Analyzing powers for mirror states in $^{12}C(^6Li,^7Li/^7Be)$ at $E_{^6Li}=50$ MeV: Evaluation of channel coupling

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A complete set $(iT_{11},T_{20},T_{21},T_{22})$ of analyzing powers (AP's) has been obtained for the single nucleon transfer reaction $^{12}C(^6Li,^7Li)^{11}C$. In addition, iT_{11} and T_{21} AP data have been obtained for $^{12}C(^6Li,^7Be)^{11}B$. A finite range distorted wave Born approximation calculation provides a qualitatively good description of the ground-state transfer data iT_{11}, but is out of phase at small angles. It describes the magnitude but not the detail of the rank-2 AP over the measured angular range. A coupled-channels Born approximation (CCBA) analysis describes the elastic, inelastic, and ground-state transfer reaction cross section and AP data well. The excited-state transfer cross section description is also good, but the AP data are less well described. CCBA calculations indicate that coupling to states in ^6Li and ^{12}C is not crucial to the description, but that coupling in the final state between the ground and first excited states of ^7Li or ^7Be is needed to describe the small-angle oscillations in the ground-state transfer iT_{11} data. [S0556-2813(97)00905-9]

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I. INTRODUCTION

Recent analyses [1–3] of polarized ^6Li elastic analyzing powers have allowed the importance of contributions to the elastic scattering from virtual excitation of the projectile, explicit spin-orbit interaction, and ground state reorientation to be quantified. It has been found that the tensor analyzing power T_{21} arises from the ground-state (g.s.) reorientation of the ^6Li, T_{20}, and T_{22} from projectile excitation and reorientation and that the vector analyzing power iT_{11} is produced when an explicit spin-orbit is combined with the other effects. In the present work, the first complete set of analyzing powers have been measured for the $^{12}C(^6Li,^7Li)^{11}C$ reaction to determine whether transfer processes strongly influence elastic scattering and whether projectile-ejectile excitation is important in the transfer process.

The earliest reported $(^6Li,^7Li)$ measurement [4] studied the $^{14}N(^6Li,^7Li/^7Be)$ reactions to look for isospin effects in heavy-ion reactions. While finite-range distorted wave Born approximation (FRDWBA) calculations gave a reasonable description of the data, the calculations appear to be shifted to larger angles by about 3°. Since these were early FRDWBA calculations, the difference could be attributed to numerical approximations made. An early extensive study of ^6Li and ^7Li induced scattering and single nucleon transfer reactions [5] found that the $(^6Li,^7Li)$ reaction FRDWBA calculations were quite sensitive to the choice of optical model parameters used whereas they found that $(^7Li,^6Li)$ calculations were relatively insensitive to these parameters. The large negative-Q value for most of the studied $(^6Li,^7Li)$ transitions produced a large momentum mismatch in the reaction, which could account for the increased potential sensitivity. Recently, the vector analyzing power (VAP) for the $^{26}Mg(^6\vec{L}i,^7Li)^{25}Mg$ reaction [6] was measured and while the VAP was described by FRDWBA calculations at larger angles, the data and calculations were of opposite sign at smaller angles and the calculated angular distribution was shifted to larger angles by about 3° when compared with the data.

The present work reports data and FRDWBA and coupled-channels Born approximation (CCBA) calculations for the reactions $^{12}C(^6Li,^7Li/^7Li^*)$ and $^{12}C(^6Li,^7Be/^7Be^*)$. The approach taken in the calculations was to require that the elastic-scattering cross sections and analyzing powers be described as well as the transfer data. This requirement ensures that the role of channel coupling in the entrance and exit channel on the transfer process is not overemphasized in the analysis.

II. EXPERIMENT

Analyzing power (AP) $(iT_{11},T_{20},T_{21},T_{22})$ and cross-section data for the $^{12}C(^6Li,^7Li)$ and $^{12}C(^6Li,^7Be)$ reactions were obtained in a series of measurements of the elastic and inelastic reactions $^{12}C(^6Li,^6Li^*)^{12}C^*$ [3]. The experimental details of the measurements of the transfer reaction AP are the same as given earlier in a report focusing on the inelastic scattering [3], and so will not be repeated here.

