Failure of finite-range distorted-wave Born approximation and coupled-channels Born approximation to describe (^{7}Li,^{6}Li) single particle transitions

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(Received 6 July 1988)

Coupled-reaction channels calculations for ^{12}C(^{7}Li,^{6}Li)^{13}C($\frac{1}{2}^+$, 3.09 MeV) which include the reorientation of ^{7}Li, excitation of the $\frac{1}{2}^-$ 0.48 MeV state of ^{7}Li, the transition from this state to the ground state of ^{6}Li, and transitions between the ground and first excited state of ^{12}C and ^{13}C, are almost identical to finite-range distorted-wave Born approximation calculations, and are highly oscillatory, whereas the data are structureless. These calculations show that multistep processes between ^{7}Li and ^{12}C are not responsible for producing the unstructured $l=1$ transfer measured in ^{12}C(^{7}Li,^{6}Li)^{13}C($\frac{1}{2}^+$, 3.09 MeV). Data are reported for elastic and inelastic scattering of ^{7}Li+^{16}O and the single nucleon transfers (^{7}Li,^{6}Li/^{6}He). Once again, the ^{16}O(^{7}Li,^{6}Li)^{17}O($\frac{1}{2}^+$, 0.87 MeV) angular distribution data are structureless, while finite-range distorted-wave Born approximation calculations are highly structured.

I. INTRODUCTION

There is still considerable uncertainty in our ability to predict ahead of time whether the results from a heavy-ion-induced single-nucleon-transfer experiment will be described by finite-range distorted-wave Born approximation (FRDWBA) calculations. Early transfer reaction studies[1] showed that a servere test of our reaction understanding was provided by transitions that could only take place by a single l transfer, as for example, those between $1p$ and $2s$ orbits, which proceed by $l=1$ transfer. It was found that the $l=1$ transfer data and calculations are exactly out of phase for the reaction ^{12}C(^{14}N,^{13}N)^{13}C at 100 MeV. While an initial survey[2] of $l=1$ transfers appeared to show that one could determine whether the data and calculations would be in or out of phase based on the incident projectile wave number, subsequent measurements[3] have shown violations of this rule. The importance of studying pure $l=1$ transitions was shown also when detailed measurements[4] of the ^{40}Ca(^{13}C,^{14}N)^{39}K to the 2.53 MeV, $s_{1/2}$ state were again out of phase with the data. Extensive measurements[5,6] with other projectile-ejectile combinations have not given a consistent explanation of single-proton-pickup reactions to this state.

Initial results[2,7] for the ^{12}C(^{7}Li,^{6}Li)^{13}C($\frac{1}{2}^+$, 3.09 MeV) transition seemed to show that FRDWBA calculations reproduced the data extremely well, in contrast to most other heavy-ion projectiles. However, more detailed measurements[8,9] showed that the apparent success in describing (^{7}Li,^{6}Li) to the ^{13}C 3.09 MeV state was a result of gaps in the angular distribution data. The (^{7}Li,^{6}Li) transition suffers from a different problem than that for (^{14}N,^{13}N). The calculated (^{7}Li,^{6}Li) angular distribution is highly structured, as is expected for this $l=1$ transition, whereas the data are almost featureless. Detailed (^{7}Li,^{6}Li) measurements[10] of transitions to $2s_{1/2}$ states in ^{12}B and ^{14}C have confirmed this general feature. In addition, the measured angular distributions to $1p_{1/2}$ states, which are structured, are shifted forward in angle by about 3° relative to FRDWBA calculations. Angular distribution measurements[11] of the ^{12}C(d,p)^{13}C reaction are well described by distorted-wave Born approximation (DWBA) calculations at several energies. The transition to the 3.09 MeV state has a spectroscopic factor of ≈ 1, and coupled-channel Born approximation (CCBA) calculations[11] confirm that it is a single-particle $2s_{1/2}$ state, thus removing any doubts as to the structure of this state.

