^{7}Li+^{12}C: Complete sets of analyzing powers for inelastic scattering and single-nucleon stripping

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Complete sets of analyzing powers have been obtained for a large number of inelastic scattering and single-nucleon stripping channels for 34-MeV polarized ^{7}Li+^{12}C. We present data for inelastic excitation to the 0.478-MeV 1/2^{-} state of ^{7}Li, the 4.44-MeV 2^{+}, 7.65-MeV 0^{+}, and 9.64-MeV 3^{-} states of ^{12}C and for mutual excitation of the 1/2^{-} and 2^{+} states, single-neutron stripping to the 0.0-MeV 1/2^{-}, 3.09-MeV 1/2^{+}, and 3.85-MeV 5/2^{+} states and an unresolved multiplet centered at 7.6 MeV of ^{13}C, and single-proton stripping to the 0.0-MeV 1/2^{-} state and an unresolved doublet of the 3.51-MeV 3/2^{-} and 3.55-MeV 5/2^{+} states of ^{13}N. These data are analyzed with the continuum-discretized-coupled-channels approach using cluster-folding model form factors in a calculation that includes all the known physics for these systems.

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I. INTRODUCTION

One of the major goals of nuclear reaction studies is to be able to describe a wide range of different reactions within a single coherent theoretical framework. Reactions involving weakly bound projectiles, such as ^{6,7}Li and ^{9}Be provide a severe test of reaction theories, as for these systems inelastic excitation of the projectile is important, in addition to inelastic excitation of the target and rearrangement reactions. The availability of polarization observables for ^{6,7}Li projectiles provides a further stringent test of our understanding of the interaction between two colliding nuclei, particularly if a full set of analyzing powers is obtained. Furthermore, if data are obtained in the Fraunhofer scattering regime, where the Coulomb interaction is no longer dominant, we are able to test rigorously our understanding of the nuclear interaction. In a review paper summarizing the achievements of polarized heavy-ion studies published almost a decade ago, Fick *et al.* [1] commented that to further advance our knowledge, complete sets of analyzing powers for as many reaction channels as possible were required, which should then be analyzed within a single theoretical framework.

To this end, complete sets of analyzing powers have been obtained for a wide range of reactions induced by a polarized ^{7}Li beam incident on a ^{12}C target at a bombarding energy of 34 MeV. In addition to the elastic scattering data that have been published recently [2], we present here data for inelastic excitation to the 0.478-MeV 1/2^{-} state of ^{7}Li, the 4.44-MeV 2^{+}, 7.65-MeV 0^{+}, and 9.64-MeV 3^{-} states of ^{12}C and for mutual excitation of the 1/2^{-} and 2^{+} states, single-neutron stripping to the 0.0-MeV 1/2^{-}, 3.09-MeV 1/2^{+}, and 3.85-MeV 5/2^{+} states and an unresolved multiplet centred at 7.6 MeV of ^{13}C, and single-proton stripping to the 0.0-MeV 1/2^{-} state and an unresolved doublet of the 3.51-MeV 3/2^{-} and 3.55-MeV 5/2^{+} states of ^{13}N. However, for some channels, namely, inelastic excitation of the 7.65-MeV 0^{+} state of ^{12}C, single-neutron stripping to the unresolved multiplet centred at 7.6 MeV of ^{13}C, and single-proton stripping to both the 1/2^{-} ground state and the unresolved doublet of the 3.51-MeV 3/2^{-} and 3.55-MeV 5/2^{+} states of ^{13}N, the statistics were such that meaningful values could not be obtained for the complete set of analyzing powers. In this work we present a complete analysis of the reaction data using a single coupled-discretized-continuum-channels (CDCC) calculation with cluster-folding (CF) model form factors. To our knowledge, this is the first time that such an extensive analysis, including couplings to target inelastic excitations and transfer channels, has been attempted while using the CDCC method to describe the ^{7}Li breakup couplings. Turkiewicz *et al.* [3] carried out a coupled-channel Born approximation analysis of ^{26}Mg($^{7}\overrightarrow{\mathrm{Li}}$,^{6}Li) and ^{120}Sn($^{7}\overrightarrow{\mathrm{Li}}$,^{6}Li) data with a similar aim to the present work, although the data described were not so extensive as those presented here and the CDCC/CF model was not used to describe the ^{7}Li excitations.

The final CDCC calculation carried out included couplings to the 1/2^{-} first excited state, the 7/2^{-} and 5/2^{-} resonances and the $L=0,1,3$ nonresonant α-t continuum of ^{7}Li, the 2^{+} and 3^{-} states of ^{12}C, single-neutron stripping to the 1/2^{-}, 1/2^{+}, and 5/2^{+} states of ^{13}C and single-proton stripping to the 1/2^{-} state of ^{13}N. Couplings to mutual excitations are not possible within our CF model, and couplings to the multiplet of unbound states in ^{13}C centred at 7.6 MeV and the unbound 3/2^{-}, 5/2^{+} doublet in ^{13}N were omitted due to the difficulty of treating transfer to unbound states in a realistic way. We also omitted coupling to the 0^{+} excited state of ^{12}C due to the uncertain structure of this state. This calculation uses known inelastic strengths and transfer spectroscopic amplitudes so that the number of free parameters adjusted to fit data is two, the CF model imaginary potential

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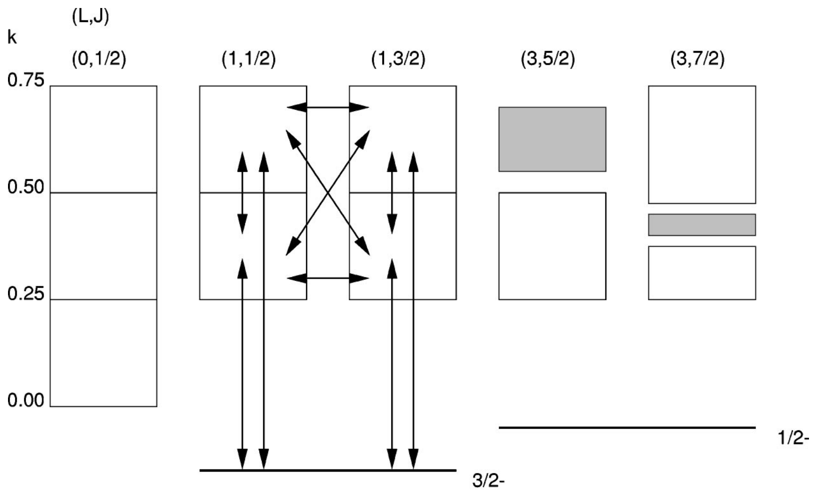

FIG. 1. ^{7}Li channels included in the calculation. The open boxes indicate nonresonant α-t continuum bins, while the shaded boxes denote the resonant bins. A sample set of couplings between the $L=1$ states are indicated. All possible couplings up to multipolarity $\lambda=2$ were included in the calculation.

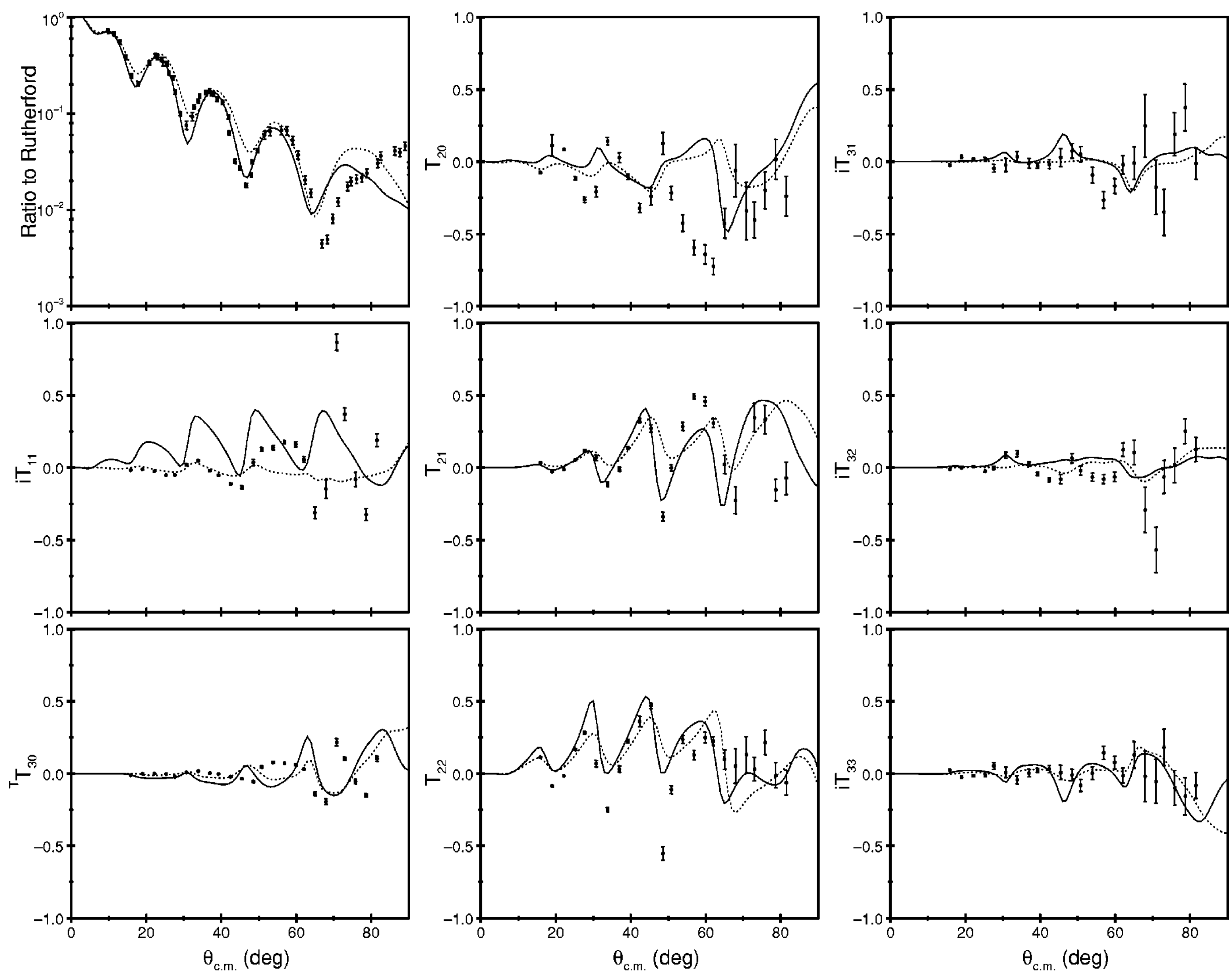

FIG. 2. Elastic scattering data for 34 MeV $^7\overrightarrow{\mathrm{Li}}+{}^{12}$C. The solid curves denote the result of the full calculation described in the text while the dotted curves denote the result of a calculation omitting couplings to the ^{12}C($^7\overrightarrow{\mathrm{Li}}$,^{6}Li)^{13}C and ^{12}C($^7\overrightarrow{\mathrm{Li}}$,^{6}He)^{13}N transfers.

strength and the radius of the $^{12}C+n$ binding potential for the 3.09-MeV $1/2^+$ state in ^{13}C.

