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Analysis of the $^{12}C(\vec{p},p')^{12}C$ reaction at 200 MeV in the distorted-wave impulse approximation

J. R. Comfort*
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260 and Department of Physics, Arizona State University, Tempe, Arizona 85287

G. L. Moake,† C. C. Foster, and P. Schwandt
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

W. G. Love
Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602
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Differential cross sections and analyzing powers are presented for discrete states of ^{12}C up to 21-MeV excitation energy as observed by the $^{12}C(\vec{p},p')^{12}C$ reaction at 200 MeV. The results of distorted-wave, impulse-approximation calculations with a 210-MeV free nucleon-nucleon t matrix are compared with the data for most of the transitions. The comparisons are divided into classes that emphasize different aspects of the effective interaction. As a whole, the comparisons are comparable to those at lower energies. However, the description of the 15.11-MeV transition to a 1^+, $T=1$ state is decidedly inferior. The effects of removing abnormal-parity amplitudes with $S=1$ are considered for several transitions. In particular, their removal produces good agreement for the 15.11-MeV state.

[NUCLEAR REACTIONS $^{12}C(\vec{p},p')^{12}C$, $E=200$ MeV, measured $\sigma(E_p,\theta)$, $A_y(E_p,\theta)$; $\theta=6°-60°$, $E_x=0-21$ MeV. DWIA analysis.]

I. INTRODUCTION

As part of a program to develop and test effective nucleon-nucleus interactions at medium energies, cross-section and analyzing-power data were presented in earlier publications[1,2] for the $^{12}C(p,p')^{12}C$ reaction near a bombarding energy of 120 MeV. Microscopic reaction calculations in the distorted-wave impulse approximation (DWIA),[3] based on realistic t matrices for free nucleon-nucleon (NN) scattering[4,5] and the wave functions of Cohen and Kurath,[6] were compared with these data and with additional cross-section data at 155 MeV.[7] Some comparisons were also made[1] with 185-MeV data[8,9] that spanned a more limited angular range.

In summary, the DWIA calculations were found to be in good to excellent agreement with the cross-section data for some transitions, especially for isovector transitions and for momentum transfers $q \lesssim 1.5$ fm^{-1}. The analyzing power data, as expected, were found to be more sensitive than the cross-section data to individual components of the interaction.[2] Although the data clearly established the necessity for some of the components, in particular the isoscalar spin-orbit and isovector tensor interactions, and also roughly confirmed their expected strengths, only some of the qualitative features of the analyzing-power data at relatively low momentum transfers could be described. The results at high q were typically unsatisfactory. Finally, isoscalar transitions involving spin transfer were found to have large contributions from knockon-exchange mechanisms and were typically in poor agreement with the data over most of the angular range. The agreement with the cross-section data at the higher energies was comparable to, and in a few cases better than, that at 120 MeV.

Owing to the limited set of observables that have been measured and the complexity of the calculations, it is very difficult to diagnose the source(s) of the discrepancies between the calculations and the data. Among the possible sources are the wave functions of the nuclear states, the reaction mechanism, and the effective interaction. Although arguments can be made for each of these items, the effective interaction is perhaps the most suspect. For example, different t matrices were used in the two earlier papers of the 120-MeV data.[1,2] The results obtained by using the second interaction, which was more directly fit to the free NN scattering and amplitudes,[5] were typically inferior[2] to those of the first, whose tensor component was obtained from the Sussex matrix elements.[4] In addition to this ambiguity, both Pauli blocking and Fermi averaging give rise to density-dependent (medium) corrections to the effective interaction. Such corrections have been found to improve the agreement of the calculations with the data for several transitions.[10,11]

In view of the complexity, better insight is most likely to come from systematic studies of the experimental data at a variety of beam energies. Such studies need to be done in any case in order to give assurance that the successful aspects of the calculations are well understood.

To this end, a full set of cross-section and analyzing-power data have been obtained for the $^{12}C(\vec{p},p')^{12}C$ reaction at 200 MeV. Angular distributions were obtained for discrete states up to 21-MeV excitation energy and covered the momentum-transfer range out to 2.5–3.0 fm^{-1}. Additional information regarding the continuum that underlies the states above 8-MeV excitation was also obtained and will be discussed in a subsequent paper.[12] The present paper is devoted to a comparison of the data for discrete states with microscopic DWIA calculations. Some of the data have been presented in earlier publications[7,13] with regard to other issues. However, no comparisons with DWIA calculations have been made. These calculations will make use of the recently developed 210-MeV t matrix of Love and Franey.[5] It was constructed in the same manner as the 140-MeV t matrix used in Ref. 2.

The higher energy used in this experiment is expected to have a number of advantages for the theoretical analysis. Pauli-blocking and Fermi-momentum effects should be reduced by raising the projectile energy further above the Fermi energy of about 40 MeV. Also, if the basic idea of the impluse approximation is valid, multistep contributions should also be reduced. They were estimated as not being too important at 120 MeV for inelastic transitions[1] and, for elastic transitions, their effects on the diagonal optical potential were found to be very small near 180 MeV.[14]

For a two-body interaction of a given range, one might expect the knockon-exchange contributions to decrease as the bombarding energy increases. The reason is that when the wavelength of the projectile is short compared with the range of the interaction, the oscillations in the form factor of the exchange integrals will result in small values due to cancellations. However, the contributions also depend on the overall modeling of the interaction. The 210-MeV t matrix used in the present study differs from the 140-MeV t matrix used in Ref. 2 in that a term of very short range $R = 0.15$ fm is introduced in the tensor component. Consequently, the knockon-exchange contributions are not expected to diminish and are treated fully. Within the spirit of the impulse approximation, the changes in the experimental data at different energies should primarily reflect changes in the free nucleon-nucleon scattering at the corresponding energies.

II. EXPERIMENTAL PROCEDURES

A. Data acquisition

Data for the $^{12}C(\vec{p},p')^{12}C$ reaction were obtained at the Indiana University Cyclotron Facility (IUCF) with polarized proton beams of energies of 200.1 and 199.8 MeV. Two natural carbon targets with thicknesses of 3.74 ± 0.08 mg/cm^2 and 21.5 ± 0.5 mg/cm^2 were used in the experiment. Protons from the reaction were momentum analyzed in a quadrupole-dipole-dipole-multipole magnetic spectrometer and detected in a helical-cathode position-sensitive proportional chamber[15] located in the focal plane. Two plastic scintillator detectors of thicknesses 0.63 and 1.27 cm were placed behind the chamber and were used for particle identification. The electronics setup and data-acquisition procedures were similar to those used in earlier experiments.[1,2,7]

The momentum acceptance of the spectrometer permitted the observation of more than 10 MeV of excitation energy for a given magnetic field setting. With two settings, spectra were obtained that covered the entire range of excitation energies up to 21 MeV. Low-excitation spectra were obtained over the range of laboratory angles from 6° to 60° in 2° steps. The high-excitation data spanned the range of 6° to 40° in 2° steps, followed by 3° steps to 49°. Some spectra were taken with the spectrometer on both sides of the beam line and an angular offset of 0.05° from the nominal scattering angle was determined. The relative scattering angle is believed to be correct to 0.04° and the absolute angular scale is known to better than 0.1°.

