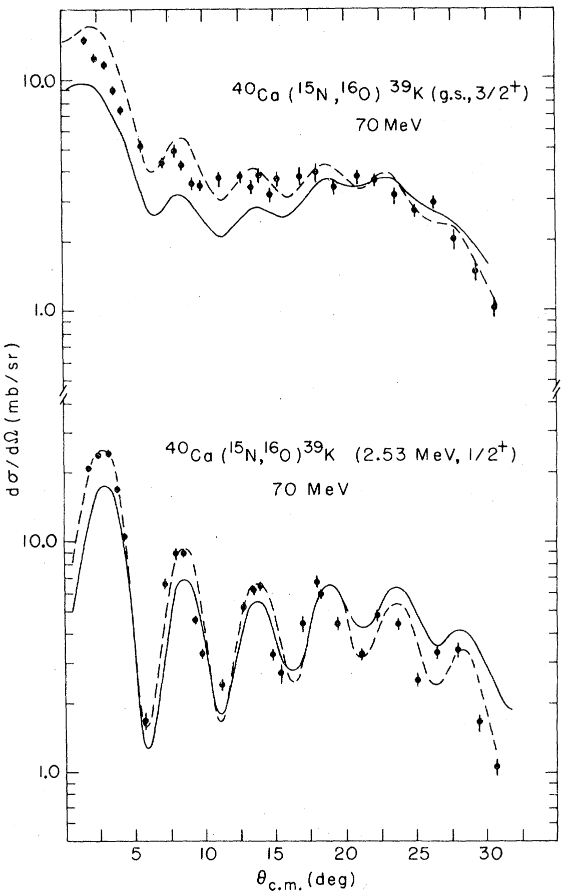

FIG. 5. The ^{40}Ca (^{15}N, ^{16}O) ^{39}K reactions leading to the g.s. and $s_{1/2}$ excited state of ^{39}K, measured at 70 MeV bombarding energy. The solid lines are DWBA calculations described in the text.

+1.2 MeV than to +4.3 MeV, the value which is obtained from semiclassical considerations for the optimum cross section. As a check of this conjecture, a calculation was made for the $d_{3/2}$ state, using the $s_{1/2}$ Q value but the $d_{3/2}$ form factor, and a highly oscillatory structure was obtained.

The calculations shown here generally give satisfactory results for the absolute cross sections. The factors by which the calculated cross sections in Figs. 3–5 have been multiplied are given in Table II. It was found that the normalization of the (^{15}N, ^{16}O) reaction was extremely sensitive to parameter changes because of the strong binding of the proton in ^{16}O. Inclusion of a spin orbit potential in the bound states made a slight change in the calculated cross section, but a 4% change in the bound state radius produced a 50% change in the predicted cross section while having no significant effect on the shape of the angular distribution. The magnitudes of the cross sections for (^{15}N, ^{16}O) are also extremely sensitive to optical parameters so that a normalization factor for this reaction should not be viewed as a serious problem (see Ref. 16).

IV. DISCUSSION

The "normal" parity angular momentum transfer to both the $d_{3/2}$ and $s_{1/2}$ states is $L=1$. However, in the case of the $d_{3/2}$ state, a non-normal parity component of $L=2$ is also allowed. Hence, the $s_{1/2}$ state is the more straightforward test of the reaction mechanism since only the $L=1$ normal transfer enters. The $L=1$ transfer can have only projections $M=0$, ±1 along the beam axis and, since $M=\pm1$ dominates the DWBA at energies somewhat above the Coulomb barrier,[3,4] a DWBA solution of the out-of-phase behavior of the $s_{1/2}$ state in the (^{13}C, ^{14}N) reaction at 68 MeV would have to come from an anomalous $M=0$ domination of the cross section. In contrast, for the three cases presented here to the same $s_{1/2}$ state, DWBA calculations and data agree with the expected $M=\pm1$ dominance.

For the $d_{3/2}$ state the situation is not so clear. The out-of-phase behavior could arise either from a dominance of the normal $M=0$ or the $M=\pm2$ non-normal partial cross section. The non-normal cross section is calculated to be weak, and the dominance of the normal $M=0$ partial cross section was pointed out[4] to be very unlikely. Furthermore, since $M=\pm1$ dominates the $s_{1/2}$ state correctly in the three cases measured here, it should also dominate for the $d_{3/2}$ state as the DWBA predicts.