The experimental procedure was described in Bartosz *et al.* [2] and Cathers *et al.* [4] and thus will not be further detailed here. The steps taken to determine the input for the final calculation are described in Sec. II and the results are compared with the data in Sec. III. Data for channels not analyzed is also presented in Sec. III, and in Sec. IV we discuss our results.

II. CALCULATIONS

This section describes test calculations carried out to explore the applicability of the CDCC method to the present large data set and the ingredients of the final calculation, the results of which are compared with the data in Sec. III. All calculations were carried out using the code FRESCO [5], version FRXP14.

The basis for the calculations was a CDCC/CF model description of ^{7}Li similar to that of Bartosz *et al.* [2]. We have employed the CF model rather than the fully microscopic double-folding method as it provides a consistent treatment of both diagonal and coupling potentials and also generates the imaginary parts of these potentials, which the double-folding procedure does not. All partial waves up to $l=45\hbar$ were included and the coupled equations were integrated out to a radius of 30 fm. Couplings to the 0.478-MeV $1/2^-$ bound state, the 4.63-MeV $7/2^-$, and 6.68 MeV $5/2^-$ resonances and the $L=0,1,3$ α-t continuum in ^{7}Li were included. The continuum binning scheme was as used by Bartosz *et al.* [2], the α-t relative momentum k being limited to $0.0\leqslant k\leqslant 0.75$ fm^{-1} with a bin width of $\Delta k=0.25$ fm^{-1}. The lowest $0.0\leqslant k\leqslant 0.25$ fm^{-1} bins were omitted from all but the $L=0$ continuum as these bins were found to have little influence on the elastic scattering and do not contribute significantly to the total α-t breakup cross section. The binning scheme was suitably modified for the $L=3$ continuum to avoid double counting in the presence of the $L=3$ reso-

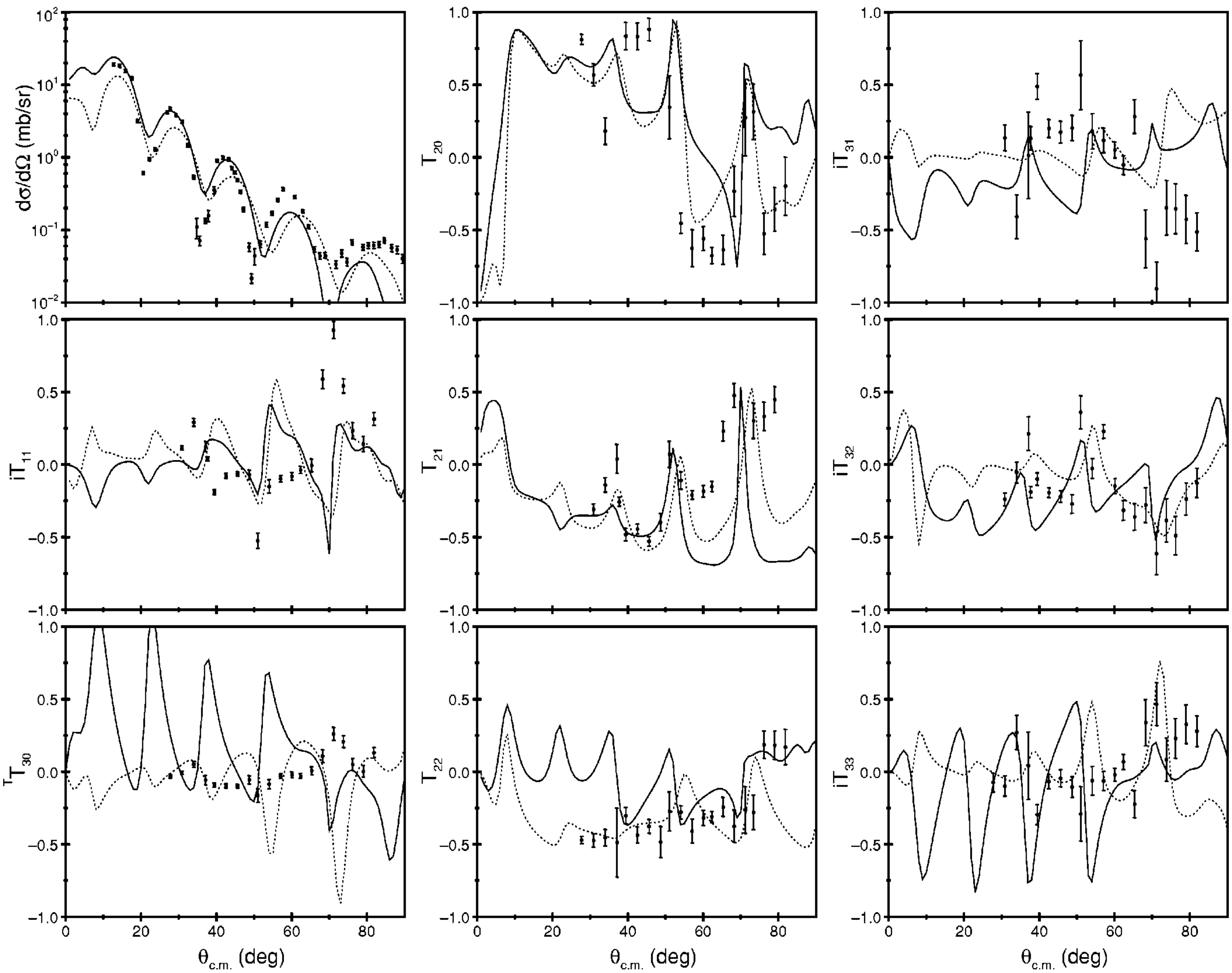

FIG. 3. Inelastic scattering data for excitation of the 0.478-MeV $1/2^-$ state of ^{7}Li. The solid curves denote the result of the calculation described in the text while the dotted curves denote the result of a calculation omitting couplings to the ^{12}C($^7\overrightarrow{\mathrm{Li}}$,^{6}Li)^{13}C and ^{12}C($^7\overrightarrow{\mathrm{Li}}$,^{6}He)^{13}N transfers.