The nucleus ^{7}Li has a large ground-state quadrupole moment that substantially contributes to the elastic scattering of ^{7}Li, resulting in structureless elastic scattering angular distributions.[12–15] It is possible that the addition of a transfer contribution arising from the reorientation of ^{7}Li followed by a single-neutron stripping to the direct-stripping component can account for the featureless angular distributions to $2s_{1/2}$ states. This work reports the results of coupled reaction-channels (CRC) calculations that include reorientation of the $\frac{3}{2}^-$ ground state of ^{7}Li, excitation of the $\frac{1}{2}^-$ first excited state of ^{7}Li, and the transition from the $\frac{1}{2}^-$ first excited state of ^{7}Li to the ground state of ^{6}Li. No substantial differences between these calculations and standard FRDWBA calculations are found. The contribution to the transfer from the recently proposed (Ref. 16) $f_{7/2}$ component in the ^{7}Li ground-state wave function was found to be small.

New measurements are reported for the ^{16}O(^{7}Li,^{6}Li/^{6}He) reactions. The measurements were made to eliminate possible strong target-coupling effects

in the previously reported measurements. The new data to the 0.87 MeV, $\frac{1}{2}^+$ state in ^{17}O have the same structureless angular distribution as those previously reported. It has been shown[17] that the spin-orbit interaction can substantially alter single-nucleon-transfer calculations. Finite-range DWBA calculations were performed for ^{16}O(^{7}Li,^{6}Li)^{17}O that included a spin-orbit potential in the exit channel obtained from recent ^{6}Li+^{16}O measurements.[18] No influence from the presence of the spin-orbit potential in the calculations was found.

Elastic and projectile excitation scattering data are also presented. These data were analyzed in coupled channels with a microscopic interaction to determine if the previously observed success[14,15] for $A \geq 40$ targets of this approach when compared with standard coupled-channels calculations is observed for a light target like ^{16}O.

II. COUPLED-CHANNEL REACTION ANALYSIS: ^{12}C(^{7}Li,^{6}Li)^{13}C

The effects of projectile couplings in the ^{12}C(^{7}Li,^{6}Li)^{13}C reaction at 34 MeV were investigated using the Neils Bohr Institute version of the coupled-channels program CHUCK (Ref. 19) and the single-particle transfer form-factor program ONEFF.[20] First, a finite-range DWBA calculation (FRDWBA) of the transfer to the $\frac{1}{2}^+$, 3.09 MeV state of ^{13}C was made and is shown as the full line of Fig. 1. Optical potential VII from Ref. 21 was used to generate the distorted waves for ^{7}Li+^{12}C and potential III for ^{6}Li+^{13}C. It has been shown in Ref. 21 that these potentials produce excellent fits to 34 MeV ^{7}Li+^{12}C and 30 MeV ^{6}Li+^{12}C elastic scattering, respectively. The bound-state wave functions were calculated with a radius parameter of 1.25 fm, diffuseness of 0.65 fm, and a spin-orbit parameter λ of 25. Population of the $\frac{1}{2}^+$ state of ^{13}C, assumed to be a neutron bound to ^{12}C in a $2s_{1/2}$ orbital, proceeds through $l=1$ only. On the basis of our results in Ref. 9, a target spectroscopic factor $C^2S=0.75$ was used. The $p_{3/2}$ and $p_{1/2}$ transfers for ^{7}Li$\rightarrow^6$Li+n give the same angular distributions, apart from the magnitudes. A total p-shell spectroscopic factor $C^2S=0.72$ (Ref. 22) was used for the projectile. It is noticed that the data in Fig. 1 decrease in magnitude smoothly, whereas the calculations are oscillatory. A characteristic discrepancy found for all $2s_{1/2}$ angular distributions measured well above the Coulomb barrier.

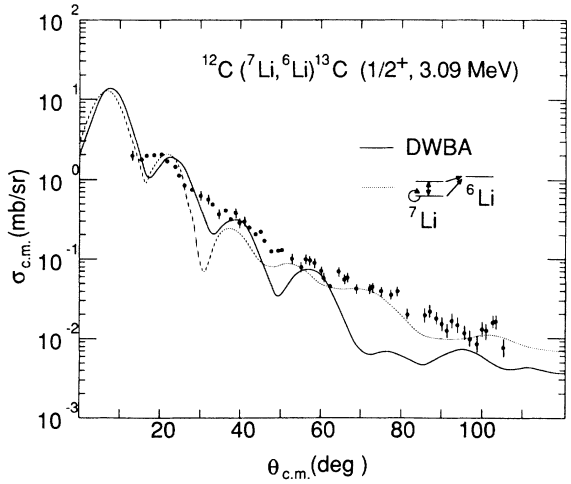

FIG. 1. Typical results of exact finite-range DWBA calculations and coupled-reaction channels calculations for the $2s_{1/2}$ transition to ^{13}C and the corresponding experimental data.