It has been suggested[8,16] that the solution to the out-of-phase angular distribution for the $d_{3/2}$ and $s_{1/2}$ states in the (^{13}C, ^{14}N) reaction at 68 MeV lies in a coupled channels route through the inelastically excited 3^- and 5^- states in ^{40}Ca (see Ref. 17). Since the importance of the two-step route depends upon matching conditions, it is expected[8] that only when the single-step process is somewhat mismatched can the multistep route contribute enough to change the phase of the angular distribution. Indeed, in the (^{15}N, ^{16}O) reaction the Q value is close to optimum, and the phase of the angular distributions is reasonably reproduced by the DWBA. If these multistep routes are important, one would also expect to see the coupled channels effect in the (^{14}N, ^{15}O) reaction because the Q values are about the same as for (^{13}C, ^{14}N), and calculations of inelastic scattering to the 3^- state in ^{40}Ca with ^{14}N at 70 MeV indicate the inelastic cross section should be as large as with ^{13}C at 68 MeV and larger than that with ^{13}C at 50 MeV. Thus, it would be expected that the same problem should occur both in (^{13}C, ^{14}N) at 68 MeV and (^{14}N, ^{15}O) at 70 MeV; such is not the case. In the (^{14}N, ^{15}O) reactions the $d_{3/2}$ data seem to have some phase problems, but the data for the $s_{1/2}$ state are in phase and have the correct magnitude.

Coupled channels calculations involving the excitation of the projectile have also been suggested[18] as a possible solution to the out-of-phase behavior but will also be severely tested by the present data since three different projectiles have been used.

Another suggestion, which was made in an earlier Letter,[4] has been investigated further, that of the possibility of the spin-orbit potential in the scattering of heavy ions. One of the few attempts at measuring the effect[19] indicated that the effect on inelastic scattering (the spin-flip probability) was small (~10^{-3}). Calculations performed with the code DWUCK4[20] indicate that a value of the spin-orbit potential for which the elastic scattering is not drastically changed and the spin-flip probability is of the order of the upper limit stated in Ref. 19 can dramatically change the $L=1$ cross sections (see also Refs. 9 and 21). Figure 6 shows that a spin-orbit term in the optical potential can even change the phase of the oscillations. In these calculations the diffusivity in the ^{14}N + ^{39}K optical potential has been changed from that in Table I so the elastic scattering would be about the same as that without the spin-orbit potential, and the spin-orbit term has been chosen to be the standard Thomas form with the optical potential geometry. For the $L=4$ transfer, the results indicate little or no effect. It should be noted, however, that the phases of the oscillations in the elastic scattering on the exponential falloff from $\sigma/\sigma_R \sim 1$ are also changed with this value of V_{so} (Fig. 6). This calculation is not definitive, and recent calculations[22] indicate that V_{so} should be *much* smaller (about a factor of 100), but the transfer result is intriguing enough to encourage further investigation.

In contrast to the sensitivity of the $L=1$ angular distributions to various parameters, it is interesting to consider the $L=4$ transitions. The coupled channels calculation of Ref. 8 did not influence the angular distribution of the $L=4$ (^{13}C, ^{12}C) reaction, partly because of Q matching and partly because a smaller L transfer was involved in the transfer through the coupled channels