The polarization of the proton beam was determined by asymmetry measurements of the elastic scattering from helium. The polarimeter was located in the beam line between the injector and main cyclotrons at IUCF, where the beam energy was

15.2 MeV. Calculations indicate that there should be no significant depolarization of the beam in the main cyclotron or high-energy beam lines. Indeed, the measurement of analyzing powers of 0.99 in this experiment is evidence that very little depolarization exists. In addition, measurements of A_y for $^{12}C+\vec{p}$ elastic scattering for laboratory angles of 9° and 12.5° in the energy range 120–200 MeV at IUCF agree within ± 0.02 with the systematics of published values.[16] The polarization was checked periodically throughout the experiments. It varied slowly with time and was typically about 70%. The spin direction of the beam and the active spectra of data acquisition were switched at about 1-minute intervals under automatic computer control. This procedure was intended to reduce long-term systematic errors in the measurements of the analyzing powers.

A Faraday cup internal to the scattering chamber was used for angles less than 23°. It was divided down the middle and the beam current from each of the electrically isolated sections was integrated separately. The currents were also used to stabilize the centering of the beam on the targets by means of a feedback loop to a steering magnet. An external Faraday cup was used for angles greater than 23°. It produced much lower background counting rates in the detectors. Spectra taken at the same angles with each cup resulted in the conclusion that the internal Faraday cup failed to collect about one-third of the total beam charge. This was attributed to insufficient thickness of the stopping material. There is no indication that the fractional amount of lost charge varied throughout the measurements. Nevertheless, a 5% error was added in quadrature to the statistical errors for all the data taken with the internal cup. Apart from these errors, the relative cross sections are believed to be correct to better than 3%. Considering all sources of error, and previous experience at IUCF, the uncertainty in the absolute cross-section scale is conservatively estimated to be better than 10%.

B. Data reduction

Representative spectra of the $^{12}C(\vec{p},p')^{12}C$ reaction at 200 MeV are shown in Fig. 1. These spectra are constructed from the original spin-up and spin-down spectra of the experiment. Denoting the cross section (per channel) of the original spectra as $(d\sigma/d\Omega)_u$ and $(d\sigma/d\Omega)_d$, and the measured polarizations of the corresponding spin-up and spin-down beams as P_u and P_d, respectively, the equivalent un-

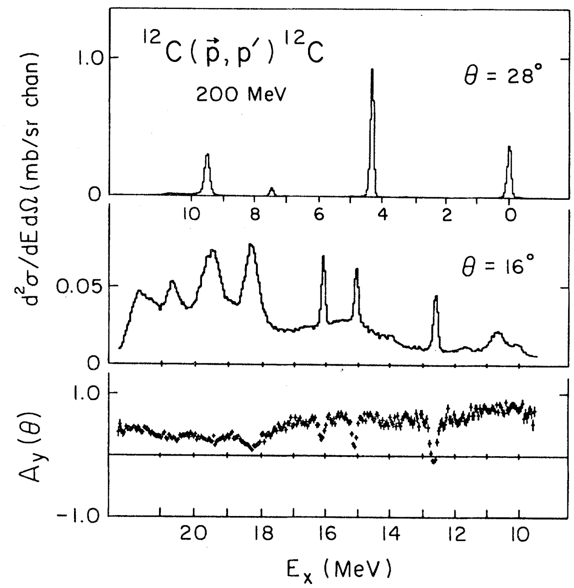

FIG. 1. Sample spectra of the equivalent unpolarized cross sections for the $^{12}C(\vec{p},p')^{12}C$ reaction at 200 MeV plotted against excitation energy. The analyzing powers for the high-excitation region are shown in the bottom segment.

polarized cross section (per channel) is given as

$$\frac{d\sigma_0}{d\Omega}=\frac{P_d(d\sigma/d\Omega)_u+P_u(d\sigma/d\Omega)_d}{P_u+P_d} \tag{1}$$

and the analyzing power is

$$A_y=\frac{(d\sigma/d\Omega)_u-(d\sigma/d\Omega)_d}{(P_u+P_d)(d\sigma_0/d\Omega)}\ . \tag{2}$$

The analyzing powers are shown in Fig. 1 only for the high-excitation region in which discrete states lie on top of a three-body continuum. Uncertainties in the values of A_y are also shown. These were determined by proper statistical methods and take into account all sources of error.

Differential cross sections and analyzing powers were easily obtained for the discrete states in the low-excitation spectra. Although the 9.64-MeV state was near the end of the helix detector for most of the spectra, there is no indication that the data are materially affected by lower efficiencies. The relative efficiency of the detector across the focal plane was surveyed before data acquisition and was found to be uniform in all areas where the states of ^{12}C were later observed. The elastic-scattering data obtained during this experiment have been reported and discussed elsewhere.[17]

The high-excitation region of ^{12}C contains a mixture of narrow and broad levels. In some cases, the broader states overlapped. The yields for the narrow states were extracted by fitting polynomials to the background (continuum) to the immediate right and left of the peaks and assuming that the polynomials represented the backgrounds underneath the peaks. A number of comparisons with other methods yielded similar results. Yields for the broad levels at 13.35, 14.08, and 16.58 MeV were obtained by fitting the data with Gaussian peak shapes on top of quadratic background polynomials.

The region from 17 to 21 MeV excitation energy appeared to be dominated by no less than four states at nominal energies of 18.4, 19.2, 19.7, and 20.5 MeV. Their widths appeared to be approximately equal and were thus assumed to be so. The lower three states were fit simultaneously with Gaussian peak shapes on a quadratic background. The 20.5-MeV state was fit separately with a Gaussian peak shape and the background was derived from the parameters used for the 18–20 MeV region. An attempt was made to make the error associated with each peak reflect both the statistical error and the uncertainty involved in estimating the background.

This experiment did not provide evidence for any states other than the ones listed between 18 and 21 MeV, although, of course, more could be present and unresolved. In particular, the spectra of the analyzing powers did not show any significant changes in values across the region of any one of the states. Such changes, if present, could suggest the presence of more than one state with different spins and/or isospins since, in many cases, the angular patterns would also be different.

Finally, the yields for the very broad state at 15.3 MeV were extracted by replacing the narrow peaks on top of it with smooth backgrounds, compressing the resultant spectra into fewer channels, and then estimating the continuum underneath the broad state. The same technique was used for this state in the earlier data at 120 MeV.[1] The error bars shown for the data are statistical and do not take into account any systematic biases in the procedure.