A series of calculations was then undertaken to investigate the projectile-coupling effects. These included ground-state reorientation of ^{7}Li, excitation of the $\frac{1}{2}^-$ 0.48 MeV state of ^{7}Li, and the transition from the $\frac{1}{2}^-$ state of ^{7}Li to the ground state of ^{6}Li. The particle-transfer form factors were treated either as one-way couplings (CCBA calculations) or as two-way coupled reaction channel couplings (CRC calculations). A deformation length of 2.0 fm was used for the rotational transitions in ^{7}Li and the ^{7}Li+^{12}C optical potential was changed to the coupled-channels potential given in Ref. 9 for ^{7}Li$\frac{3}{2}^-$-$\frac{1}{2}^-$ coupling. By using this procedure we ensure that the elastic scattering and projectile excitation of ^{7}Li+^{12}C were described as best as possible. The same bound-state wave functions, spectroscopic factors, and ^{6}Li+^{13}C potential as before were used. The results of the CRC calculation including all the couplings described above are shown as the dashed line in Fig. 1. It is apparent that the couplings have little effect on the angular distribution. Transitions were also calculated between the ground and first excited states of ^{12}C and ^{13}C, and again the coupling had little effect.

Earlier, Bayman *et al.*[17] included the contribution of reorientation of the ground state, because of the large quadrupole moments of ^{14}N and ^{39}K, on the transfer reaction ^{40}Ca(^{13}C,^{14}N)^{39}K through non-recoil approximation DWBA calculations and found that the shape of the calculated angular distributions were unaffected. To make certain that the result was not produced by a cancellation between the two quadrupole moments, they also performed calculations with only one quadrupole moment included and again observed no shift in the calculations. Even though ^{7}Li has a ground-state quadrupole moment twice as large as ^{14}N, its presence strongly influences the elastic scattering, and exact finite-range CRC calculations were carried out in our work, the same conclusion as in Ref. 17 was found for (^{7}Li,^{6}Li).

Kraushaar *et al.*[16] have suggested that ^{7}Li(p,d)^{6}Li at high energies shows the need for an admixture of 15–20% $1f_{7/2}$ in the ^{7}Li wave function. A DWBA calculation was made as before with an $f_{7/2}$ component having a spectroscopic factor of 10% that of the p component. The cross sections from the $f_{7/2}$ component were found to be negligible in comparison with the p component.

In Ref. 9, different optical potentials, taken from Ref. 21, had been used in the DWBA calculations and were found to give similar results. All these potentials, referred to here as deep potentials, had real parts with a depth of 150–300 MeV and a radius of $\sim 1.2A_t^{1/3}$ fm. Moore *et al.*[23] had previously found that FRDWBA calculations carried out with shallow potentials with $V \sim 50$

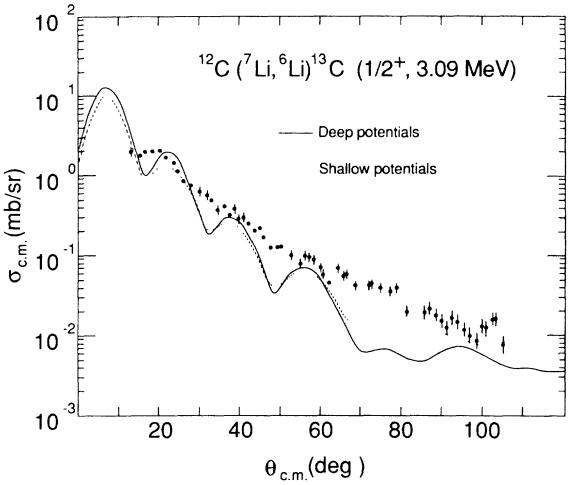

FIG. 2. Results of FRDWBA calculations with ^{7}Li distorting potentials whose real depth are about 230 MeV (deep potential) and about 75 MeV (shallow potential).