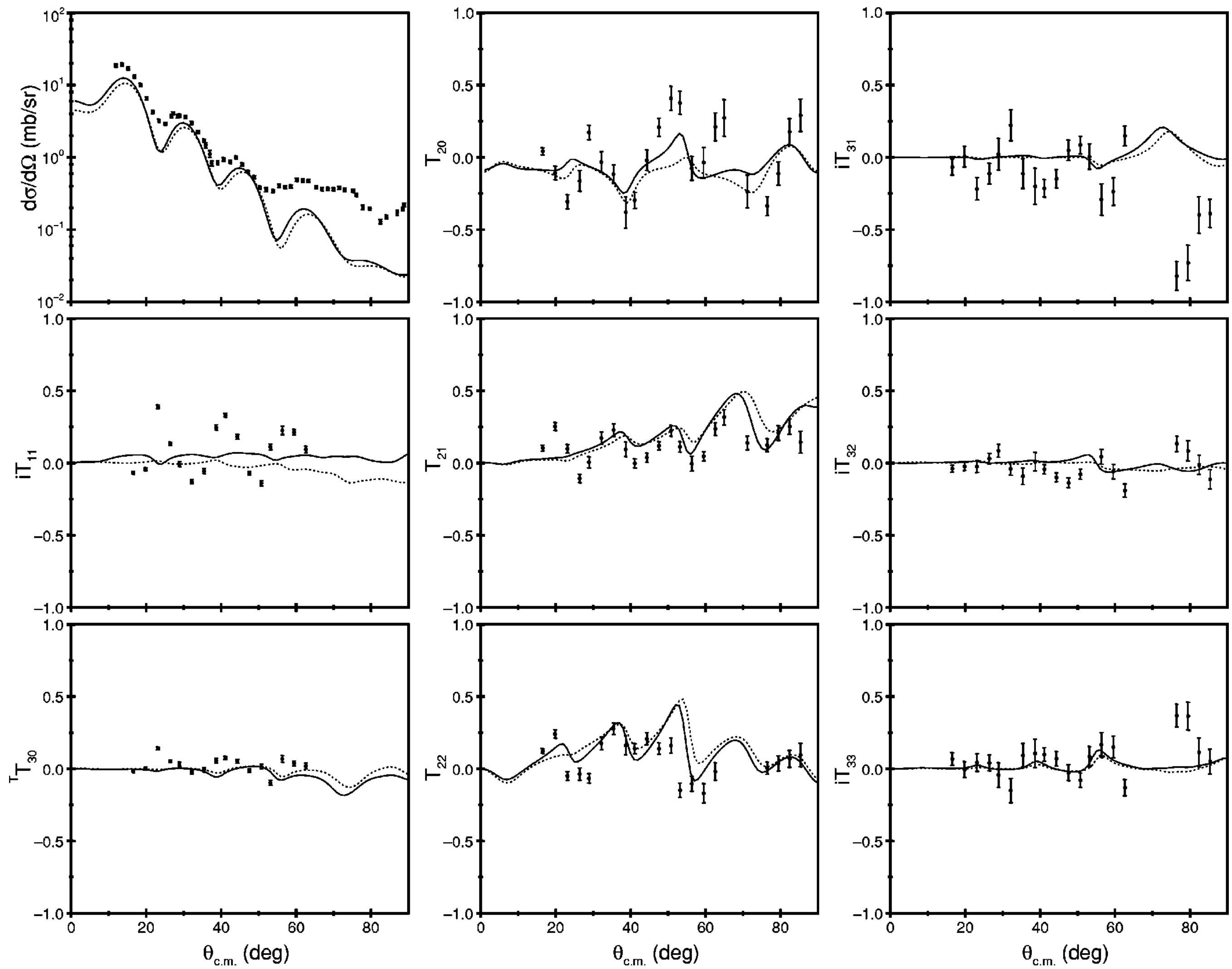

FIG. 4. Inelastic scattering data for excitation of the 4.44-MeV 2^+ state of ^{12}C. The solid curves denote the result of the calculation described in the text while the dotted curves denote the result of a calculation omitting couplings to the $^{12}C(^{7}\overrightarrow{Li},^{6}Li)^{13}C$ and $^{12}C(^{7}\overrightarrow{Li},^{6}He)^{13}N$ transfers.

nances, which were also treated as momentum bins, of width sufficient to accommodate their main strength. These widths were equivalent to energy spreads of 0.2 and 2.0 MeV for the $7/2^-$ and $5/2^-$ resonances, respectively. All possible couplings, including reorientation where appropriate, up to multipolarity $\lambda=2$ were included in the calculation. Figure 1 shows all the ^{7}Li channels included and a sample set of couplings, between the $L=1$ states, is indicated.

The α-^{12}C and t-^{12}C potentials required as input to the CF model were based on those of Ober and Johnson [6] and Schmelzbach *et al.* [7], respectively. To obtain a good description of the elastic scattering data the CF model potentials calculated using these α-^{12}C and t-^{12}C potentials must be renormalized. However, previous calculations with renormalized CF potentials [2] did not describe the $^{7}\mathrm{Li}+{}^{12}\mathrm{C}$ elastic scattering data in the angular range $60° \leqslant \theta_{c.m.} \leqslant 80°$, so the first part of this work was to develop a new approach to obtaining the CF potential. One successful approach to developing semimicroscopic heavy-ion potentials has been that of double folding. While ^{7}Li real potentials obtained in this way must be renormalized by factors of ~ 0.6 in order to describe the data in optical model calculations, it has been shown that including the ground-state reorientation of ^{7}Li [8] and couplings to the α-t resonances and continuum [9] removes the need for this renormalization. Thus, it is reasonable to assume that the double-folding method provides a realistic "bare" real potential. Consequently, it was decided to first explore the differences between the CF and double-folded real potentials. A comparison of the CF model real potential calculated using the unrenormalized α-^{12}C and t-^{12}C potentials with a DF potential obtained by folding ^{7}Li [10] and ^{12}C [11] densities with the M3Y effective nucleon-nucleon interaction [12] revealed that the cluster-folded potential had a similar depth and shape as that of the double-folded one, but a larger effective radius. Thus, instead of renormalizing the real part of the CF model potential, as is usually done, the radius and diffuseness parameters of the real parts of the component α-^{12}C and t-^{12}C potentials were

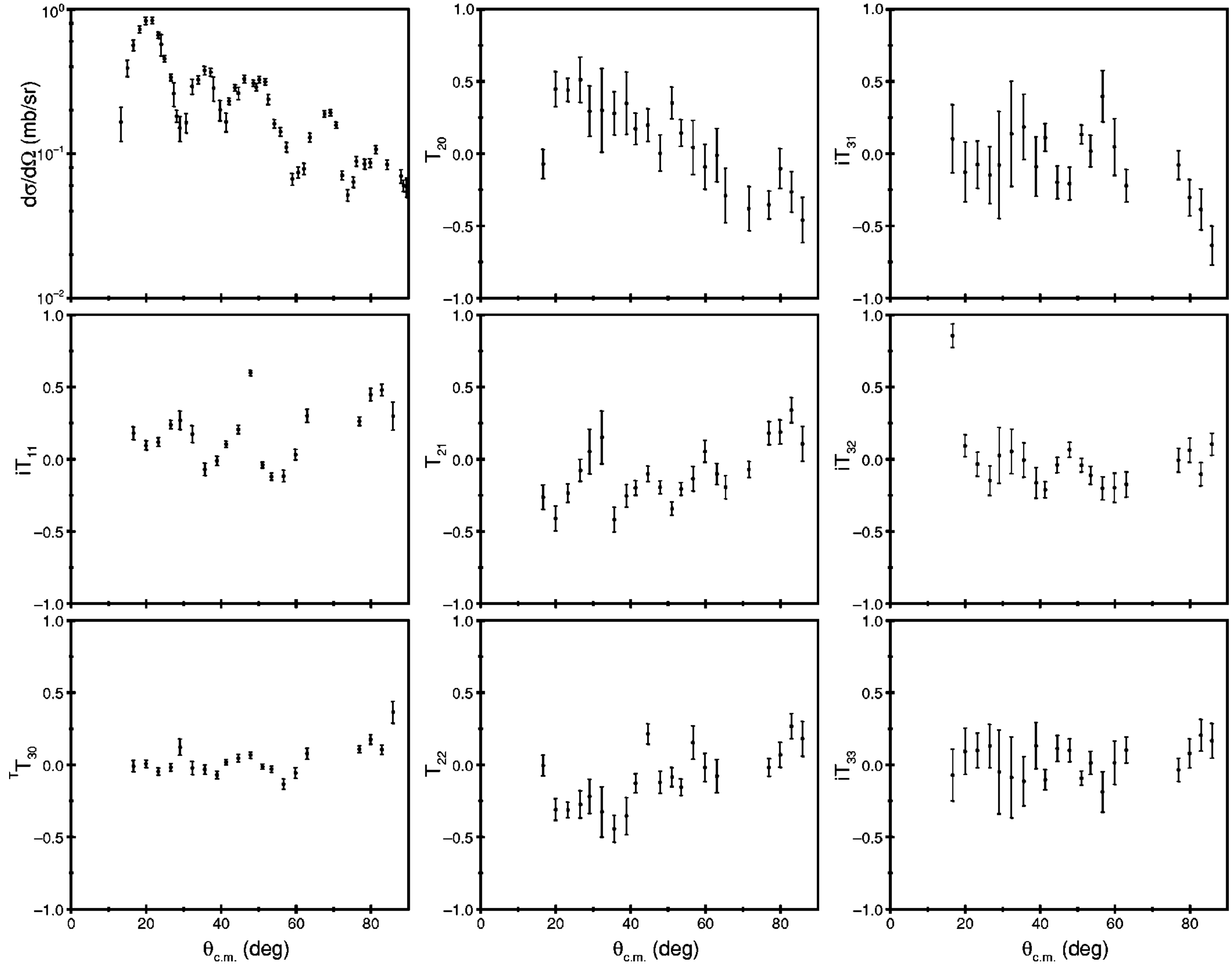

FIG. 5. Inelastic scattering data for mutual excitation of the 0.478-MeV $1/2^-$ state of ^{7}Li and the 4.44-MeV 2^+ state of ^{12}C.

tuned to produce a CF model real potential that closely matched the double-folded one. The imaginary part of the CF model potential was renormalized by a factor of 0.9, found by giving the best description of the ^{7}Li+^{12}C elastic scattering cross section. This procedure produced considerably better agreement with the elastic scattering cross section angular distribution, particularly in the angular range $60° \leqslant \theta_{c.m.} \leqslant 80°$, than the usual method of renormalizing both the real and imaginary CF model potentials.

Having thus established a firm basis for our analysis we then proceeded to include couplings to all the important observed reaction channels for the 34-MeV ^{7}Li+^{12}C system. In order to reduce the number of free parameters to the absolute minimum the input for these couplings was taken from the literature, either in the form of theoretical calculations or experimental measurements. In this way we hoped to obtain insight into which reaction processes are important for the various experimental quantities by a rigorous test of current reaction theory.

Couplings to the ^{12}C 2^+ and 3^- states were implemented using the rotation-vibration model, following Cook *et al.* [13]. The 0^+ ground state and the 4.44-MeV 2^+ state were considered to be the first two members of a $K=0$ rotational band, while the 9.64-MeV 3^- state was treated as an octopole vibrational state, again following Cook *et al.* [13]. Couplings between the 2^+ and 3^- states were not included. The form factors were obtained by deforming the bare CF model potential, with deformation lengths $\delta_2 = -1.4$ fm and $\delta_3 = 1.11$ fm for coupling to the 2^+ and 3^- states, respectively, taken from Cook *et al.* [13]. The Coulomb coupling strengths were obtained from measured $B(E2)$ and $B(E3)$ values [14,15].

All transfer couplings were treated using the post form of the finite-range coupled-reactions-channels method, incorporating a full complex remnant term. For the (^{7}Li,^{6}Li) transfers the ^{6}Li+^{13}C optical potential was taken from Table I of Schumacher *et al.* [16]. Single-neutron stripping from both the $3/2^-$ ground state and $1/2^-$ first excited state of ^{7}Li was included, the neutron being considered to be bound in a mixture of $1p_{3/2}$ and $1p_{1/2}$ states in each case, with spectroscopic amplitudes taken from Cohen and Kurath [17]. The neutron was bound to the ^{6}Li core with a standard Woods-Saxon potential of radius $1.25 \times 6^{1/3}$ fm and diffuseness 0.65 fm, the well depth being adjusted to obtain the correct binding energy.