Differential cross sections and analyzing powers for most of the discrete states will be shown in Secs. IV to VI in comparison with microscopic DWIA calculations. Data for the transitions that are not analyzed theoretically are shown in Figs. 2 and 3. Discussion of the continuum will be given in a later article.[12] For purposes of the later discussion, it is useful to note that 10° of the angular scale corresponds approximately to 100 MeV/c of momentum transfer q. Additional details on the experimental

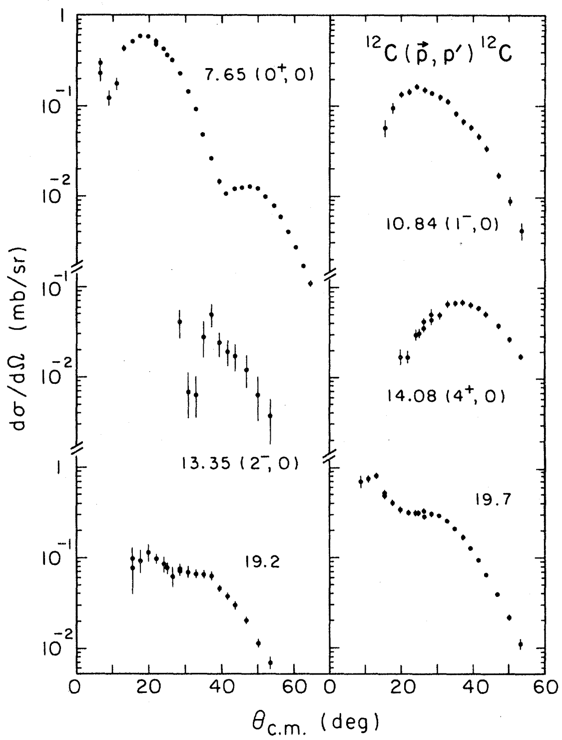

FIG. 2. Differential cross sections for excited states of ^{12}C. The excitation energies are given in units of MeV and the J^{π}, T values are listed where known.

procedures and a tabulation of the differential cross sections and analyzing powers for all the observed states have been deposited with the Physics Auxiliary Publication Service.[18]

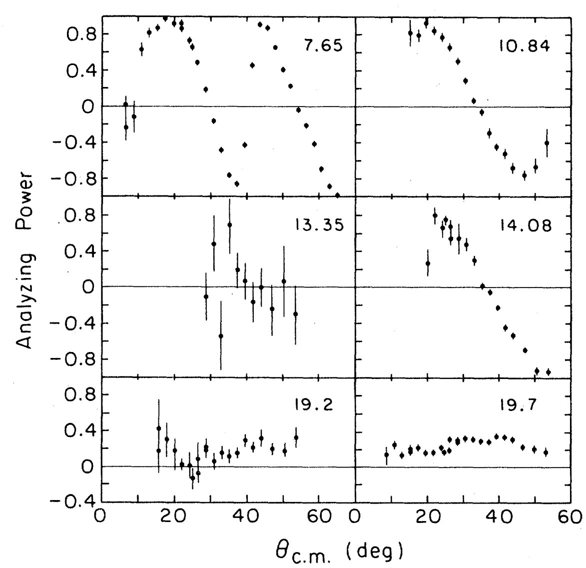

FIG. 3. Analyzing powers for excited states of ^{12}C. The excitation energy (MeV) is shown for each state.

III. MICROSCOPIC DWIA CALCULATIONS

Comparisons of differential cross sections and analyzing-power data for the $^{12}C(\vec{p},p')^{12}C$ reaction near 120 MeV bombarding energy with the results of microscopic DWIA calculations have been presented in earlier publications.[1,2,7,11] Very similar procedures will be followed for the present 200-MeV data. The procedures shall be outlined briefly.

A. The effective interaction

In the impulse approximation, the effective NN interaction for (p,p') reactions is identified with the t matrix for free two-nucleon scattering at an energy near that of the reaction.[3–5] It is common to write the effective two-nucleon interaction as

$$V_{12}^{\rm eff} = V_{12}^{\rm cent} + V_{12}^{\rm so} + V_{12}^{\rm tens} \tag{3}$$

where

$$V_{12}^{\rm cent} = V_0 + V_\sigma \vec{\sigma}_1 \cdot \vec{\sigma}_2 + V_\tau \vec{\tau}_1 \cdot \vec{\tau}_2 + V_{\sigma\tau}(\vec{\sigma}_1 \cdot \vec{\sigma}_2)(\vec{\tau}_1 \cdot \vec{\tau}_2) \,, \tag{4a}$$

$$V_{12}^{\rm so} = (V_{LS} + V_{LS\tau} \vec{\tau}_1 \cdot \vec{\tau}_2)\vec{\rm L} \cdot \vec{\rm S} \,, \tag{4b}$$

$$V_{12}^{\rm tens} = (V_T + V_{T\tau} \vec{\tau}_1 \cdot \vec{\tau}_2) S_{12} \,, \tag{4c}$$

and

$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{r}_{12})(\vec{\sigma}_2 \cdot \hat{r}_{12}) - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \,. \tag{5}$$

All interaction strengths are functions of the relative coordinate $\vec{r}_{12}$.

In the present work, the interaction strengths are taken from a recent representation[5] of the antisymmetrized on-shell NN t matrix based on the 210-MeV free two-nucleon scattering amplitudes of Bugg *et al.*[19] In this representation, the strengths of the $V^{\rm cent}$ and $V^{\rm so}$ terms consist of sums of Yukawa functions while the $V^{\rm tens}$ term consists of sums of $r^2 \times$ Yukawa functions. Some model dependence is thus introduced into the impulse approximation (IA) calculations, particularly with respect to the off-shell extrapolation of the amplitudes. In the earlier work at lower energies,[1,2,7] the 140-MeV t matrix was based on the free NN amplitudes of Arndt.[20] At present it is not known whether the change in the systematics of the analysis of free NN scattering data results in any other model dependence in the IA calculations.

Knockon-exchange contributions were found to be very important in the DWIA calculations at lower energies,[1,2,7] and remain so at 200 MeV (Ref. 5) (see Sec. I). Some difficulties with the tensor-exchange contributions will be noted in the discussion of individual transitions.

B. The transition densities

For ease of comparison with the earlier work,[1,2,7] the spectroscopy of Kurath and co-workers is used for the transitions of ^{12}C. The wave functions of Cohen and Kurath[6] (CKWF), based on the $(8-16)$POT interaction, are used for the positive-parity states and the wave functions of Millener and Kurath[21] (MKWF) are used for the negative-parity states. Since these wave functions do not fully account for core polarization effects on the collective transitions, renormalizations of the cross sections, constrained by electromagnetic data, will be made. In a few cases, some specific modifications of the CKWF will also be made or alternative wave functions used instead.