MeV, $R_R \sim 1.8 A_t^{1/3}$ has less structure in the ^{24}Mg(^{7}Li,^{6}Li)^{25}Mg $\frac{1}{2}^{+}$(0.58 MeV) transition than did those with $V \sim 200$ MeV, $R_R \sim 1.2 A_t^{1/3}$, although even here the calculations had more structure than did the data. Therefore, the 34 MeV ^{7}Li+^{12}C elastic scattering data of Ref. 21 were refitted with a shallow potential, resulting in the parameters $V=72.9$ MeV, $R_R=1.48 A_t^{1/3}$ fm, $a_R=0.86$ fm, $W=10.2$ MeV, $R_I=1.99 A_t^{1/3}$ fm, $a_I=1.13$ fm. A DWBA calculation of the ^{12}C(^{7}Li,^{6}Li)^{13}C $\frac{1}{2}^{+}$ reaction was then made using this potential for both the entrance and exit channels. The results are compared with the data and a calculation using a deep potential in Fig. 2. To obtain the same magnitude as before, it was necessary to use a target spectroscopic factor of $C^2S=1.0$. The calculated angular distribution is still oscillatory, at small angles, with a different phase from before. Considering the number of different potentials that have been tried, it is unlikely that a potential can be found which wil simultaneously describe the elastic scattering of ^{7}Li+^{12}C and the ^{12}C(^{7}Li,^{6}Li)^{13}C $\frac{1}{2}^{+}$ transfer reaction.

Since the excited states of ^{12}C are strongly coupled to the ground state, it is possible that target effects are present but are not treated correctly in the CRC calculations. Therefore, measurements for the ^{16}O(^{7}Li,^{6}Li)^{17}O reaction, which changes the target coupling in the reaction, were made and are reported in the next section.

III. THE ^{16}O(^{7}Li, ^{6}Li/^{6}He) REACTION

A. Experimental procedure

Data were taken simultaneously for both elastic and inelastic scattering and single-nucleon stripping reactions for a ^{7}Li beam bombarding a target containing ^{16}O. The ^{7}Li beam was extracted from a sputter source, injected into the Florida State University super FN tandem Van de Graaff, and accelerated to 34 MeV. The data were obtained with Si surface barrier $\Delta E + E$ counter telescopes consisting of 40 μm ΔE and 300 μm E detectors. A monitor detector was used during the runs to provide continous information on carbon buildup on the target, so that no confusion could occur between contaminant peaks and the peaks of interest. The pulses were amplified and pulse height analyzed by analog-to-digital converters (ADC's) interfaced with a PDP-11 computer. Mass gates for ^{7}Li, ^{6}Li, and ^{6}He were drawn around the individual mass groups and sorted into singles spectra during acquisition.

Both BeO and SiO_2 were used to provide the target ^{16}O nuclei. The BeO target was used for lab angles less than 33° because the ^{29}Si 6.19 and 6.38 MeV peaks from (^{7}Li,^{6}Li) interfered with the ^{17}O ground- and first-excited-state peaks of interest. At 33°, the ^{10}Be ground state begins to interfere with the ^{17}O ground state and so SiO_2 targets were used for the lab angles greater than 33°. Data have not been reported previously for the transfer to the 0.87 MeV, $\frac{1}{2}^{+}$ state in ^{17}O presumably because of the problem of contaminant peaks. Data were obtained in 1° steps for the laboratory angular range 8°–46°.

The absolute cross sections for the data were found by normalizing the elastic scattering yield for ^{7}Li+^{9}Be obtained with the BeO target to previously determined[24] cross sections and assuming a one to one ratio of ^{9}Be nuclei to ^{16}O nuclei on the target. Care was taken to make certain that water buildup did not occur in the target handling. A check on the absolute cross section can be made by computing the ^{7}Li+^{16}O elastic scattering cross sections from the optical-model parameters found by Schumacher *et al.*[7] for 36 MeV ^{7}Li+^{16}O scattering. The overall normalization of the two sets of data were found to agree to within 5%. An absolute error of ±13% is given to the present data, arising primarily from the error reported earlier for the ^{7}Li+^{9}Be scattering.

B. Transfer reaction analysis ^{16}O(^{7}Li,^{6}Li/^{6}He)

The distorting potentials needed for the finite-range distorted-wave Born-approximation (FRDWBA) calculations of the ^{16}O(^{7}Li,^{6}Li/^{6}He) one-nucleon transfer reactions studied were obtained for the ^{7}Li+^{16}O channel by carrying out optical-model calculations for the elastic data measured as part of the present study. As a starting point, the potential parameter sets of Schumacher *et al.*[7] for ^{7}Li+^{16}O were used in the optical-model calculations. Only slight modifications to those sets had to be made to describe the more complete data set reported here, the chief modification being a decrease in the imaginary diffuseness. The final parameter set is $V=240.6$ MeV, $R_R=1.19 A_t^{1/3}$ fm, $a_R=0.73$ fm, $W=16.3$ MeV, $R_I=2.08 A_t^{1/3}$ fm, $a_I=0.71$ fm. The ^{6}Li parameters for the exit channel were taken from an extensive analysis of the ^{6}Li+^{16}O scattering system.[18] Details of the exact finite-range DWBA calculations were described in the preceding section of this paper.