Following the $^{12}C(d,p)^{13}C$ analysis of Tanifuji *et al.* [18], neutron transfer via the 2^+ excited state as well as the ground state of ^{12}C was included for the $1/2^+$ and $5/2^+$ states of ^{13}C, while the $1/2^-$ ground state of ^{13}C was treated as a pure $1p_{1/2}$ single particle state. The spectroscopic amplitude for the $1/2^-$ state was taken from Cohen and Kurath [17], while the spectroscopic amplitudes for the $1/2^+$ and $5/2^+$ states were taken from Tanifuji *et al.* [18]. For the $1/2^-$ and $5/2^+$ states the neutron was bound to the ^{12}C core with a Woods-Saxon potential of radius $1.25\times 12^{1/3}$ fm and diffuseness 0.65 fm. For the $1/2^+$ state the radius was increased to $2.0\times 12^{1/3}$ fm, due to the halo nature of this state [19]. In all cases the well depth was adjusted to obtain the correct binding energy.

For the $^{12}C(^7Li,^6He)^{13}N$ transfer we again used the $^6Li+^{13}C$ potential of Schumacher *et al.* [16] for the $^6He+^{13}N$ optical potential, there being no suitable ^6He potentials available in the literature. Single-proton stripping from both the $3/2^-$ ground state and $1/2^-$ first excited state of ^7Li was included, with the proton considered to be bound in a $1p_{3/2}$ state only. The spectroscopic amplitudes were taken from Cohen and Kurath [17]. As this reference does not give the spectroscopic amplitude for the $^7Li(1/2^-)/^6He$ overlap we used the same value as for the $^7Li(3/2^-)/^6He$ overlap. The $1/2^-$ state of ^{13}N was treated as a pure $1p_{1/2}$ single particle state, with the spectroscopic amplitude taken from Cohen and Kurath [17]. The proton was bound to both the ^6Li and ^{12}C cores by standard Woods-Saxon potentials with a radius of $1.25A_{\rm core}^{1/3}$ fm and diffuseness 0.65 fm in both cases, with the well depth again being adjusted to give the correct binding energy.

III. RESULTS

The data are presented in Figs. 2–13, together with the theoretical predictions for those channels that were included in our calculation. While the overall description of the data is remarkably good, certain details are poorly described. In particular, while the agreement between the measured and calculated cross sections for inelastic scattering to the 0.478-MeV $1/2^-$ state is very good, the analyzing powers are poorly described, and for inelastic scattering to the ^{12}C 9.64-MeV 3^- state the description of both cross section and analyzing power data by the calculation is poor. Another problem is the poor description of the first rank analyzing power iT_{11} in all channels, with the exception of single-neutron stripping to the $1/2^-$ and $1/2^+$ states of ^{13}C and single-proton stripping to the $1/2^-$ state of ^{13}N. The third rank analyzing powers are also, in general, poorly described by the calculation.

On the plus side, both the cross sections (with the exceptions noted above) and the second rank analyzing powers, T_{20}, T_{21}, and T_{22}, are rather well described. Exceptions to this observation for the second rank analyzing powers are the $1/2^-$ state of ^7Li, for which none of the analyzing powers are well described, and the 3^- state of ^{12}C, where our calculation is unable to describe either the cross section or the

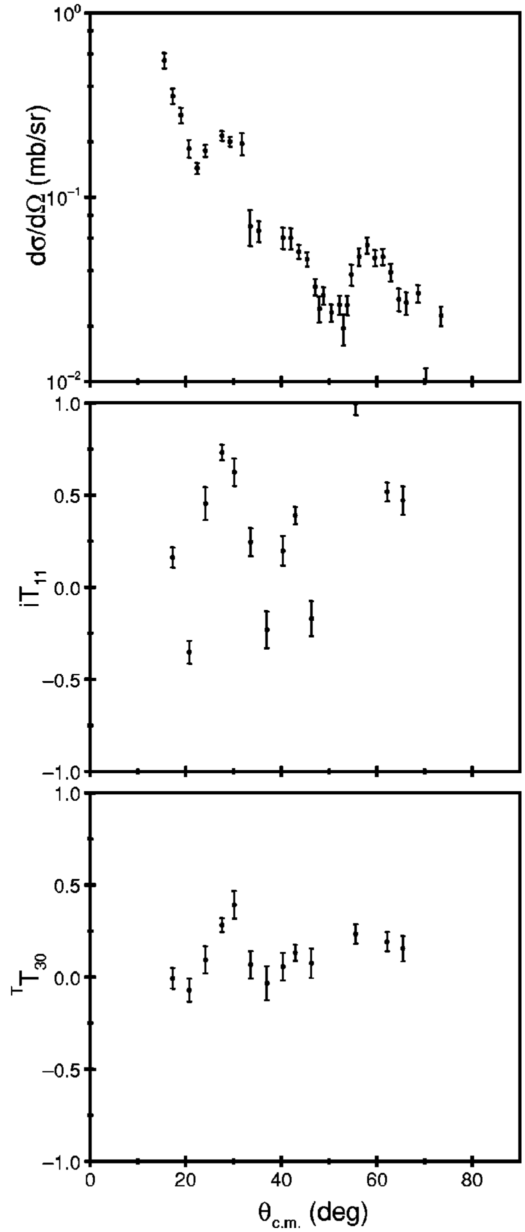

FIG. 6. Inelastic scattering data for excitation of the 7.65-MeV 0^+ state of ^{12}C. No second rank tensor analyzing powers are presented as the data for these observables contain no meaningful information due to their large error bars. The same comments apply to the third rank analyzing powers iT_{31}, iT_{32}, and iT_{33}.

analyzing powers. For the elastic scattering, the good agreement between calculation and data for the second rank analyzing powers is not surprising, as it was shown previously [2] that these analyzing powers are largely generated by the ^7Li ground-state reorientation coupling.

We also show, as the dotted curves in Figs. 2–4 and 7, the result of a calculation that omits the transfer couplings, to illustrate their effect on the elastic and inelastic scattering. The effect of the transfer couplings on the elastic scattering may be seen by comparing the solid and dotted curves in Fig. 2. It is readily apparent that the largest effect is on the first rank analyzing power iT_{11}. The effect of these couplings on the second rank analyzing powers, while not as dramatic as

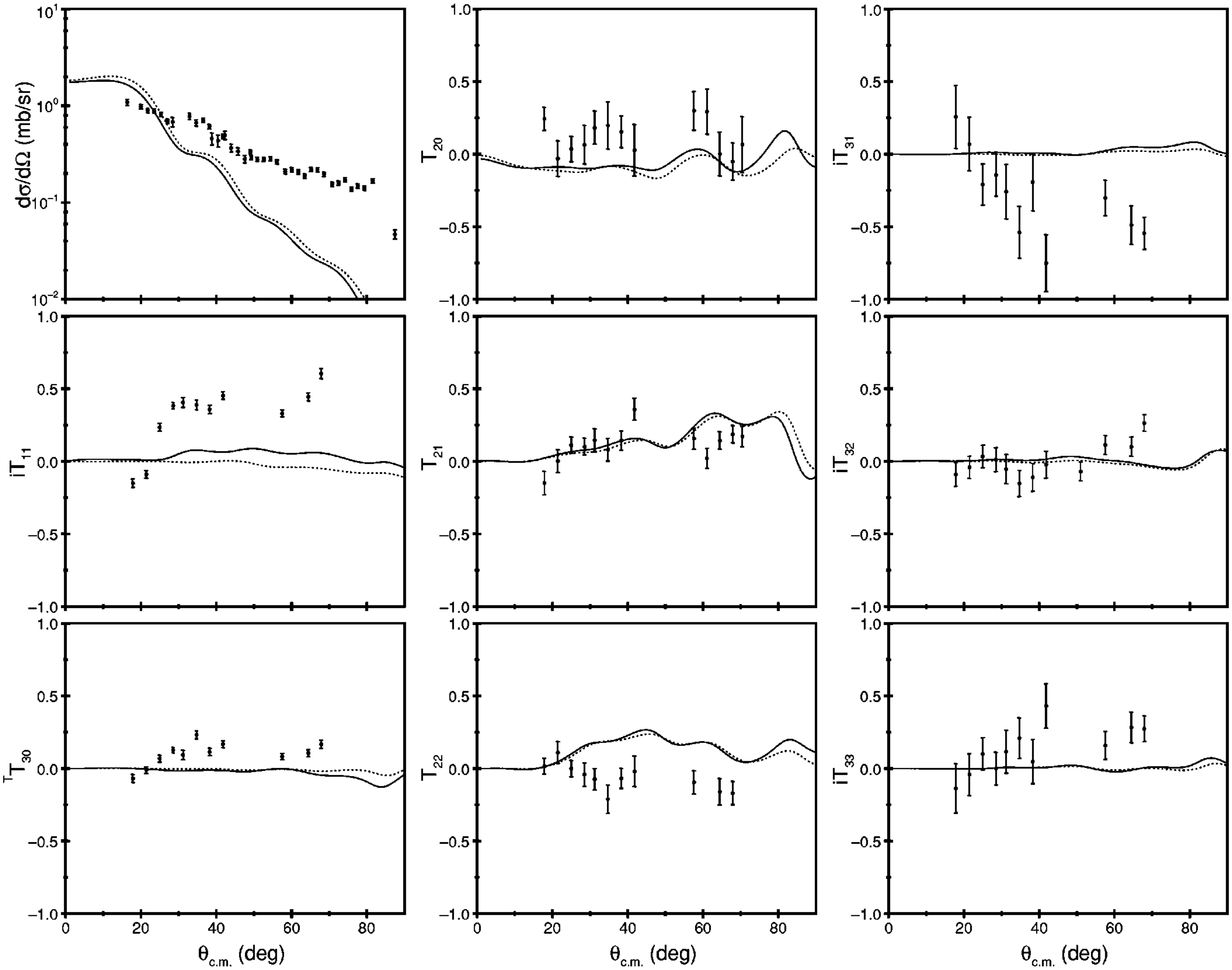

FIG. 7. Inelastic scattering data for excitation of the 9.64-MeV 3^{-} state of ^{12}C. The solid curves denote the result of the calculation described in the text while the dotted curves denote the result of a calculation omitting couplings to the ^{12}C($^{7}\overrightarrow{\mathrm{Li}}$,^{6}Li)^{13}C and ^{12}C($^{7}\overrightarrow{\mathrm{Li}}$,^{6}He)^{13}N transfers.

that on iT_{11}, is to significantly improve the agreement between the measured and calculated values. While the effect on the third rank analyzing powers is significant, the agreement between calculation and data cannot be said to be improved by the addition of the transfer couplings. It will also be noticed that the transfer couplings have a significant effect on the elastic scattering cross section, acting to deepen the interference minima for angles $\theta_{\mathrm{c.m.}} \leqslant 50°$, improving the agreement between the calculation and the data.