The detector resolution in the present work and the lack of any low-lying excited states in ^{11}C allowed the first excited state of ^7Li and ^7Be analyzing power to be measured in addition to those for the ground states. The spin difference between these two states, $3/2^-$ for the ^7Li g.s. and $1/2^-$ for the 0.48-MeV first excited ^7Li state, allows simple j dependence in the analyzing powers to be observed if reorientation affects do not overwhelm the reaction process.

III. ANALYSIS

A. Calculations

The single nucleon transfer data were analyzed in the coupled-channels Born approximation (CCBA) using the coupled channels (CC) code FRESCO. A six-channel calculation recently reported [3] provides a good description of the elastic and inelastic $^{12}C(^6Li,^6Li^*)^{12}C^*$ reactions, and was used as the starting point for the transfer calculations. A detailed description of this calculation is given in Ref. [3].

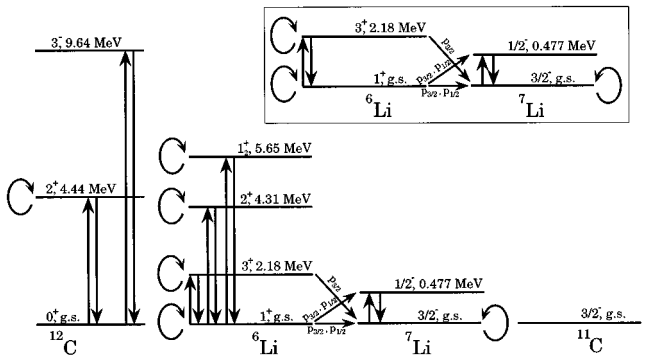

FIG. 1. Full eight-channel and simpler four-channel (inset) CCBA coupling schemes used for the ^{12}C(^{6}Li, ^{7}Li) calculations. The four-channel coupling scheme was used for optimization of the exit channel optical model parameters and evaluation of each coupling and transfer term. A similar eight-channel scheme was used in the case of ^{12}C(^{6}Li,^{7}Be). The $p_{3/2}$ and $p_{1/2}$ indicate the final state of the transferred neutron.

The real central potential used is calculated in the double folding formalism, while the imaginary central potential is of the Woods-Saxon form.

For the transfer reaction, the two additional channels ^{7}Li($3/2^{-}$, g.s.) and ^{7}Li($1/2^{-}$, 0.477 MeV) were added to the six-channel elastic-inelastic calculation. The single nucleon transfer amplitudes were obtained from Cohen and Kurath [7]. A phase difference between this reference and FRESCO required using an opposite sign for one of the amplitudes. Also included was the reorientation of the ^{7}Li(g.s.) and coupling between the ^{7}Li g.s. and 0.477 MeV states. This resulted in an eight-channel CCBA calculation, and required about 55 min of CPU time on a DEC Station 5000 Alpha machine.

The exit channel optical model parameters for ^{7}Li+^{11}C were obtained from the ^{7}Li+^{12}C work of Zeller *et al.* [8], since there is no published data for ^{7}Li+^{11}C. The exit channel and bound-state potentials are of the Woods-Saxon form, and the spin-orbit potential used in the exit (and entrance) channels is of the Thomas spin-orbit form.

Both $p_{3/2}$ and $p_{1/2}$ neutron transfers are possible from the ^{6}Li(g.s.), and are included in the calculation. Also included is neutron transfer from the ^{6}Li(3^{+}, 2.18 MeV) state to form the ^{7}Li ejectile. Neutron transfer from the ^{6}Li(2.18) to form the ^{7}Li(0.477) ejectile, and ^{12}C(0^{+}, g.s.),^{12}C(3^{-}, 9.64) and ^{7}Li($1/2^{-}$, 0.477) reorientation terms are not possible because of angular momentum restrictions. It was assumed that the ^{7}Li states have a $K=1/2$ bandhead with reversed level order due to the decoupling parameter [9]. The coupling and transfer scheme used is shown in Fig. 1, and the spectroscopic amplitudes are given in Table I.