Results of the FRDWBA calculations for the ground and first excited states are shown in Fig. 3. As can be seen, the problems exhibited on other targets for (^{7}Li,^{6}Li) reactions also are found for the target ^{16}O. For the tran-

sition to the ^{17}O ground state, which has a large $1d_{5/2}$ single-particle strength,[25] there is structure in the data that also occurs in the calculations. However, the calculations are shifted to larger angles by 2.5° c.m. when compared to the data. The data to the 0.87 MeV, $\frac{1}{2}^+$ state, which is again, a single-particle $2s_{1/2}$ state,[25] are slightly oscillatory, while the calculation is highly structured as expected for the $l=1$ transfer that is permitted for this single-step transition. The spectroscopic factor is 1.2 for the ground-state $\frac{5}{2}^+$ transition and 0.76 for the $\frac{1}{2}^+$, 0.87 MeV transition, showing that the magnitudes of the calculated cross sections are reasonable.

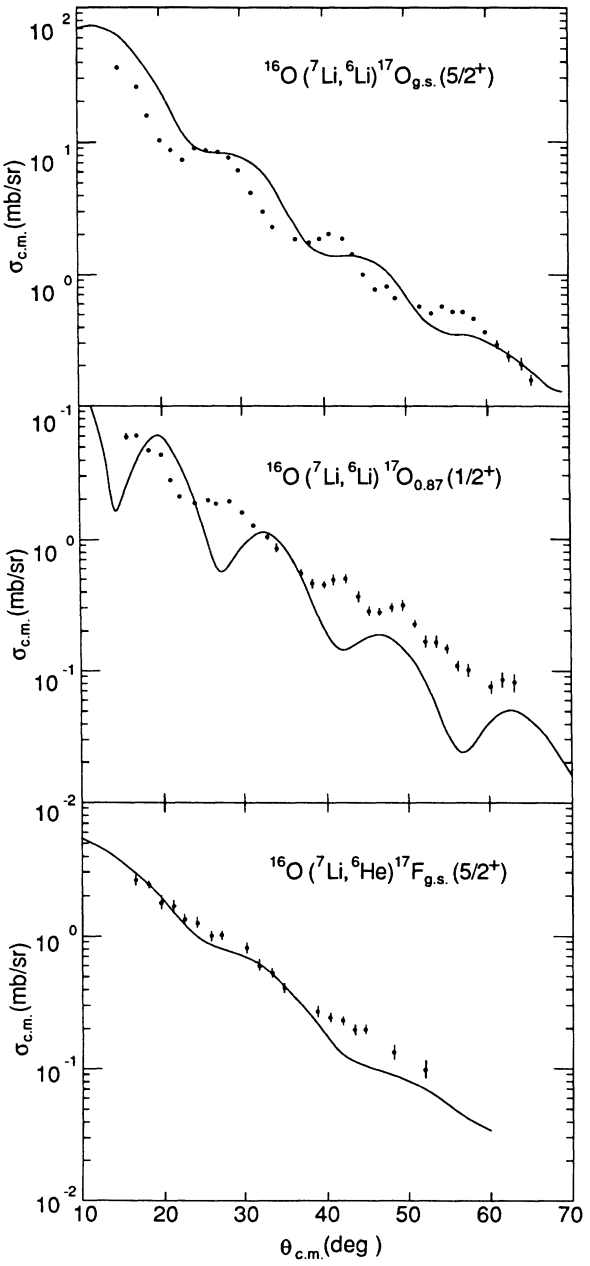

FIG. 3. Data for the single-nucleon-transfer reactions ^{16}O(^{7}Li,^{6}Li/^{6}He) taken at a ^{7}Li lab energy of 34 MeV. The results of FRDWBA calculations are shown.