As Figs. 4 and 7 show, the influence of the transfer couplings on inelastic scattering to the ^{12}C 4.44-MeV 2^{+} and 9.64-MeV 3^{-} states is negligible (with the exception of the first rank analyzing power iT_{11}, where the transfer couplings have a small effect). In contrast, Fig. 3 shows that the transfer couplings have a profound effect on inelastic scattering to the ^{7}Li 0.478-MeV $1/2^{-}$ state. While the addition of the transfer couplings significantly improves the agreement between the calculated and measured cross sections it destroys any trace of agreement with the analyzing powers, introducing large oscillations in the calculated analyzing powers that are not present in the data.

IV. DISCUSSION

The main goal of the present work was to attempt the analysis of a comprehensive set of data, including a full set of analyzing powers, within a single theoretical framework. The aim was to determine whether a calculation including the most important observed reaction processes as accurately as possible could provide a satisfactory simultaneous description of the complete body of data. This aim has been largely realized, as the overall agreement between the calculation and the data is rather good. However, there are a number of aspects that are poorly described: the third rank analyzing powers in all channels, the first rank analyzing power iT_{11} for channels in the entrance partition, all analyzing powers for inelastic excitation of the 0.478-MeV $1/2^{-}$ state in ^{7}Li and all observables (cross section and analyzing powers)

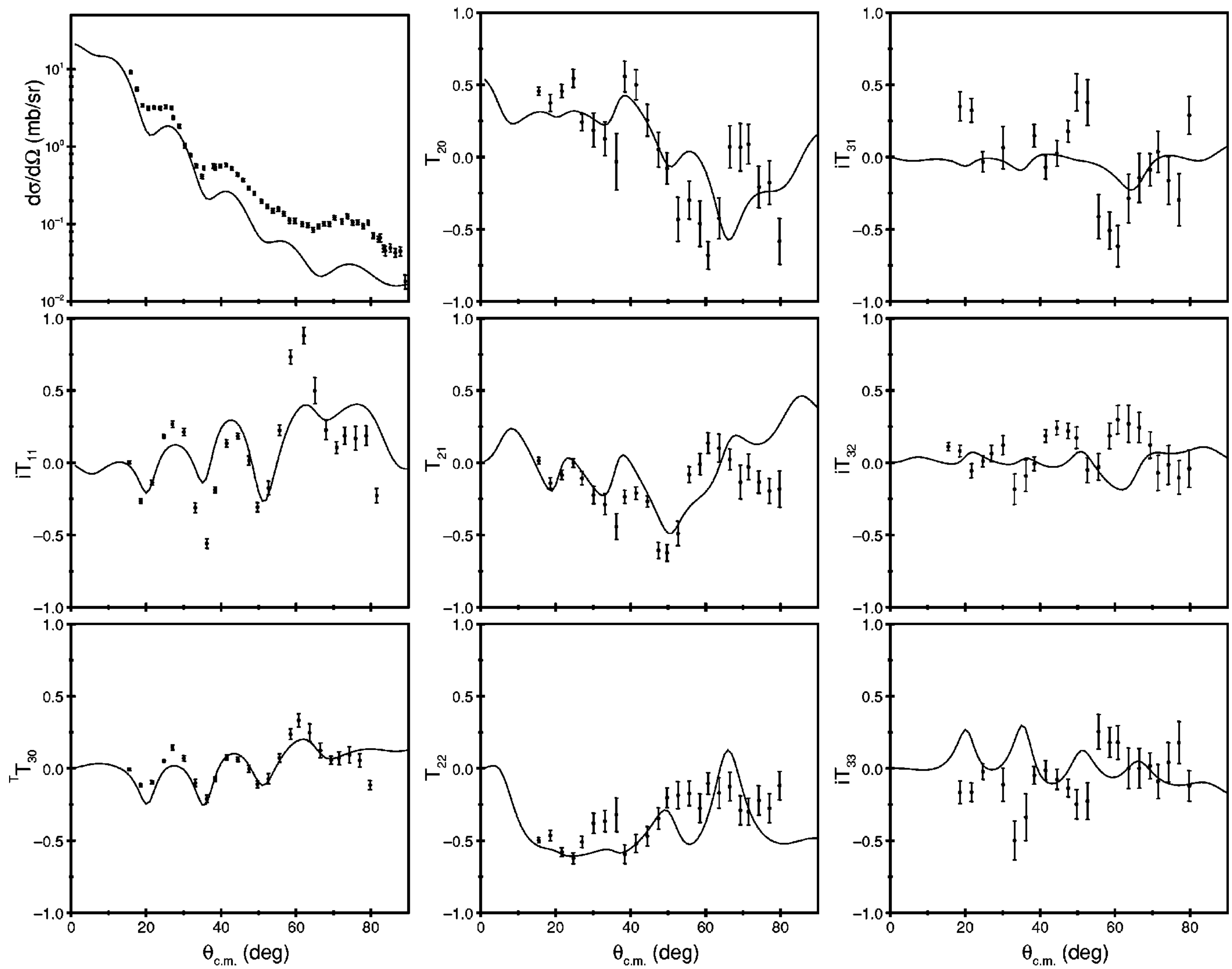

FIG. 8. Data for the $^{12}C(^{7}\vec{Li},^{6}Li)^{13}C_{1/2-}$ transfer. The solid curves denote the result of the calculation described in the text.

for inelastic excitation of the 9.64-MeV 3^- state in ^{12}C. In the following discussion each channel will be considered in turn, beginning with the elastic scattering, with particular consideration being given to possible causes for these failings in the calculation.

The elastic scattering is, in general, well described, with the addition of the single-nucleon stripping couplings having significant effects on all observables. The most noticeable effects are on iT_{11} and the cross section. The effect on the cross section, a deepening of the interference minima for angles $\theta_{c.m.} \leqslant 50°$, may be explained as due to the attractive real dynamic polarization potential produced by couplings to the single-nucleon stripping channels. This leads to an increase in the surface strength of the effective real potential that accentuates the interference minima in the elastic scattering. The most striking effect of the single-nucleon stripping couplings is, however, on iT_{11}. Coupling to these channels produces large oscillations in the calculated angular distribution for iT_{11}. For angles $\theta_{c.m.} \leqslant 40°$ these oscillations are considerably larger than those in the measured angular distribution, and coupling to the stripping channels destroys the good agreement between the calculated and measured iT_{11} obtained without these couplings (compare the dotted and full curves in Fig. 2). Thus, it would appear that the couplings that we have not included in our calculation, act to damp out these forward angle oscillations in iT_{11}. On a positive note, our calculation does suggest that the large peak in the measured angular distribution of iT_{11} at an angle $\theta_{c.m.} \approx 70°$ is at least partly due to coupling to single-nucleon stripping, as a comparison between the dotted and full curves in Fig. 2 shows that these couplings generate a large peak in the calculated iT_{11} angular distribution at approximately this angle. The effect of the single-nucleon stripping couplings on the second and third rank analyzing powers is much smaller than that on the cross section and first rank analyzing power, and may be ascribed to the modification of the effective optical potential produced by the DPP due to these couplings.