Transition densities were constructed from the spectroscopic amplitudes obtained from the wave functions by the use of harmonic oscillator single-particle wave functions. The harmonic oscillator length parameter b for the transitions was chosen to match the prominent maxima of the longitudinal and transverse form factors $F_L(q)$ and $F_T(q)$, respectively, obtained from (e,e') experiments.[22,23] Values of the b parameter for the transitions studied are listed in Table I and are quoted for the case where the nucleons are bound to a mass-12 core.[2] As noted in an earlier paper,[2] corrections for the center of mass motion are not easily made in the coordinate-space (p,p') calculations. However, a reasonable approximation to these corrections is ob-

TABLE I. Values of the harmonic-oscillator parameter b used to compute the single-particle wave function for each state. The $l=0$ radial dependence is given by $\sim\exp(-\frac{1}{2}r^2/b^2)$

Excitation (MeV)	b (fm)
4.44	1.68
9.63	1.82
11.83	1.68
12.71	1.57
15.11	1.87
15.30	1.57
16.11	1.57
16.58	1.68
18.40	1.57
20.54	1.68

tained by rescaling the b values obtained from the (e,e') analyses (where the corrections are easily made in momentum space) by the factor $(\frac{11}{12})^{1/2}$. The values in Table I include the rescaling factor. Renormalizations of the cross sections by a factor $(\frac{12}{11})^L$ are also necessary, where L is the orbital angular momentum transfer.

C. The optical potential

Several optical potentials were considered for use in the DWIA calculations. Cross sections and analyzing powers have recently been presented for 200-MeV proton scattering from ^{12}C.[17] The data covered an angular range out to about 110°. It was found that optical potentials of the conventional form (central Woods-Saxon and Thomas spin-orbit terms) did not reproduce the data over the full angular range, especially the analyzing powers. Substantial improvement was obtained by using a combination to two complex potentials of the conventional form, labeled a double Woods-Saxon (DWS) potential. The resulting radial dependences of the terms of the DWS potential were quite unusual, but were similar to potentials derived microscopically in the impulse approximation.

Nucleon-nucleus elastic- and inelastic-scattering processes computed in the impulse approximation have on-shell contributions from the NN t matrix only out to about 60°, where the momentum transfer in the scattering is equal to the momentum of the projectile. The off-shell properties, which are not determined by the free NN scattering data and are represented by a model, make contributions at all angles, most especially at angles greater than about 60°. It was noticed also that the geometric parameters of the conventional potential in Ref. 17 differed considerably from the systematics established in Ref. 14. Consequently, the 200-MeV data for angles less than about 65° (center of mass) were reanalyzed within the spirit of Ref. 14. Results comparable to those of the DWS of Ref. 17 were obtained (better for cross sections; worse for analyzing powers, especially near 20°) over this restricted angular range. The parameters of the new potential, in the conventions of Ref. 1, are listed in Table II. A third potential whose central term consisted of a narrow Gaussian potential centered on a Woods-Saxon potential (cf. Ref. 11) was also obtained. Since both the elastic and inelastic properties obtained with it were nearly indistinguishable from those of the conventional potential of Table II, it was not considered further.

TABLE II. The proton optical potential used for the distorted wave calculations. The potential was obtained in a manner consistent with the procedures of Ref. 14, where the form of the potential is defined.

$V = -13.4$ MeV	$W = -12.8$ MeV
$r_0 = 1.20$ fm	$r' = 1.20$ fm
$a = 0.643$ fm	$a' = 0.637$ fm
$V_{so} = -13.4$ MeV	
$r_{so} = 0.93$ fm	
$a_{so} = 0.47$ fm	

Although the elastic-scattering properties obtained with the conventional potential of Table II and the DWS potential of Ref. 17 are very similar, there are numerous differences for inelastic scattering. DWIA calculations have been carried out for the 2^+, $T=0$ state at 4.44 MeV and for the 1^+, $T=1$ state at 15.11 MeV in ^{12}C, which are excited by very different parts of the effective interaction. As seen in Fig. 4, the cross sections obtained with the DWS potential are typically lower by about 15% and the analyzing powers are distinctively different. The sensitivity to the optical potential found here for inelastic transitions, while the elastic scattering remains nearly unaffected, is opposite to

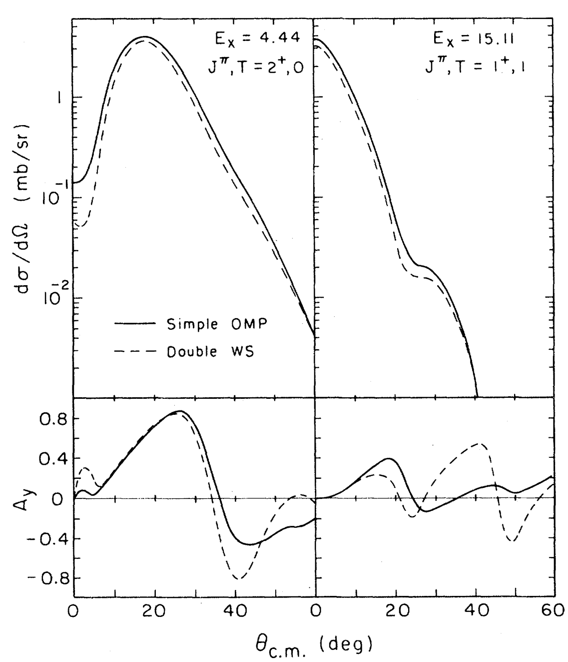

FIG. 4. DWIA calculations for two ($\vec{p}$,p') transitions in ^{12}C. The solid curve is based on the optical-model parameters of Table II and the dashed curve is based on the parameters of Ref. 17.

the sensitivities noted in an earlier analysis at 120 MeV.[11] The origin of the differences in Fig. 4 is not understood at this time.

For simplicity and conformity with earlier publications,[1,2,7] the potential of Table II is used for the calculations in the remainder of this paper. This choice is justified further by the observation that the calculations do not appear to be especially dependent on the choice of the optical potential over the range of momentum transfers out to about 1.5 fm^{-1}, which corresponds to about 30°. The nuclear structure wave functions and other factors in the calculations are not anticipated to be very reliable beyond this point. The increased sensitivity to the details of the optical potential at the higher momentum transfers will, of course, make comparisons between the calculations and the data more difficult to interpret.

IV. THE $T=1$ TRANSITIONS

The $T=1$ excitations of ^{12}C may be conveniently divided into two classes, the natural-parity transitions with parity change $\Delta\pi=(-1)^J$ and the unnatural-parity transitions with $\Delta\pi=(-1)^{J+1}$. As has been noted and discussed in the earlier papers,[1,2,7] the latter are believed to be dominated by the part of the effective interaction that is related to the exchange of virtual pseudoscalar pions. Heavier isovector mesons such as the rho may also contribute, especially at large momentum transfers. Pion exchange is not permitted in the direct amplitudes for the natural-parity transitions. Hence, in lowest order, the two classes may be used to interpret the effective contributions of pion exchange and rho-meson exchange processes in the nuclear medium.