It has been found[26] that the data for the reaction (^{19}F, ^{16}O) is out of phase with DWBA calculations. One suggested solution to this problem was the inclusion of a spin-orbit force. The possible importance of the spin-orbit interaction in a heavy-ion transfer reaction has also been demonstrated in studies of the ^{40}Ca(^{13}C, ^{14}N)^{39}K $l=1$ anomaly.[17]

The existence of vector analyzing power data[18] for $^6\vec{\text{Li}}+^{16}$O allows us to perform calculations with a spin-orbit potential obtained from experimental data. The inclusion of the spin-orbit potential made no difference in the calculated angular distribution. Since the exit channel in this reaction study, ^{6}Li+^{17}O, can also have a spin-orbit contribution arising from the $\frac{5}{2}$ spin of the ^{17}O residual nucleus, the spin-orbit potential found from $^6\vec{\text{Li}}+^{16}$O was mutliplied by 2.5 and added to the $^6\vec{\text{Li}}+^{16}$O potential. Again, no difference in DWBA calculations was found.

Data were also taken for the ^{16}O(^{7}Li,^{6}He)^{17}F ($\frac{5}{2}^+$, g.s.) transition. The data and FRDWBA calculations are shown in Fig. 3. It was not possible to observe the $\frac{1}{2}^+$, 0.5 MeV transition reliably because of its small cross section and the presence of background peaks from target contaminants. The $\frac{5}{2}^+$ transition is more poorly angular momentum matched than is (^{7}Li,^{6}Li) by $2\hbar$, which washes out the structure in the angular distribution and consequently makes a detailed comparison between the shape of the calculation and data less straigthforward. However, it does appear that the (^{7}Li,^{6}He) calculation describes the data better than do those for (^{7}Li,^{6}Li). The spectroscopic factor for ^{16}O+$p\rightarrow{}^{17}$F is $C^2S=0.54$ assuming $C^2S=0.593$ for ^{6}He+$p\rightarrow{}^7$Li from Cohen and Kurath.[22]

IV. ^{7}Li+^{16}O ELASTIC AND INELASTIC SCATTERING

As stated earlier, a single-channel, optical-model calculation was carried out for the elastic scattering. Standard Woods-Saxon-shaped potentials were employed and the parameters searched on by the code HERMES (Ref. 27) to obtain the best fit to the elastic data. The resulting calculation is shown as the dotted line in Fig. 4, and the parameters have been given in Sec. III. These same parameters were also used in a DWBA calculation of the ^{7}Li ($\frac{1}{2}^-$) 0.48 MeV cross section, shown as the dotted line in Fig. 4. The elastic cross section is described quite well, while the inelastic calculation is out of phase with the data. This same result was also found for ^{7}Li+^{12}C at 34, 48, and 78 MeV,[9,8,28] and ^{7}Li+^{54}Fe (Ref. 29) and ^{40}Ca.[15]

It has been shown[14,15] that coupled-channels (CC) calculations employing microscopic double-folded (DF) potentials were found to give the correct phase of the ^{7}Li ($\frac{1}{2}^-$) cross section. To investigate the effects of channel coupling in ^{7}Li+^{16}O, the CC code CHUCK (Ref. 19) was used to calculate the elastic and ^{7}Li ($\frac{1}{2}^-$) cross sections. Coupling to the ^{7}Li ($\frac{1}{2}^-$) 0.48 MeV state and reorientation of the ^{7}Li ground state were included in the calculation. The real potential was obtained from the double-folding model with the normalization of the potential

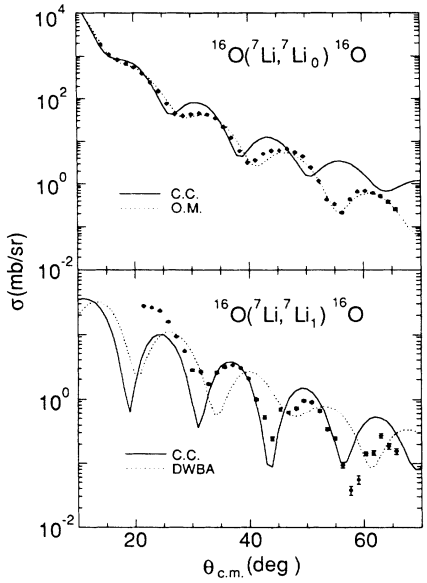

FIG. 4. Data for elastic and inelastic scattering (^{7}Li, 0.48 MeV) taken at a ^{7}Li lab energy of 34 MeV. The results of an optical-model calculation with Woods-Saxon real and imaginary potentials for the elastic scattering and DWBA calculation for the scattering to the 0.48 MeV first-excited state are shown. Also shown are the results of coupled-channels calculations that employ a microscopic real and a Woods-Saxon imaginary interaction.

fixed to 1.0. The details for determining the real optical and real and imaginary transition potentials are given in Ref. 15.