For inelastic scattering to the 0.478-MeV $1/2^-$ state of ^{7}Li the calculation describes the cross section very well, but fails to describe the analyzing powers. The calculated ana-

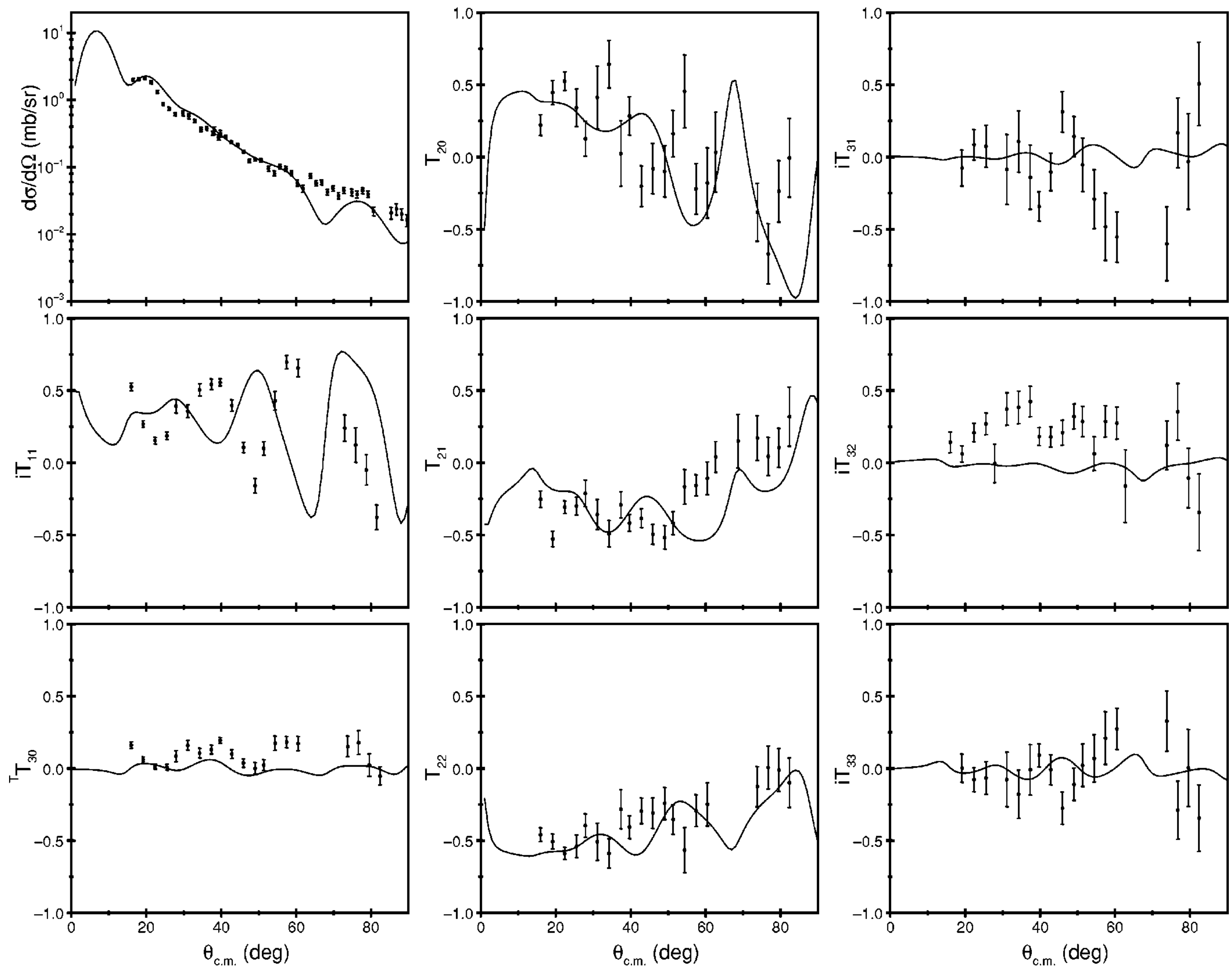

FIG. 9. Data for the ^{12}C($^7\vec{\mathrm{Li}}$,^{6}Li)^{13}C$_{1/2+}$ transfer. The solid curves denote the result of the calculation described in the text.

lyzing powers show large oscillations that are not present in the data. This may be traced to the effect of the single-nucleon stripping couplings. A comparison of the dotted and full curves in Fig. 3 shows that while these couplings produce a considerable improvement in the agreement between the calculated and measured cross sections they destroy what was a reasonable agreement between calculated and measured analyzing powers, producing the large oscillations in the calculated angular distributions referred to above. The improvement in the agreement between the calculated and measured cross sections produced by including the single-nucleon stripping couplings suggests that these couplings are both necessary and, at least on average, correctly included in our calculation. The large oscillations induced in the analyzing powers by the single-nucleon stripping couplings further suggest an interference effect between these couplings and the inelastic excitation of the ^{7}Li 0.478-MeV $1/2^-$ state. This could indicate a relatively small error in the way the stripping channels are included in our calculation, such that the cross section is not affected, or that there are couplings, important for this channel, that we have not included.

The data for inelastic scattering leading to the 4.44-MeV 2^+ state of ^{12}C are reasonably well described by our calculation (see Fig. 4). The calculated cross section exhibits oscillations in phase with those of the measured one, although the interference minima are rather too deep compared to the data. This could be due to the underlying potential (in this case the bare CF potential) or be due to missing couplings. The poor description of iT_{11} in this channel suggests the latter: while the measured angular distribution for this analyzing power shows large oscillations, the calculated one is essentially equal to zero at all angles. It is doubtful whether any modification of the potential could produce such oscillations in iT_{11}, and their absence from the calculated angular distribution is a strong indication of missing couplings important to this channel. A possible candidate is coupling between the 4.44-MeV 2^+ and the 14.1-MeV 4^+ state, considered to be part of a ground state rotational band in ^{12}C. However, as this state (the 14.1-MeV 4^+ state) is unbound and we have no data for inelastic scattering to it we have not included this coupling in our calculation. The third rank analyzing powers for this channel are poorly described, with the

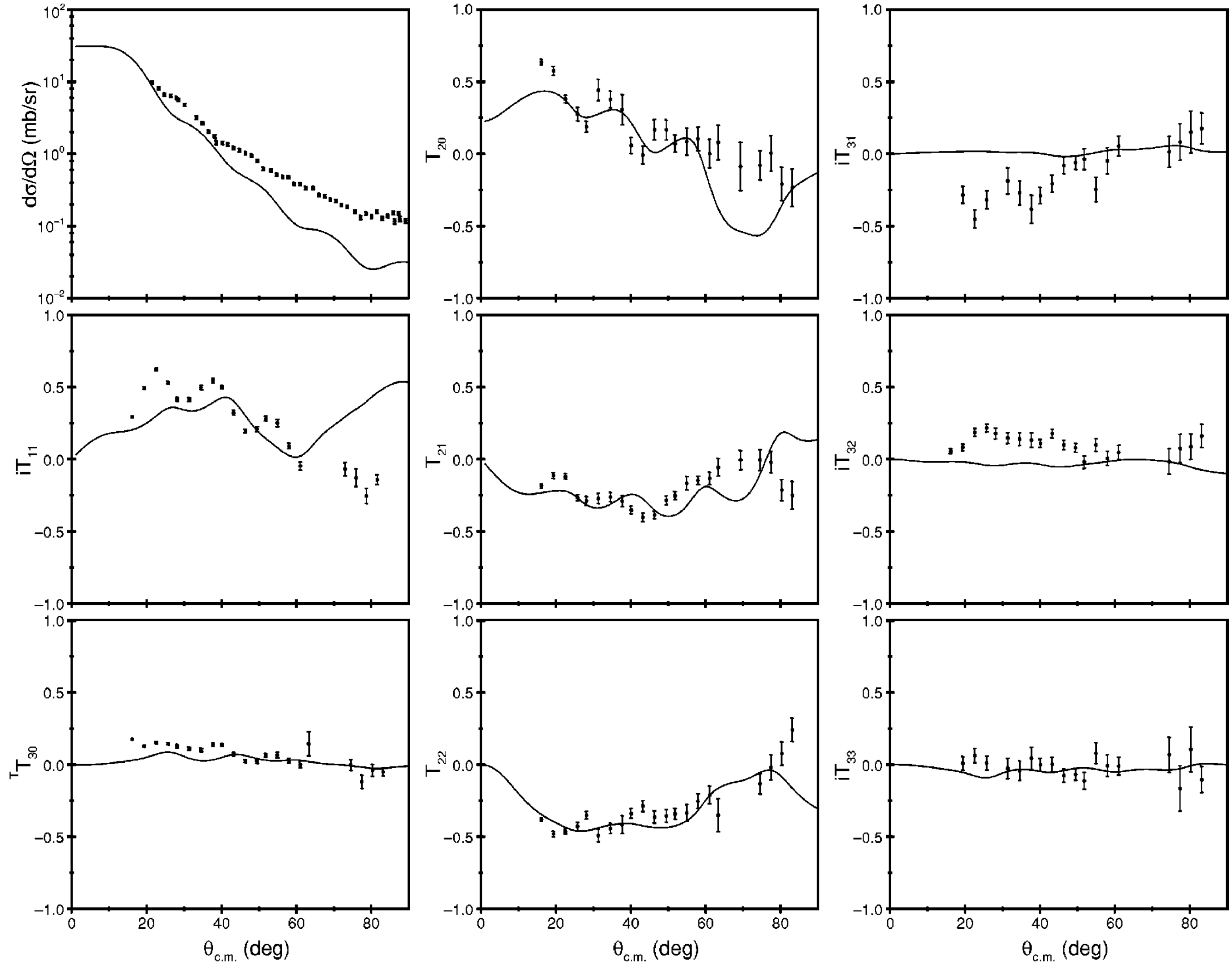

FIG. 10. Data for the $^{12}\mathrm{C}(^{7}\overrightarrow{\mathrm{Li}},^{6}\mathrm{Li})^{13}\mathrm{C}_{5/2+}$ transfer. The solid curves denote the result of the calculation described in the text.

exception of iT_{33} for angles $\theta_{\mathrm{c.m.}} \leqslant 60°$. By contrast, the second rank analyzing powers are well described. A test calculation that omitted the ^{12}C 4.44-MeV 2^+ reorientation coupling found that, unlike the elastic scattering second rank analyzing powers, the 2^+ inelastic scattering second rank analyzing powers are not due to reorientation: omission of the 2^+ reorientation coupling did not affect the calculated second rank analyzing powers for this channel.

The poor description of the data for excitation of the 9.64-MeV 3^- state of ^{12}C, shown in Fig. 7, is probably merely indicative of the inadequacy of treating this state as purely an octopole vibration. The good description of the data for excitation of the 4.44-MeV 2^+ state (see Fig. 4) suggests that the basic potential is reasonable and that the problem lies with the description of the excitation mechanism. Cook *et al.* [13] found that a better description of the cross section could be obtained by assuming that the 9.64-MeV 3^- state is a $K=3$ state, rather than $K=0$ as we have assumed. However, at present FRESCO cannot couple between states of different *K*, so we were unable to test the effect of this assumption on the analyzing powers.