A. Unnatural-parity transitions

The direct transition matrix elements for isovector unnatural-parity transitions will have contributions from the $V_{\sigma\tau}$, $V_{LS\tau}$, and $V_{T\tau}$ parts of the effective interaction defined in Eqs. (4). The isovector spin-orbit contribution is weak and typically unimportant as is also the imaginary part of $V_{\sigma\tau}$. Inclusion of the tensor interaction has previously been shown to be essential.[1,2,4,5,24]

1. The 15.11-MeV state

The DWIA calculations of the earlier publications[1,2,7] were relatively successful in reproducing the data for the transition to the 1^+, $T=1$ state at 15.11 MeV. There were, however, some persistent difficulties at large momentum transfer that are not understood, although they do not appear to be related to precritical behavior near the pion-condensation threshold.[7,25] Also, the effective interaction that was most directly related to the free *NN* scattering amplitudes reproduced the analyzing-power data much less effectively over most of the angular range than did an alternative interaction.[1,2,4]

Results from the present DWIA calculations are shown as solid lines in Fig. 5. The comparison with the 200-MeV cross sections is less satisfactory than at 120 MeV (Refs. 1 and 2) and 155 MeV (Ref. 7). In particular, the minimum that has developed near 25° is not reproduced. A similar minimum in the 155-MeV data was obtained with the 140 MeV *t* matrix used in the earlier work.[7] More importantly, the calculated analyzing powers appear to have little resemblance to the data in Fig. 5; they have the wrong sign over most of the angular range. Once again it is clear that the tensor interaction is essential. Although its omission would improve the A_y calculations slightly, the agreement with the data is still very poor. In addition, as is seen by the dashed curve in Fig.5, the cross-section results would be decidedly inferior.

The analyzing-power results are improved considerably, however, if one of the four independent spectroscopic amplitudes of the transition is set to zero. In the *LS* representation, this amplitude has $[LSJ]=[111]$. Although it is by far the largest amplitude for the transition,[26] very few reaction probes are sensitive to it. For example, it does not contribute to electromagnetic processes including (e,e') reactions. Being an abnormal-parity amplitude with $\Delta\pi=(-1)^{L+1}$ it cannot contribute to the direct matrix elements of the (p,p') reaction. Instead, it contributes to the knockon-exchange processes where it is found to be driven primarily by the tensor-exchange interaction.

With so little in the way of experimental constraint, it is possible that the shell-model effective interaction of Cohen and Kurath[6] misrepresents the properties of such abnormal-parity amplitudes. An extensive set of shell-model calculations was therefore carried out in which selective classes of the Cohen-Kurath two-body matrix elements (those believed to be less reliably determined) were set to zero. However, almost no changes in the $[111]$ amplitude were found. It should also be noted that β-decay experiments of ^{12}B and ^{12}N can provide some

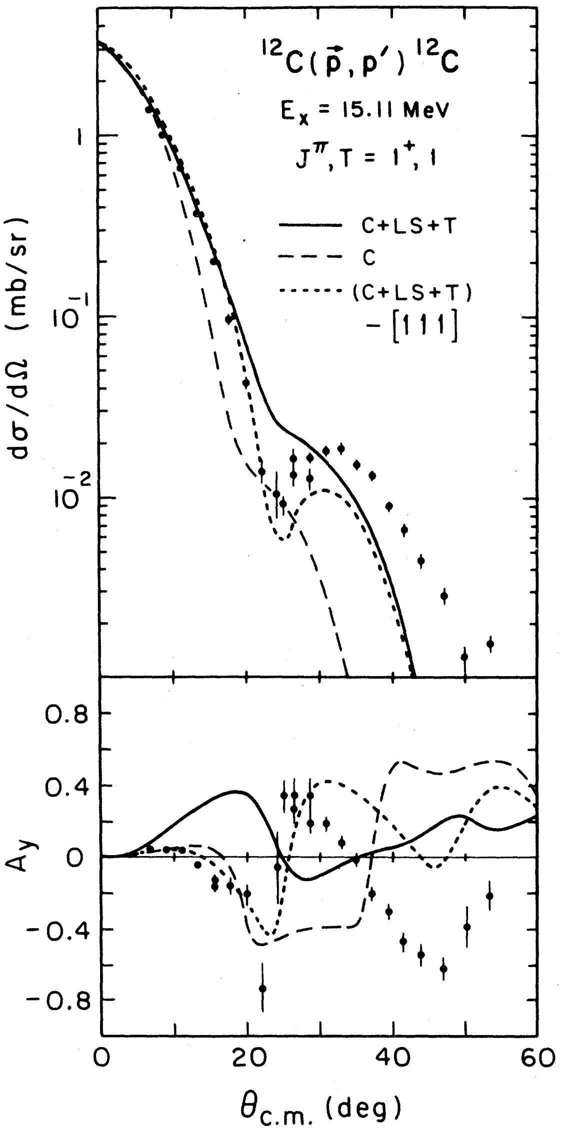

FIG. 5. DWIA calcuations for the 15.11-MeV state of ^{12}C. The solid curve is the CKWF result with central (*C*), spin-orbit (*LS*), and tensor (*T*) interactions. The abnormal-parity $[LSJ]=[111]$ amplitude has been removed for the calculation given by the short dashed curve.

sensitivity to the [111] amplitude for the 15.11-MeV transition through the effects of a $\vec{\sigma}\times\vec{L}$ operator that appears in the energy dependence of β-γ correlations.[27,28] The data appear to be in agreement with predictions from the CKWF (meson-exchange corrections were not considered).[29] Finally, recent (*P-A*) data at forward angles for the $^{12}C(\vec{p},p')$ reaction suggest the importance of retaining the [111] term.[30] Hence, apart from the present $(\vec{p},p')$ results, there seems to be little motivation for eliminating the [111] amplitude.

An alternative to the CKWF amplitudes in this transition has been provided by Dubach and Haxton (DH) who obtained a set of effective *p*-shell transition amplitudes directly from (e,e') and β-decay data.[31] Inspection of the amplitudes in the *LS* representation reveals that the [111] term is small but not well determined. DWIA calculations with the DH amplitudes yield results that are qualitatively similar to the dotted lines in Fig. 5 and differ only in details.

At this time it cannot be determined whether the difficulties with the 15.11-MeV transition are related to the nuclear-structure amplitudes or to the effective interaction, particularly to the tensor-exchange portion. The main change in the 200-MeV calculations from those at lower energies[1,2,7] has been in the effective interaction. The sharp deterioration of the results, expecially the A_y, seems to point the greatest suspicion to it.