The ^{7}Li g.s. Coulomb reorientation was included using $M(E2)=5.22$ efm^2, while the nuclear reorientation used a deformation length $\delta_2=2.37$. Both of these values were obtained from the g.s. spectroscopic quadrupole moment [10] and rms radius of ^{7}Li. The Coulomb excitation strength of 5.76 efm^2 was obtained from the $B(E2)$ value [10].

The bound-state potentials for ^{11}C+n and ^{6}Li+n in the ^{12}C(^{6}Li,^{7}Li) case were obtained by running a ^{12}C(^{6}Li,^{7}Li) DWBA calculation with the code DWUCK5. This code will search on the potential strength to give the specified binding energy. The same was done to obtain the ^{11}B+p and ^{6}Li+p bound-state potentials for the ^{12}C(^{6}Li,^{7}Be) case.

TABLE I. Spectroscopic amplitudes ($C\sqrt{S}$) for the ^{12}C(^{6}Li,^{7}Li)^{11}C CCBA FRESCO calculations. A phase factor difference in FRESCO requires an opposite sign for one of the amplitudes corresponding to $p_{1/2}$ or $p_{3/2}$ transfer. Identical values were used for the ^{12}C(^{6}Li,^{7}Be)^{11}B calculations.

System	Cohen-Kurath	Present
^{12}C$\rightarrow{}^{11}$C+n	1.67	0.600
^{7}Li(g.s.)$\rightarrow{}^{6}$Li+$n(p_{3/2})$	0.657	0.657
^{7}Li(g.s.)$\rightarrow{}^{6}$Li+$n(p_{1/2})$	0.538	−0.538
^{7}Li(0.477)$\rightarrow{}^{6}$Li+$n(p_{3/2})$	0.924	0.924
^{7}Li(0.477)$\rightarrow{}^{6}$Li+$n(p_{1/2})$	0.196	−0.196
^{7}Li(g.s.)$\rightarrow{}^{6}$Li(2.18)+$n(p_{3/2})$	0.744	0.744

B. Results

The eight-channel CCBA calculation describes the elastic and inelastic data as well as the previous six-channel CC calculation presented in Ref. [3]. That is, the neutron transfer has little affect on the elastic and inelastic CC calculation. The only parameter varied from the pure elastic and inelastic six-channel calculation was the imaginary central potential strength W, which was changed from 10.0 to 10.5 MeV. When the ^{11}C+n spectroscopic factor was adjusted to bring the magnitude of the transfer reaction cross sections into agreement with the data at small angles, the phase and magnitude of the calculations over all measured angles were in quite good agreement with the cross-section data.

To determine the sensitivity of the transfer calculations to the ^{6}Li and ^{7}Li optical potential parameters, a study was first carried out to determine the minimum number of channels needed for the CCBA transfer calculations to be essentially the same as the full eight-channel calculations. The smaller number of channels yields much shorter computing times. A four-channel transfer calculation with only the first two states in ^{6}Li and the first two states in ^{7}Li included, produced transfer results almost identical to the eight-channel transfer calculation. This reduced the calculation to just 10 min of CPU time. The inset of Fig. 1 shows the reduced coupling scheme. The forward angle iT_{11} data were found to be quite sensitive to slight changes in the real radius and diffuseness in the ^{7}Li+^{11}C exit channel. However, it was felt that the improvements were not sufficiently dramatic to change the parameters away from those that give a good description of the ^{7}Li+^{12}C elastic- scattering data.