The $^{12}\mathrm{C}(^{7}\mathrm{Li},^{6}\mathrm{Li})^{13}\mathrm{C}$ transfers are, in general, fairly well described by the calculation (see Figs. 8–10), although the third rank analyzing powers are, in general, poorly described. The first rank analyzing power iT_{11} is very well described for single neutron stripping to the 0.0-MeV $1/2^-$ state of ^{13}C. For single-neutron stripping leading to the 3.09-MeV $1/2^+$ and 3.85-MeV $5/2^+$ states the description of iT_{11}, while not as good as for that leading to the $1/2^-$ ground state, is still considerably better than for any of the entrance partition channels. We shall now deal with each of the single-neutron stripping channels in detail, commencing with the ^{13}C 0.0-MeV $1/2^-$ channel.

For single-neutron stripping to the 0.0-MeV $1/2^-$ state the oscillations at $\theta_{\mathrm{c.m.}} \approx 25°$ and 40° in the calculated cross section are slightly out of phase with the data, and the magnitude of the calculated cross section is too small, which could be rectified by an increase in either the spectroscopic amplitude or the $n+{}^{12}\mathrm{C}$ binding potential radius. Another possibility is that this state may also have a component built on the ^{12}C 4.44-MeV 2^+ state, as was considered to be the case for the $1/2^+$ and $5/2^+$ states. The addition of such a compo-

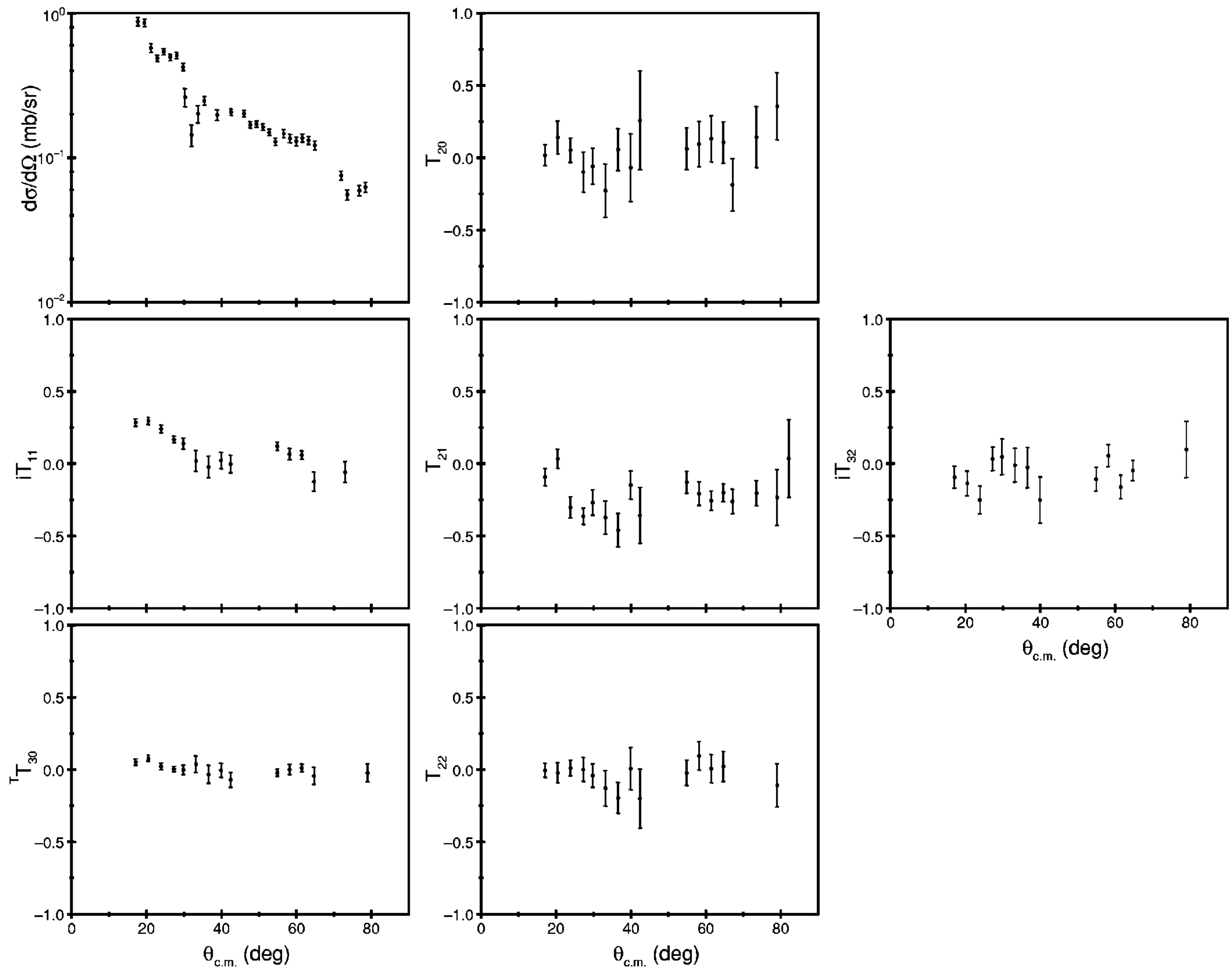

FIG. 11. Data for the ^{12}C($^{7}\vec{\mathrm{Li}}$,^{6}Li)^{13}C transfer to the unresolved multiplet in ^{13}C centred at $E_x = 7.6$ MeV. No data are presented for the third rank analyzing powers iT_{31} and iT_{33} as they contain no meaningful information due to their large error bars.

nent may also increase the magnitude of the cross section, although we did not include one in our calculation as we were unable to find any suggested values for spectroscopic amplitudes in the literature. The first rank analyzing power iT_{11} is very well described for this channel and is by far the best described out of any of those considered in this work. Why iT_{11} should be so well described for this particular channel is unclear. The third rank analyzing powers are again rather poorly described, except for ${}^{T}T_{30}$, where the agreement between the calculated and measured angular distributions is excellent. However, this excellent agreement must be regarded as purely accidental, as ${}^{T}T_{30}$ is a composite analyzing power, being a linear combination of iT_{31} and iT_{33}, neither of which is particularly well described by the calculation. The second rank analyzing powers are well described, and tests have shown that these analyzing powers are equally well described by DWBA calculations, suggesting that they are mostly due to direct, single step transfers. This observation applies equally to the second rank analyzing powers for single-neutron stripping to the $1/2^{+}$ and $5/2^{+}$ states.

For single-neutron stripping leading to the 3.09-MeV $1/2^{+}$ state of ^{13}C the cross section is rather well described. The magnitude is correct and the position of the small peak at $\theta_{c.m.} \approx 20°$ is reasonably well reproduced. As discussed elsewhere [19], the best description of the cross section for this channel is obtained with a considerably increased radius for the $n+{}^{12}$C binding potential for this state. This has been linked to the halolike nature of the $1/2^{+}$ state and has its origin in the deformed shape of the ^{12}C core. The interference minimum at $\theta_{\mathrm{c.m.}} \approx 70°$ seen in the calculated cross section, but not found in the data, was found to be associated with the relatively poor description of a corresponding feature in the measured elastic scattering cross section. The first rank analyzing power iT_{11} is reasonably well described for this channel, the main problem being a phase error in the calculated angular distribution compared to the measured one. The third rank analyzing powers are again rather poorly described. The second rank analyzing powers are well described, which may be attributed to the single step transfer nature of their origin, as discussed above.