2. *The 16.58-MeV state*

DWIA calculations for the 16.58-MeV transition are compared with the data in Fig. 6. In the case of the cross sections, the full calculations are in excellent agreement with the angular pattern of the data but are too large by a factor of about 5. The central part of the effective interaction alone will correctly reproduce the experimental cross-section scale and would give an excellent fit to the data if the size parameter *b* were decreased slightly. The analyzing powers, while not entirely discriminating, are in better agreement with the results of the full interaction.

As discussed in a previous paper,[2] the principal microscopic components of the transition density involve $p_{3/2}\rightarrow 2s_{1/2}$ and $p_{3/2}\rightarrow d_{5/2}$ amplitudes with opposite phasing. Transfer of $L=1$ to the nucleus is dominant. The angular distribution is determined mainly by the large $p\rightarrow s$ amplitude with some cancellation of the first maximum at small angles by the $p\rightarrow d$ amplitude. Removal of the abnormal-parity $[LSJ]=[212]$ amplitude reduces the effective $p\rightarrow d$ contributions. This would produce an increase in the forward-angle cross sections ($\theta<15°$) by about a factor of 2, but leave the analyzing powers essentially unchanged. Hence, no information on the reliability of the abnormal-parity contributions to (p,p') reactions can be obtained from these data.

The discrepancy of the theoretical cross-section

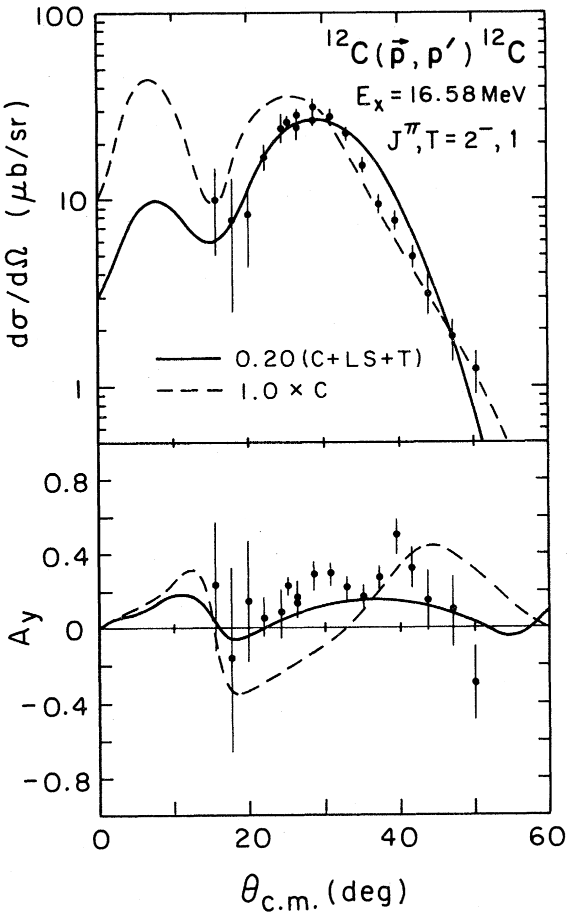

FIG. 6. DWIA calculations for the 16.58-MeV state of ^{12}C. See also the caption for Fig. 5. The theoretical cross sections shown by the solid curve have been divided by 5.

scale with the data can arise from the wave functions, the effective interaction, or other corrections to the reaction mechanism. The tensor part of the effective interaction contributes much more strongly to the 16.58-MeV transition than to the 15.11-MeV transition and is a potential source of trouble. Any modification of the wave function will have to maintain the delicate balance between the effective $p \rightarrow s$ and $p \rightarrow d$ amplitudes that seem to provide the proper angular dependence observed at 200 MeV and lower energies.[2,7]

B. Natural-parity transitions

The 16.11-MeV transition to a 2^+, $T=1$ state is the only well established isovector natural-parity excitation in ^{12}C. In principle, both the V_τ and $V_{\sigma\tau}$ portions of V^{cent} can contribute to the reaction, along with $V_{LS\tau}$ and $V_{T\tau}$. Although the $S=0$ and $S=1$ amplitudes in the CKWF are comparable, the dominance of $V_{\sigma\tau}$ over V_τ at medium energies[5] makes the $S=1$ contribution more important. Hence the isovector natural-parity transitions are primarily sensitive to the same terms in the effective interaction as the unnatural-parity transitions. However, since pion exchange cannot contribute, these transitions probe the shorter-range properties of the interaction.

DWIA calculations are compared with the data for the 16.11-MeV transition in Fig. 7. The CKWF amplitudes were modified in order to account for the suppression of the longitudinal and transverse form factors in the (e,e') reaction.[22,32] To do so, the transition amplitudes were converted to the LS representation (see Ref. 26), the $S=0$ and $S=1$ amplitudes were multiplied by factors of about 0.50 and 0.84, respectively, and the results were transformed back to the jj representation for use.

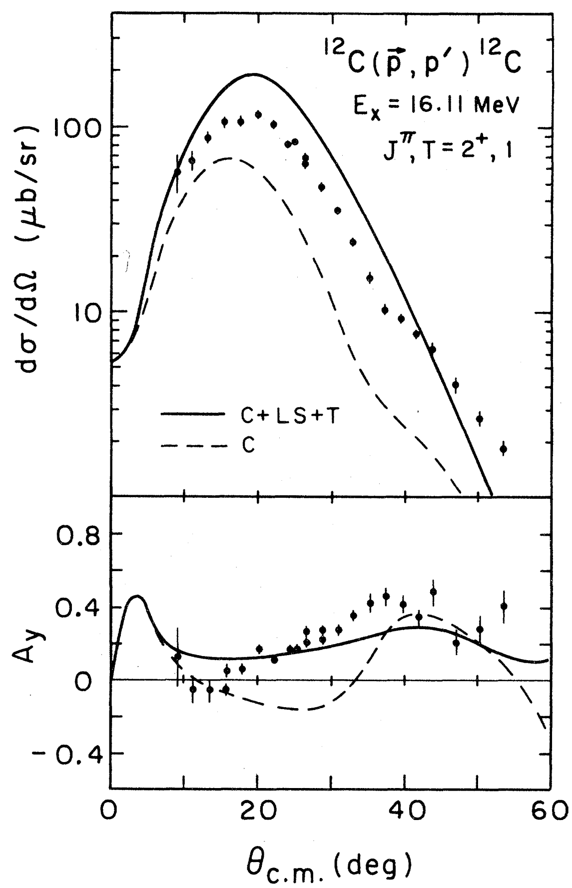

FIG. 7. DWIA calculations for the 16.11-MeV state of ^{12}C. The CKWF amplitudes have been adjusted as described in the text. See also the caption for Fig. 5.