Coupled-channels calculations employing the imaginary Woods-Saxon parameters given in Sec. III were carried out. The deformation length for the ^{7}Li ($\frac{1}{2}^-$) state was determined by fitting the magnitude of the inelastic cross section and was equal to $\delta_2^{01}=3.5$ fm, which is 25% larger than that predicted by the measured $B(E2)$ value. The reorientation deformation length, $\delta_2^{11}=3.4$ fm, was fixed by normalizing to the ^{7}Li quadrupole moment.

The calculations are shown as the solid lines in Fig. 4. Including the reorientation and the $\frac{1}{2}^-$ state in the coupling scheme results in a good description of the ^{7}Li ($\frac{1}{2}^-$) cross section data. The coupled-channels calculation predicts the correct phase of the inelastic data, confirming the results found in Refs. 14 and 15. However, the elastic scattering prediction is now shifted out of phase with the data by 3°–5°. The present set of calculations shows that the coupling of other inelastic channels did not affect the shape of the $\frac{1}{2}^-$ cross section but they did drastically affect the elastic scattering. The $\frac{1}{2}^-$ result clearly shows that coupling effects need to be accounted for, while the elastic data indicate that other channels not specifically considered here also must be important.

V. CONCLUSION

It has been observed previously that the (^{7}Li,^{6}Li) reaction to a $2s_{1/2}$ single-particle state yields an experimental angular distribution that is structureless, whereas an exact finite-range DWBA calculation predicts a highly oscillatory distribution for a pure $l=1$ transition. In the present work, the results of coupled-reaction-channels calculations for ^{12}C(^{7}Li,^{6}Li) ($\frac{1}{2}^+$, 3.09 MeV) that include both the reorientation of the ground state and excitation to the first excited state of ^{7}Li both followed by one neutron transfer to a $2s_{1/2}$ state are reported. These calculations are little changed from a standard exact finite-range DWBA transfer calculation.

Data are reported for the ^{16}O(^{7}Li,^{6}Li) reaction. Once again, the angular distribution to the $2s_{1/2}$, 0.87 MeV state is structureless, while calculations of the reaction are oscillatory. The data for the ground state $d_{5/2}$ transition have slight oscillations which are reproduced by calculation, but the structure in the calculation occurs at angles about 3° larger than that for the data. These results along with the CRC calculations carried out for ^{12}C(^{7}Li,^{6}Li) imply that a contribution to the transfer process must occur from virtual excitation of ^{6}Li with the residual nucleus. The importance of this process in explaining vector polarized ^{6}Li scattering has been demonstrated recently,[30] and perhaps measurements of the elastic analyzing power and inelastic excitation of ^{6}Li using the interchange[31] of projectile and target for ^{6}Li+^{13}C will give further insight into this process.

The projectile excitation data for the ^{7}Li, $\frac{1}{2}^-$, 0.48 MeV first excited state of ^{7}Li are out of phase with DWBA calculations, but are in phase with a coupled-channels calculation that includes the ^{7}Li ground-state reorientation contribution. The latter calculation fails to describe the elastic scattering, demonstrating the need to include in the coupling other channels, as suggested by numerous authors.[30,32]

ACKNOWLEDGMENTS

The authors wish to acknowledge an enlightening discussion with Prof. P. J. Ellis. This work was supported by the State of Florida and the National Science Foundation.

[1]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).

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

[3]W. Treu, C. W. Towsley, K. G. Nair, and H. Voit, Phys. Rev. C **19**, 96 (1979).

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

[5]P. D. Bond, M. J. LeVine, D. J. Pisano, C. E. Thorn, and L. L. Lee, Jr., Phys. Rev. C **19**, 2160 (1979).

[6]C. W. Glover, K. W. Kemper, and A. D. Frawley, Phys. Rev. C **22**, 522 (1980); C. F. Maguire, G. L. Bomar, A. V. Ramayya, R. B. Piercey, J. Gomez del Campo, D. Shapira, and D. Hensley, *ibid.* **22**, 1097 (1980).