The top of Fig. 2 shows the ^{7}Li(g.s.) cross section and full eight-channel AP calculations, along with the data. The bottom of Fig. 2 shows the ^{7}Li(0.477 MeV) calculations and data. The ^{7}Li(g.s.) transfer cross section and AP data are described reasonably well. The ^{7}Li(0.477) cross section and rank-2 AP data are also described reasonably well, but the iT_{11} data are more positive than the calculation. Table II gives the optical model parameters and coupling parameters used in the full calculation. Calculations were then carried out to determine the effect of the different channel couplings

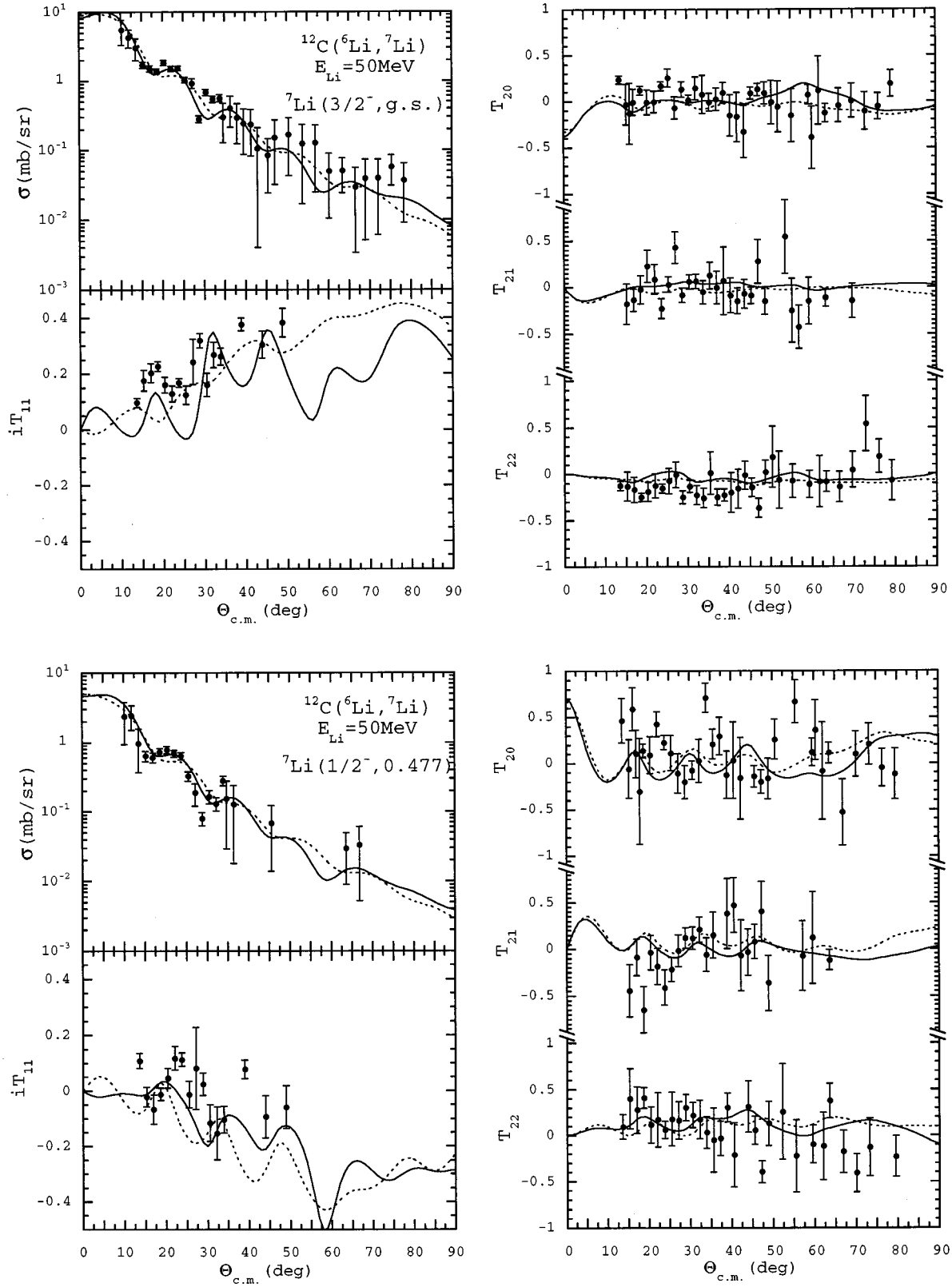

FIG. 2. Eight-channel CCBA calculations (solid) for the ^{12}C(^{6}Li,^{7}Li) transfer reaction cross sections and AP's, along with the data. The calculations shown are for the ^{7}Li($3/2^-$, g.s.) (top) and ^{7}Li($1/2^-$, 0.477 MeV) states (bottom). Also shown are the FRDWBA calculations (dotted) for both states.

by removing the couplings one at a time. The starting point of these investigations was the inset coupling scheme of Fig. 1.