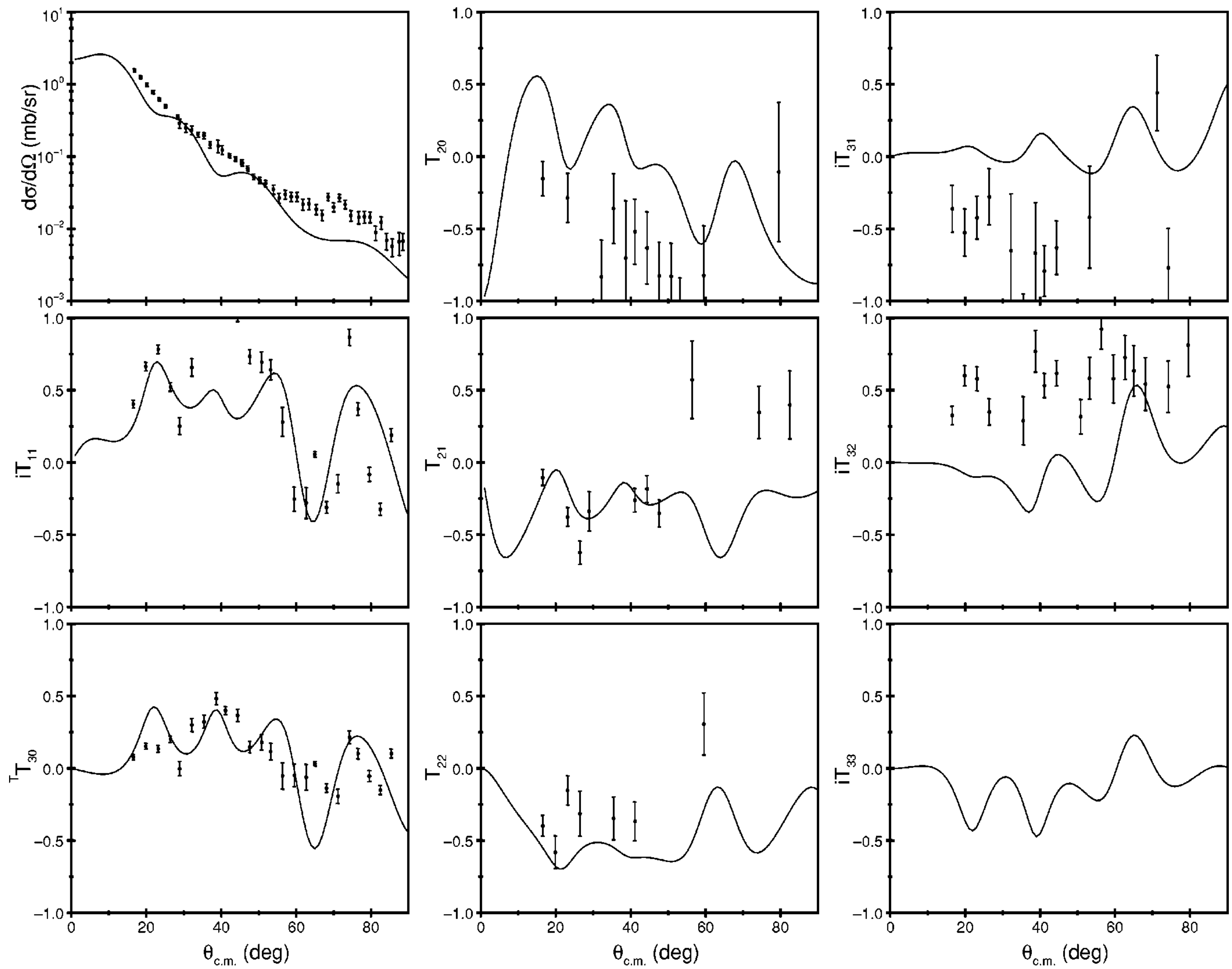

FIG. 12. Data for the ^{12}C($^{7}\vec{\mathrm{Li}}$,^{6}He)^{13}N$_{1/2-}$ transfer. The solid curves denote the result of the calculation described in the text. No data are presented for iT_{32} as they contain no meaningful information due to large error bars.

For single-neutron stripping to the 3.85-MeV $5/2^{+}$ state of ^{13}C the magnitude of the calculated cross section is a good match to the data at forward angles, although it falls off too quickly with angle compared to the measured values. This could be due to the choice of optical potential in this channel, or may indicate that couplings between states in ^{13}C are important for this channel. In a CCBA study of the ^{12}C(^{14}N,^{13}N)^{13}C reaction Nagel [20] has shown that such couplings can have important effects. For angles $\theta_{c.m.} \leqslant 60°$, the first rank analyzing power is reasonably well described. The poor description for angles greater than this may be linked with the failure to describe the cross section adequately at these angles. As usual, the third rank analyzing powers are poorly described while the description of the second ranks is good. This seems to indicate quite clearly that the third rank analyzing powers give us information about multistep processes, which the second ranks do not. The poor description of the third rank analyzing powers suggests that there are important multistep effects that are missing from our calculation—as discussed previously, the second ranks seem to arise mainly due to direct, single step processes that appear to be well described in our calculations.

Finally, for the ^{12}C(^{7}Li,^{6}He)^{13}N single-proton stripping reaction to the 0.0-MeV $1/2^{-}$ state of ^{13}N the magnitude of the calculated cross section is slightly smaller than the measured one. The agreement could be improved by a slight increase in either the spectroscopic amplitude or the ^{12}C $+p$ binding potential radius. The difference in shape between the calculated and measured measured cross sections could be due to the use of a ^{6}Li+^{13}C optical model potential in this channel, due to the lack of a ^{6}He+^{13}N potential, or it may indicate the omission of multistep processes. The description of the first rank analyzing power iT_{11} is very good, indicating that for this reaction iT_{11} is mainly produced by the single step proton stripping process. The description of the second rank analyzing powers is reasonable, though not as good as for the single-neutron stripping reaction channels or the inelastic excitations. The data are, however, rather

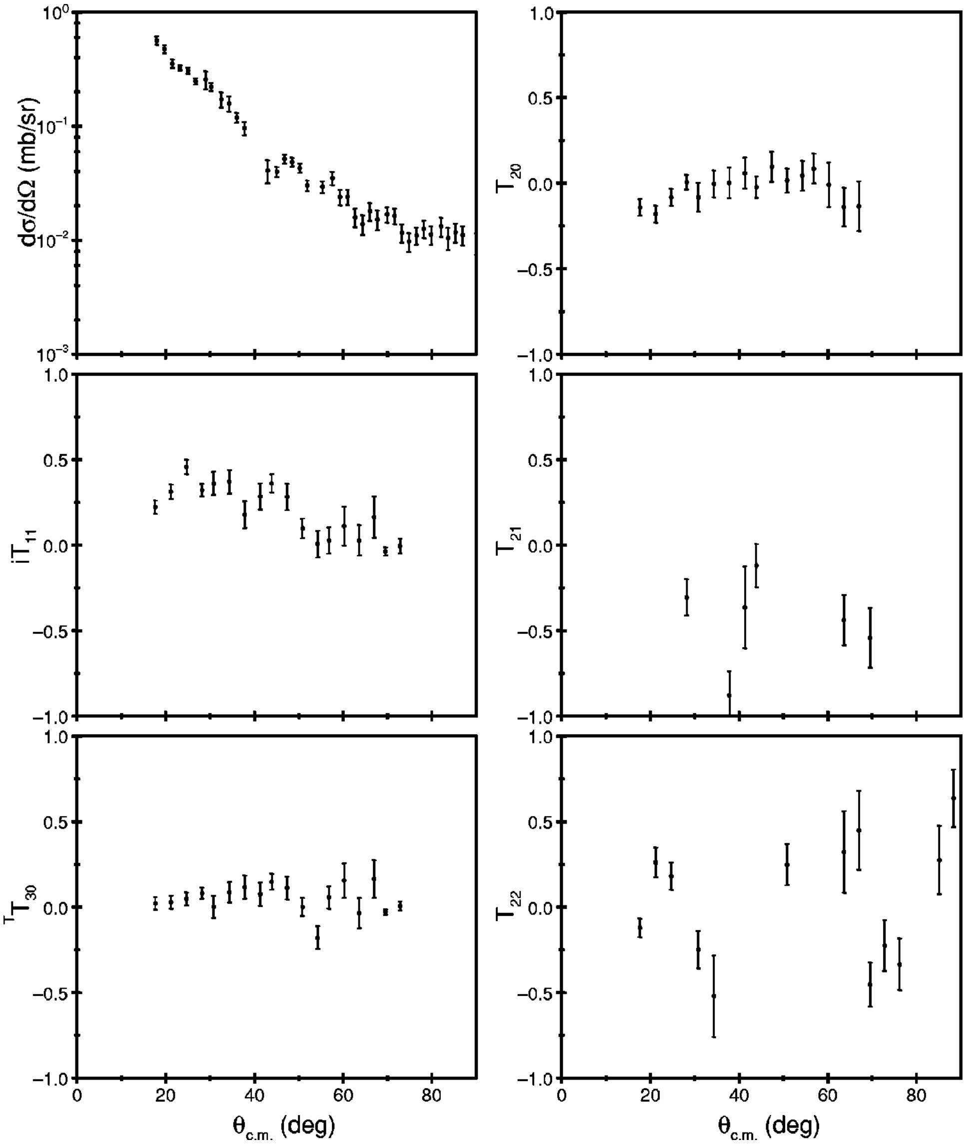

FIG. 13. Data for the $^{12}C(^{7}\vec{Li},^{6}He)^{13}N$ transfer to the unresolved doublet of the 3.51-MeV $3/2^{-}$ and 3.55-MeV $5/2^{+}$ states of ^{13}N. No data are presented for the third rank analyzing powers iT_{31}, iT_{32}, and iT_{33} as the data for these observables contain no meaningful information due to their large error bars.

sparse for these observables in this channel, thus making any conclusions rather weaker. The same observations apply to the third rank analyzing powers, with the exception of ${}^{T}T_{30}$. The description of ${}^{T}T_{30}$ is good, although the lack of data for iT_{33} is such that we are unable to say definitively whether this good agreement is purely accidental, like that for single-neutron stripping to the $1/2^{-}$ state of ^{13}C, or more significant. The data for iT_{31}, while rather sparse, appear to indicate the former, while iT_{32} is poorly described.

In summary, we have carried out a large calculation that simultaneously analyses a large number of reaction channels for the 34-MeV $^{7}\vec{Li}+^{12}C$ system. This calculation may be regarded as the current ''state of the art'' for this type of analysis. Although the overall description is good, a number of details are poorly described and these were discussed at length. There are still some limitations on this type of calculation due to constraints on available computing power that prevent us from including further couplings that may be important. Nevertheless, we are approaching the stage where it is possible to identify and hopefully rectify shortcomings in the various models used in direct reaction analysis. Some general comments may be made: we still do not fully understand by what mechanism or mechanisms the third rank analyzing powers are produced, other than that it appears to be some sort of multistep process or processes. On the other hand, the second rank analyzing powers seems to be mainly produced by single step processes. We are also unable to explain the first rank analyzing powers in the entrance partition, although we may again speculate that they are caused by couplings omitted from our calculation rather than by problems with the underlying CF model potential. Finally, we have two very good illustrations of the value of analyzing powers, in general, and a full set of analyzing powers in particular. As remarked above, the calculation described here produces a good description of the cross section for inelastic scattering leading to the 0.478-MeV $1/2^{-}$ state of ^{7}Li while failing to describe the analyzing powers. Without the measurement of the analyzing powers we would have assumed that our calculation produced a good description of the reaction processes important for this excitation. The single neutron stripping reaction to the 0.0-MeV $1/2^-$ state of ^{13}C provides an example of the value of a complete set of analyzing powers: the excellent description of $^{T}T_{30}$ was revealed to be purely accidental by the failure to also describe iT_{31} and iT_{33}, the components of the composite analyzing power $^{T}T_{30}$. If a measurement of $^{T}T_{30}$ alone had been available this problem would not have been discovered.

Thus, although we still cannot claim to have reached the goal set out by Fick *et al.* [1] almost a decade ago, we do have the necessary data available and are at least well on the way towards a thorough understanding of it.

ACKNOWLEDGMENTS

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