[7]P. Schumacher, N. Ueta, H. H. Duhm, K.-I. Kubo, and W. J. Klages, Nucl. Phys. **A212**, 573 (1973).

[8]A. F. Zeller, K. W. Kemper, D. C. Weisser, T. R. Ophel, D. F. Hebbard, and A. Johnston, Nucl. Phys. **A323**, 477 (1979).

[9]J. Cook, M. N. Stephens, K. W. Kemper, and A. K. Abdallah, Phys. Rev. C **33**, 915 (1986).

[10]J. Cook, M. N. Stephens, and K. W. Kemper, Nucl. Phys. **A466**, 168 (1987).

[11]H. Ohnuma, N. Hoshino, O. Mikoshiba, K. Raywood, A. Sakaguchi, G. G. Shute, B. M. Spicer, M. H. Tanaka, M. Tanifuji, T. Terasawa, and M. Yasue, Nucl. Phys. **A448**, 205 (1985); S. E. Darden, S. Sen, H. R. Hiddleston, J. A. Aymar, and W. A. Yoh, *ibid.* **A208**, 77 (1973).

[12]J. S. Blair, Phys. Rev. **115**, 928 (1959).

[13]F. Petrovich and D. P. Stanley, Nucl. Phys **A275**, 487 (1977).

[14]V. Hnizdo, K. W. Kemper, and J. Szymakowski, Phys. Rev. Lett. **46**, 590 (1981).

[15]D. P. Sanderson, S. P. Van Verst, J. Cook, K. W. Kemper, and J. S. Eck, Phys. Rev. C **32**, 887 (1985).

[16]J. J. Kraushaar, P. D. Kunz, J. H. Mitchell, J. M. Cameron, D. A. Hutcheon, R. P. Liejestrand, W. J. McDonald, C. A. Miller, W. C. Olsen, J. R. Tinsley, and C. E. Stronach, Phys. Rev. C **32**, 1083 (1985).

[17]B. F. Bayman, A. Dudek-Ellis, and P. J. Ellis, Nucl. Phys. **A301**, 141 (1978); P. J. Ellis, *ibid.* **A302**, 257 (1978).

[18]S. P. Van Verst, Ph.D. dissertation, Florida State University, 1988.

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

[20]R. A. Broglia, R. Liotta, B. N. Nilsson, and A. Winther, Phys. Rep. **29C**, 291 (1977).

[21]M. F. Vineyard, J. Cook, K. W. Kemper, and M. N. Stephens, Phys. Rev. C **30**, 916 (1984).

[22]S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965); **A101**, 1 (1967).

[23]G. E. Moore, K. W. Kemper, and L. A. Charlton, Phys. Rev. C **11**, 1099 (1975).

[24]K. W. Kemper, G. E. Moore, R. J. Puigh, and R. L. White, Phys. Rev. C **15**, 1726 (1977).

[25]M. D. Cooper, W. F. Hornyak, and P. G. Roos, Nucl. Phys. **A218**, 249 (1974).

[26]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).

[27]J. Cook, Comput. Phys. Commun. **31**, 363 (1984).

[28]A. F. Zeller, Y.-W. Lui, R. G. Tribble, and D. M. Tanner, Phys. Rev. C **22**, 1534 (1980).

[29]K. W. Kemper, A. F. Zeller, T. R. Ophel, D. F. Hebbard, A. Johnston, and D. C. Weisser, Nucl. Phys. **A320**, 413 (1979).

[30]H. Nishioka, J. A. Tostevin, R. C. Johnson, and K.-I. Kubo, Nucl. Phys. **A415**, 230 (1984); Y. Sakuragi, Phys. Rev. C **35**, 2161 (1987).

[31]M. F. Vineyard, J. Cook, and K. W. Kemper, Phys. Rev. C **31**, 879 (1985); J. Cook, A. K. Abdallah, M. N. Stephens, and K. W. Kemper, *ibid.* **35**, 126 (1987).

[32]F. Petrovich, R. J. Philpott, A. W. Carpenter, and J. A. Carr, Nucl. Phys. **A425**, 609 (1984); I. J. Thompson and M. A. Nagarajan, Phys. Lett. **106B**, 163 (1981); Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. **68**, 322 (1982); **70**, 1047 (1983).