The first process removed from the calculation was the neutron transfer to the 2.18 MeV state of ^{6}Li. This affected mainly the transfer iT_{11} AP, and mostly beyond 50° c.m. It also reduced the amplitude of the small-angle oscillations slightly. It had no affect on the elastic and inelastic calcula-

TABLE II. Optical model, double folding, and coupling strength parameters for the DWBA and eight-channel CCBA FRESCO calculations. All radii use the convention $R_x = r_x A_T^{1/3}$.

Channel		r_c (fm)	V (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_I (fm)	a_I (fm)	V_{LS} (MeV)	r_{LS} (fm)	a_{LS} (fm)	N	SNKE[a] (MeV)
Entrance	CCBA	2.24				10.50	2.22	0.55	0.50	0.90	0.80	0.985	−356
	DWBA	2.24	256.0	1.13	0.76	13.49	2.17	0.63	1.24	0.12	0.22		
Exit		1.30	145.6	1.22	0.83	12.09	2.22	0.69					
Bound states:													
	$^{11}C+n$	1.25	38.66	2.00	0.65								
	$^{6}Li+n$	1.25	37.88	1.73	0.45								
	$^{11}B+p$	1.25	38.14	2.00	0.65								
	$^{6}Li+p$	1.25	37.88	1.73	0.45								

δ_2 and δ_3 Coupling strength parameters

^{6}Li δ(g.s.r.)	^{6}Li δ(2.18)	^{6}Li δ(2.18r)	^{6}Li δ(4.31)	^{6}Li δ(4.31r)	^{6}Li δ(5.65)	^{6}Li δ(5.65r)	^{12}C δ(4.44)	^{12}C δ(4.44r)	^{12}C δ_3(9.64)	^{7}Li δ(g.s.r.)	^{7}Li δ(0.477)
−0.76	−2.04	−1.53	−1.95	−0.98	−3.72	−1.86	−1.34	−0.67	−0.80	2.37	2.37

[a]Single nucleon knockout exchange.

tions, and only a minor affect on the ^{7}Li(0.477) state transfer reaction.

Removing the ^{7}Li ground-state reorientation (g.s.r.) reduced the amplitude of the small angle oscillations of the ^{7}Li(g.s.) iT_{11} and increased iT_{11} considerably for angles greater than 50° c.m. It had a minimal effect on the ^{7}Li(0.477) state observables, and no affect on the elastic or inelastic calculations.

The ^{7}Li(g.s.)-^{7}Li(0.477) coupling had a large affect on the ^{7}Li(g.s.) iT_{11} over the whole angular region of interest, 0–90° c.m. The small-angle oscillations were reduced when this coupling was removed, moving the calculation further from the data. The ^{7}Li(0.477) iT_{11} calculation was also less oscillatory at small angles, making agreement with the data worse. Removing the coupling to the ^{6}Li(2.18) state and the ^{6}Li(g.s.r.) and ^{7}Li(g.s.r.) mainly affected the ^{7}Li(0.477) iT_{11}, making the calculation more negative and further from the data.

This scheme was further simplified, concentrating on just the ^{7}Li(g.s.) transfer. The ^{7}Li(g.s.) data could be described very well without the ^{6}Li(g.s.r.), and without the neutron transfer from or coupling to the ^{6}Li(2.18) state. That is, with only neutron transfer from the ^{6}Li(g.s.) and the ^{7}Li(g.s.)-^{7}Li(0.477) coupling, the ^{7}Li(g.s.) transfer data were described as well as when using the inset coupling scheme of Fig. 1. A slight adjustment of the real exit channel radius parameter (1.22 fm→1.37 fm) was required, however.