The theoretical results are in reasonably good agreement with the data. For the differential cross sections, an additional reduction of the theoretical values by about 0.6 is needed and the change in slope near 40° is not reproduced well. The calculations are also in good qualitative agreement with the analyzing-power data over the full angular range, although some of the details are missed. The spin-orbit and tensor interactions seem to be important and help to produce the proper behavior of the curves. The analyzing-power results are substantially better than those at 120 MeV, while those for the cross sections are comparable.[2] Removal of the abnormal-parity $[LSJ]=[112]$ amplitude reduces the theoretical cross sections by about 10%, but substantially increases the analyzing powers over the full angular range, especially for $\theta < 40°$.

V. THE $T=0$ TRANSITIONS

Once again, the isoscalar excitations of ^{12}C can be classified into those with natural parity and those with unnatural parity. The direct matrix elements of the former are driven by the V_0 part of the effective interaction, while the latter will have contributions from both the V_0 and V_σ central terms. The V_{LS} and V_T terms contribute to both classes. In terms of the lowest-order boson-exchange models, V_0 and V_{LS} will be determined primarily by the exchange of vector ω and ϕ mesons and scalar σ mesons (or two-pion exchange with equivalent quantum numbers); the vector mesons and the pseudoscalar η meson contribute to the V_σ and V_T terms.[33]

A. Natural-parity transitions

Since the direct V_T term is weak[4,5] the natural-parity transitions are mediated primarily by the V_0 and V_{LS} parts of the effective interaction. The analyzing powers for this class of transitions have a very characteristic behavior: They go to large positive values at forward angles, cross zero near 35°, and go to large negative values at large angles. Examples are found for the 1^- state at 10.83 MeV, the 2^+ state at 4.44 MeV, the 3^- state at 9.63 MeV, and the 4^+ state at 14.08 MeV (see Figs. 3, 8, and 9). The 0^+ state at 7.65 MeV and the elastic analyzing powers also oscillate between approximately ± 1 in a similar manner, but on an angular scale somewhat different from that of the other states. Only three known isoscalar natural-parity transitions will be considered here. The others will be considered in a later publication.[12]

1. The 4.44-MeV state

DWIA calculations for the 2^+, $T=0$ state at 4.44 MeV are compared with the data in Fig. 8. Electromagnetic excitation of this collective transition in the (e,e') reaction indicates that a renormalization by a factor of 2 over the pure CKWF results is needed to account for core polarization.[22] This renormalization has been included in the curves in Fig. 8. Thus, the full (p,p') calculation overestimates the peak experimental cross section by a factor of about 1.9. The microscopic spin-orbit in-

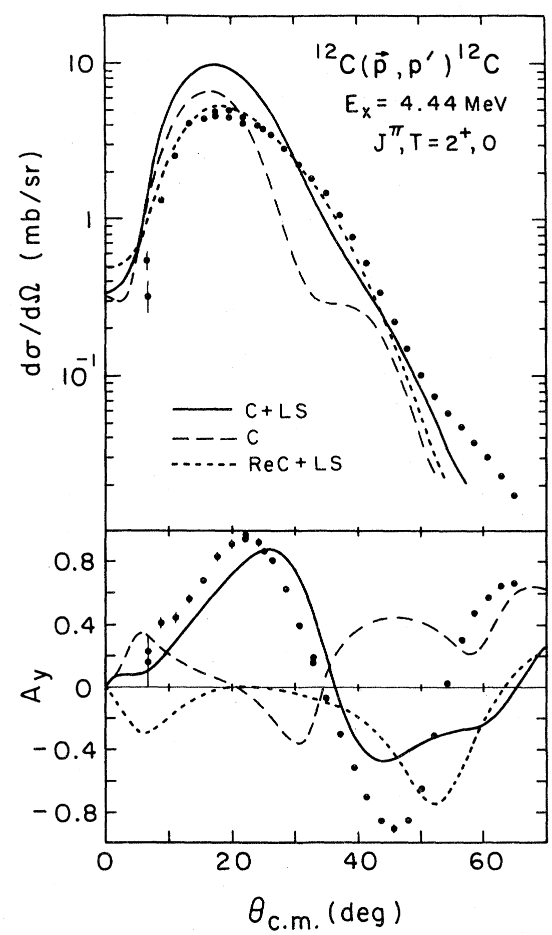

FIG. 8. DWIA calculations for the 4.44-MeV state of ^{12}C. See also the caption for Fig. 5. The calculations for the short dashed curve include only the real part of the central interaction.

teraction is seen to be essential for raising the cross sections at large angles and for establishing the correct qualitative behavior for the analyzing powers. The results at 200 MeV are comparable to those at 120 MeV.[12]

It has been noted earlier that the imaginary part of the central t matrix might be overestimated.[1,4] Calculations with this term omitted are shown as dotted lines in Fig. 8. The magnitude and shape of the differential cross sections are then reproduced very well. However, the analyzing powers bear little resemblance to the data.

A density-dependent modification of the interaction has been considered recently by Kelly *et al.*[10] for isoscalar natural-parity transitions. Very substantial improvements were found for the absolute cross-section scale, the shape of the differential cross sections, and the behavior of the analyzing powers. The procedures of Ref. 10 have not been carried out here. Sensitivity of this transition to some details of the optical potentials has already been noted in Sec. III C. Possible contributions from coupled-channel effects have been discussed elsewhere.[1,14]

2. *The 9.63-MeV state*

The longitudinal electron-scattering form factor $|F_L(q)|^2$ for the 3^-, $T=0$ state at 9.63 MeV is well reproduced by the MKWF out to a momentum transfer of ~ 1.7 fm^{-1} with an oscillator parameter $b=1.90$ (unadjusted) and an upward renormalization by a factor of 2.2.[23] The theoretical values fall below the data at larger q. The weak transverse form factor $|F_T(q)|^2$ is underestimated by the theory by a factor of about 0.6 over most of the range of the data.[23] The MKWF provides the correct phasing between the longitudinal and transverse form factors whereas other wave functions, particularly those with simple configurations, do not.[23]

The DWIA calculations for the (p,p') reaction to this state are shown along with the data in Fig. 9. The b parameter is 1.82 fm (adjusted) and the (e,e') renormalization factor of 2.2 has not been included. Except for the normalization, the theoretical cross sections are in good agreement with the data out to $q \sim 1$ fm^{-1} beyond which they fall significantly below the experimental results. The discrepancy in normalization between the (p,p') and (e,e') results is similar to that for the 4.44-MeV state and presumably has the same cause. The analyzing powers are reproduced very well by the calculations. The region beyond 40° is particularly sensitive to the b parameter and somewhat better results could be obtained with a value $b=1.68$ as for some of the other states of ^{12}C. There is essentially no sensitivity either to removal of the abnormal-parity $[LSJ]=[213]$ term or to an increase in the [313] amplitude by a factor of 1.3 as suggested by the (e,e') data. Once again, removal of the imaginary central interaction improves the agreement with the shape of the cross sections but is unacceptable for the analyzing powers.