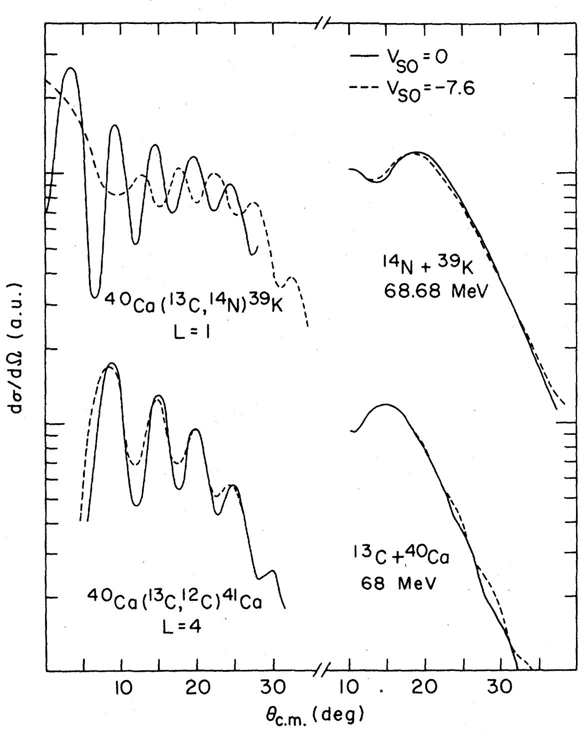

FIG. 6. Comparison of calculations of the ^{40}Ca(^{13}C, ^{14}N) ^{39}K and ^{40}Ca (^{13}C, ^{12}C) ^{41}Ca reactions with and without a spin orbit term in the optical potential.

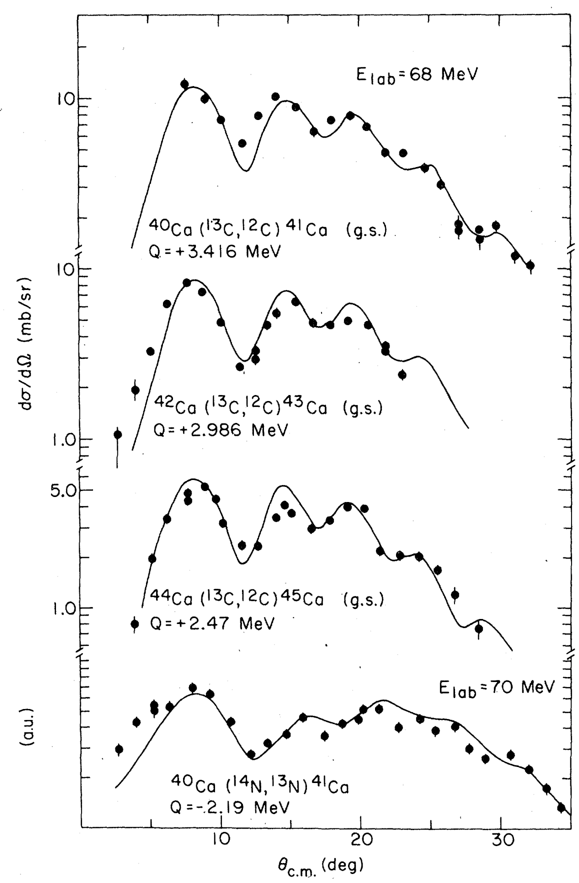

FIG. 7. Ca (^{13}C, ^{12}C) reactions measured at 68 MeV bombarding energy (from Ref. 4) and the ^{40}Ca(^{14}N, ^{13}N) reaction measured at 70 MeV. The solid lines are DWBA calculations described in the text.

route. As was shown above, the spin-orbit potential also had very little effect upon this $L=4$ angular distribution. To demonstrate that the $L=4$ reaction is also not very sensitive to the Q value, the (^{14}N, ^{13}N) reaction to the ground state of ^{41}Ca was measured at 70 MeV and is shown in Fig. 7. Here the Q value is −2.2 MeV in contrast to the (^{13}C, ^{12}C) reaction Q value of +3.4 MeV. The fit is again good except at very forward angles, indicating that the larger L transfers are particularly insensitive to the parameters which seem to be so important in the $L=1$ cases (see also Ref. 3).

V. CONCLUSION

All of the results presented in the paper indicate that there is no consistent peculiarity of $L=1$ heavy-ion induced transfer which forces the calculations to be out of phase with the experimental results as was conjectured in Ref. 10. It has been suggested[4,7,10] that the earlier difficulties could have been avoided if some special aspects of the reaction mechanism enhanced the $M=0$ contribution relative to the expected $M=1$ dominance. At large angles a shift in phase of the angular distribution can also be produced in a calculation through adjustment of potential parameters (especially the radius), but the satisfactory fit to elastic scattering is lost. The present successes arise from a straightforward fit to the data with normal potential parameters and indicate that such *ad hoc* solutions are not reasonable answers to the problems. The failures to fit the $d_{3/2}$ state in two of the reactions presented here indicates that spin assignments from heavy-ion reactions, at least for $L=1$ transfers, cannot be made reliably and that an understanding of the reaction mechanism is not yet totally in hand. However, the difficulties with some $L=1$ transfer reactions seem to be special and for larger L transfers, especially near the optimum Q value, the sensitivity of the angular distribution to coupled channels and spin-orbit potentials, for example, is very small.