The calculation for ^{12}C(^{6}Li,^{7}Be) was identical to that for ^{12}C(^{6}Li,^{7}Li) except for the necessary changes to charges, masses, binding energies, and bound-state potential strengths. However, both of these calculations were very insensitive to the bound-state potential strengths for $^{11}C+n$, $^{6}Li+n$, and $^{11}B+p$, $^{6}Li+p$ within the few tenths of MeV difference between the two corresponding bound states. The top of Fig. 3 shows the ^{7}Be(g.s.) cross section and AP calculations, along with the data. The bottom of Fig. 3 shows the ^{7}Be(0.429 MeV) calculations and data. The resulting calculation describes the ^{12}C(^{6}Li,^{7}Be) data as well as the ^{12}C(^{6}Li,^{7}Li) data. The calculations and data are in fact very similar, as might be expected for mirror states. Notice in particular the similarity between the iT_{11} data for the g.s.'s of ^{7}Li and ^{7}Be.

Finally, a FRDWBA calculation was performed for comparison. These calculations were done with FRESCO, and are shown as the dotted curves in Figs. 2 and 3. The optical model parameters used for these calculations are given in Table II. The real potential for the entrance channel is of the Woods-Saxon form and the parameters were adjusted to provide a good description of the elastic scattering in the absence of channel coupling. The $^{11}C+n$ spectroscopic factor was reduced slightly from the CCBA calculation (0.60 →0.55) to improve the description of the transfer cross sections.

The FRDWBA calculation describes the cross-section data nearly as well as the CCBA calculation, but not the iT_{11} data. In particular, the g.s. iT_{11} calculation is out of phase with the data and the CCBA calculation. A spin-orbit (SO) potential was put into the exit channel and also into the bound-state potentials, but this had virtually no effect. The rank-2 AP calculations are, however, quite similar to the CCBA calculations. These calculations show that, compared to a CCBA calculation, a DWBA calculation is not sufficient to describe the transfer AP data.

The present work differs from Ref. [6] where ^{26}Mg($^{6}\vec{\text{Li}}$,^{7}Li) was studied in that it was possible to extract analyzing powers for both the $3/2^-$, g.s. and $1/2^-$ first excited state of ^{7}Li. Santos and Gonçalves [11] have derived results within a semiclassical model for the ($^{7}\vec{\text{Li}}$,^{6}Li) reaction that allows one to determine whether there are final-state spin effects in the analyzing powers. They show that the analyzing power $^{T}T_{20}$ might be less sensitive to the ^{7}Li g.s. reorientation and hence more sensitive to the spin transfer than other AP because this aligned orientation has radial symmetry in planes parallel to the reaction plane.

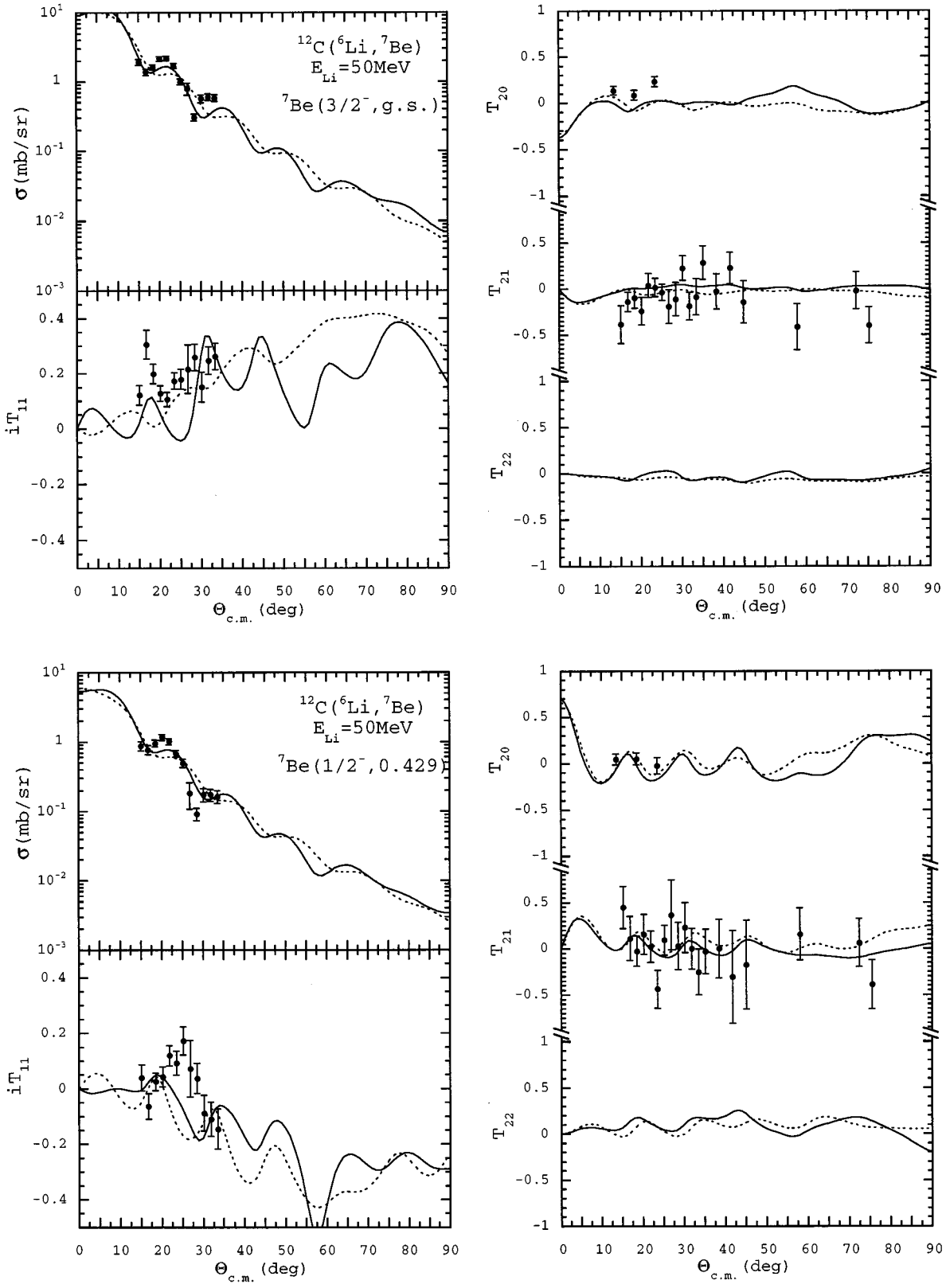

FIG. 3. Eight-channel CCBA calculations (solid) for the ^{12}C(^{6}Li,^{7}Be) transfer reaction cross sections and AP's, along with the data. The calculations shown are for the ^{7}Be($3/2^{-}$, g.s.) (top) and ^{7}Be($1/2^{-}$, 0.429 MeV) states (bottom). Also shown are the FRDWBA calculations (dotted) for both states.

The ejectile spin dependence is contained in a Racah coefficient in Eq. (22) of Ref. [11], and shows that the rank-1 AP will have the same sign for both ^{7}Li states, whereas the rank-2 AP for these states will have opposite signs. This sign prediction is borne out by iT_{11} and T_{22}. It is harder to find the sign difference in T_{20} and T_{21} because of the apparent structure in their angular distributions. Figure 4 shows the $^{T}T_{20}$ data collected and two results are apparent. The sign of