We wish to acknowledge the assistance of J. D. Garrett and A. Z. Schwarzschild in part of the data taking. This research was supported by the Division of Basic Energy Sciences, Department of Energy, under Contract No. EY-76-C-02-0016.

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

[1]M. J. Schneider, C. Chasman, E. H. Auerbach, A. J. Baltz, and S. Kahana, Phys. Rev. Lett. 31, 320 (1973); C. Chasman, S. Kahana, and M. J. Schneider, *ibid.* 31, 1074 (1973).

[2]W. Henning, D. G. Kovar, B. Zeidman, and J. R. Erskine, Phys. Rev. Lett. 32, 1015 (1974).

[3]S. Kahana, P. D. Bond, and C. Chasman, Phys. Lett. 50B, 199 (1974).

[4]P. D. Bond, C. Chasman, J. D. Garrett, C. K. Gelbke, Ole Hansen, M. J. LeVine, A. Z. Schwarzschild, and C. E. Thorn, Phys. Rev. Lett. 36, 300 (1976).

[5]R. M. DeVries, M. S. Zisman, J. G. Cramer, K-L Liu, F. D. Becchetti, B. G. Harvey, H. Homeyer, D. G. Kovar, J. Mahoney, and W. von Oertzen, Phys. Rev. Lett. 32, 680 (1974).

[6]K. G. Nair, H. Voit, M. Hamm, C. Towsley, and K. Nagatani, Phys. Rev. Lett. 33, 1588 (1974).

[7]K. I. Kubo, K. G. Nair, and K. Nagatani, Phys. Rev. Lett. 37, 222 (1976).

[8]K. S. Low, T. Tamura, and T. Udagawa, Phys. Lett. 67B, 5 (1977).

[9]A. Dudek-Ellis, B. F. Bayman, and P. J. Ellis, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, 1977*, edited by T. Marumori (Physical Society of Japan, Tokyo, 1978); Nucl. Phys. A301, 141 (1978).

[10]Ernest Seglie and Robert J. Asciutto, Phys. Rev. Lett. 39, 688 (1977).

[11]Code A-THREE, E. Auerbach, Comput. Phys. Commun. 15, 165 (1978).

[12]A. J. Baltz, P. D. Bond, J. D. Garrett, and S. Kahana, Phys. Rev. C 12, 136 (1975).

[13]R. M. DeVries, Phys. Rev. C 8, 951 (1973); R. M. DeVries, G. R. Satchler, and J. G. Cramer, Phys. Rev. Lett. 32, 1377 (1974).

[14]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[15]J. C. Hiebert, E. Newman, and R. H. Bassel, Phys. Rev. 154, 898 (1967).

[16]S. Kubono, S. J. Tripp, D. Dehnhard, T. Udagawa, and T. Tamura, Phys. Rev. C 18, 1929 (1978).

[17]P. D. Bond, M. J. LeVine, and C. E. Thorn, Phys. Lett. 68B, 327 (1977).

[18]D. Sinclair, B. T. Chair, S. Kahana, and B. S. Nilsson, Phys. Rev. C 14, 1033 (1976).

[19]C. Chasman, P. D. Bond, and K. W. Jones, Bull. Am. Phys. Soc. 20, 55 (1975).

[20]P. D. Kunz (unpublished).

[21]S. Kubono, D. Dehnhard, D. A. Lewis, T. K. Li, J. L. Artz, D. J. Weber, P. J. Ellis, and A. Dudek-Ellis, Phys. Rev. Lett. 38, 817 (1977).

[22]F. Petrovich, D. Stanley, L. A. Parks, and D. Nagel, Phys. Rev. C 17, 1642 (1978); P. J. Moffa, *ibid.* 16, 1431 (1977).