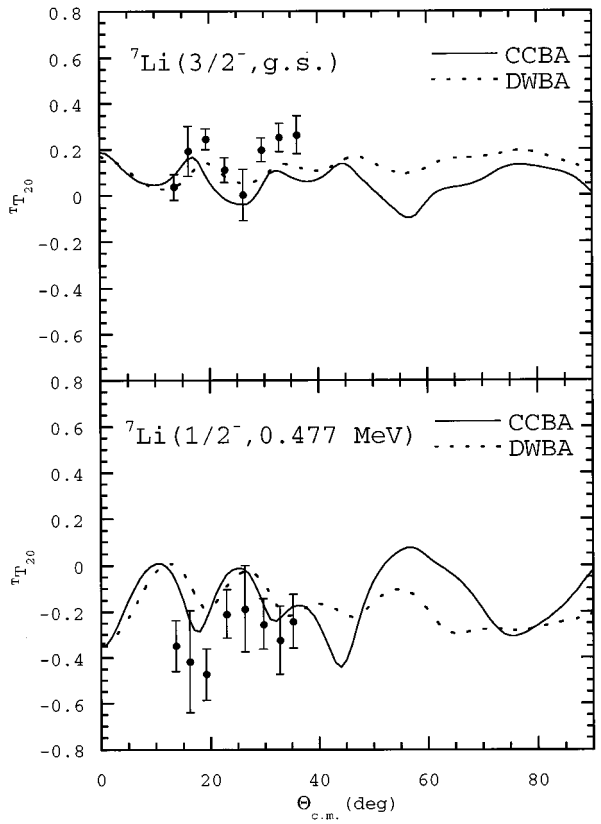

FIG. 4. The analyzing power ^{T}T$_{20}$ for the ^{7}Li(3/2$^-$, g.s.) (top) and ^{7}Li(1/2$^-$, 0.477 MeV) state (bottom). The solid curves are the results of an eight-channel CCBA calculation, while the dashed curves are the results of FRDWBA calculations.

the AP is clearly opposite for the two states, and the CCBA and DWBA calculations are quite similar, as predicted by Ref. [11].

The results of the present analysis agree quite well with those of Turkiewicz *et al.* [12] for the ^{26}Mg($^7\vec{\text{Li}}$,^{6}Li) reaction, where it was shown that there was only a weak dependence of the transfer AP on the ^{6}Li distorting potential, that target excitation was not important, and that coupling of the states in ^{7}Li, g.s. reorientation and transfer from both ^{7}Li states were important. For the case of ^{54}Fe($^7\vec{\text{Li}}$,^{6}Li) it was found by Karban *et al.* [13] that iT_{11} and $^TT_{20}$ were only weakly affected by ^{7}Li g.s. reorientation and coupling of the ^{7}Li states whereas T_{21} did need these contributions. The reason for the difference in the results of Refs. [12] and [13] are not addressed in Ref. [13] and so it is only possible to state that the present investigation supports the conclusions of Ref. [12].

IV. CONCLUSIONS

A complete set of analyzing powers has been obtained for the ^{12}C(^{6}Li,^{7}Li) transfer reaction. In addition, iT_{11}, T_{21}, and some T_{20} data have been obtained for the ^{12}C(^{6}Li,^{7}Be) transfer reaction. An eight-channel CCBA calculation describes the elastic, inelastic, and ^{7}Li(g.s.) and ^{7}Be(g.s.) transfer cross section and AP data well. The ^{7}Li(0.477) and ^{7}Be(0.429) transfer cross-section data are also described well, but the AP data are less well described. A CCBA calculation with coupling only to the ^{6}Li(2.18) and ^{7}Li(0.477) [or ^{7}Be(0.429)] states does just as well describing all the transfer data. That is, the states in ^{12}C and the higher-lying states in ^{6}Li contribute little to the transfer calculation so that the (^{6}Li,^{7}Li) and (^{6}Li,^{7}Be) AP are being produced by j dependence and final-state interactions. A calculation with coupling only to the ^{7}Li(0.477) [^{7}Be(0.429)] state does equally well describing the ^{7}Li(g.s.) [^{7}Be(g.s.)] data.

A FRDWBA calculation describes the transfer iT_{11} data poorly, and indicates that the ^{7}Li(g.s.)-^{7}Li(0.477) coupling is the most important one for describing the small-angle oscillations in the ^{7}Li(g.s.) iT_{11} data. The same holds for the ^{7}Be(g.s.) data. The two vector analyzing powers are in fact very similar, as would be expected for mirror nuclei.

A spin-orbit potential was added to both the ^{11}C+^{7}Li exit channel optical model parameters and to the ^{11}C+n and ^{6}Li+n bound-state potentials in the FRDWBA calculation to see if the ^{7}Li iT_{11} descriptions might improve, but this had little effect.

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