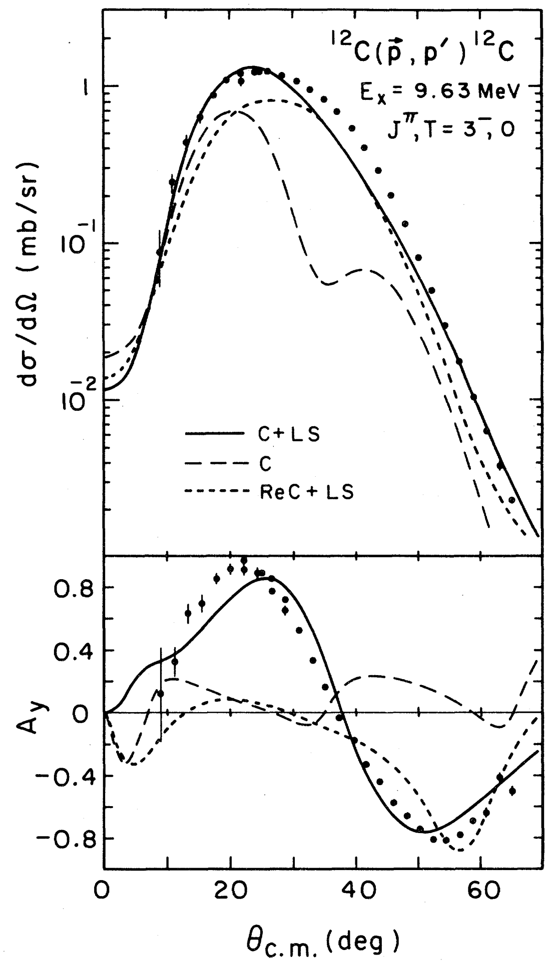

FIG. 9. DWIA calculations for the 9.63-MeV state of ^{12}C. See also the caption for Fig. 8.

3. *The 15.3-MeV state*

A very broad ($\Gamma \sim 2$ MeV) state has been seen in a number of experiments centered near an excitation energy of about 15.3 MeV in ^{12}C and most of the evidence indicates that it is a 2^+, $T=0$ state.[34,35] If so, it is readily associated with the second such state of the CKWF predicted to lie at 15.13 MeV.[6] The extraction of the differential cross sections for this state from the spectra is difficult and depends on subjective factors such as the estimate of the underlying continuum. The data in Fig. 10 resemble those obtained at 120 MeV,[1] except that the region near 30° may be relatively larger. The analyzing powers should be less dependent on systematic biases since some cancellation of their effects can be expected. The data in Fig. 10 have the characteristic pattern associated with other isoscalar natural-parity transitions (see Sec. V A).

The full DWIA calculations in Fig. 10 are not in very good agreement with the data. The theoretical cross sections are somewhat too low and the calculated analyzing powers are very small at forward angles, unlike the data. The CKWF are unusual in that the abnormal-parity amplitude is by far the largest. In the notation of Ref. 26, the values are the following: [202], 0.0099; [212], 0.0815; [112], 0.4029. Removal of the [112] amplitude produces the proper characteristics in the analyzing powers, although the magnitudes are generally too low. However, the cross sections are then about a factor of 25 below the data. The enigma is difficult to resolve.

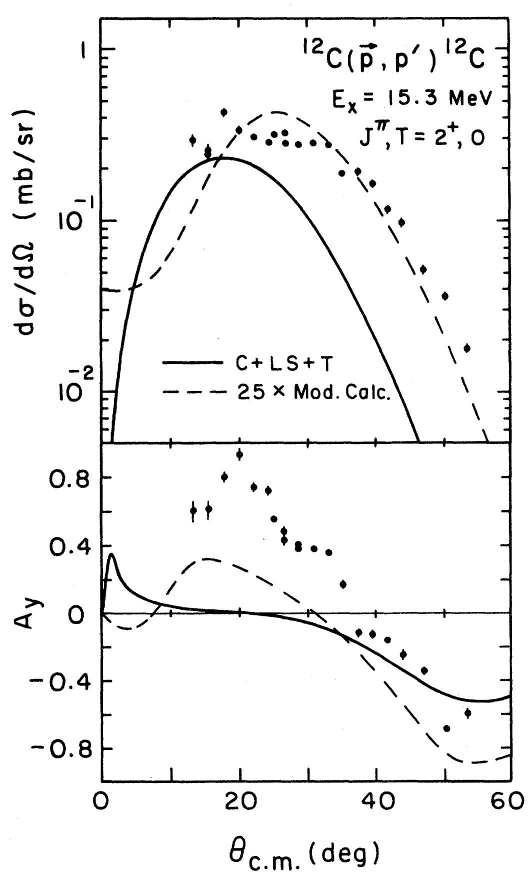

FIG. 10. DWIA calculations for the broad 15.3-MeV state of ^{12}C. The abnormal-parity $[LSJ]=[112]$ amplitude has been removed for the calculations shown by the dashed curve and the theoretical cross sections have been multiplied by 25. See also the caption for Fig. 5.

B. Unnatural-parity transitions

The V_σ term is believed to be weak and is poorly determined by the free *NN* scattering data.[1,4,5] The contribution of V_T to direct matrix elements is also weak.[1,2,4,5] There are, however, large contributions to isoscalar unnatural-parity transitions from exchange matrix elements, particularly from the isovector tensor interaction $V_{T\tau}$.[5] Hence this class of transitions is especially sensitive to the least reliable aspects of the effective interaction and the assumed one-step reaction mechanism described by the impulse approximation.

1. The 12.71-MeV state

The excitation of the 1^+, $T=0$ state at 12.71 MeV in ^{12}C has been very difficult to describe in (p,p') reactions below 200 MeV.[1,2,7] The features of the data have a substantial dependence on bombarding energy between 120 and 200 MeV.[1,2,7] In particular, the analyzing powers have opposite signs over most of the angular range at these two energies.[7,13] The sensitivity is also evident in the theoretical calculations where different effective interactions can also produce significantly different results.[7,13]

The DWIA calculations for this transition are shown in Fig. 11 along with the 200-MeV data. Although the differences between the dashed and dotted curves indicate some sensitivity to the spin-orbit interaction, in fact the sensitivity is weak after the tensor interaction has been included. The spin-orbit interaction could be removed from the full calculations with little change in either the cross sections or the analyzing powers. The theoretical cross sections do not differ very much from those calculated at 120 MeV.[2] However, since the experimental cross sections at large angles are now relatively smaller than at the lower energies,[1,7] there is better agreement with the data. There is also good agreement with the analyzing powers out to at least 35°.

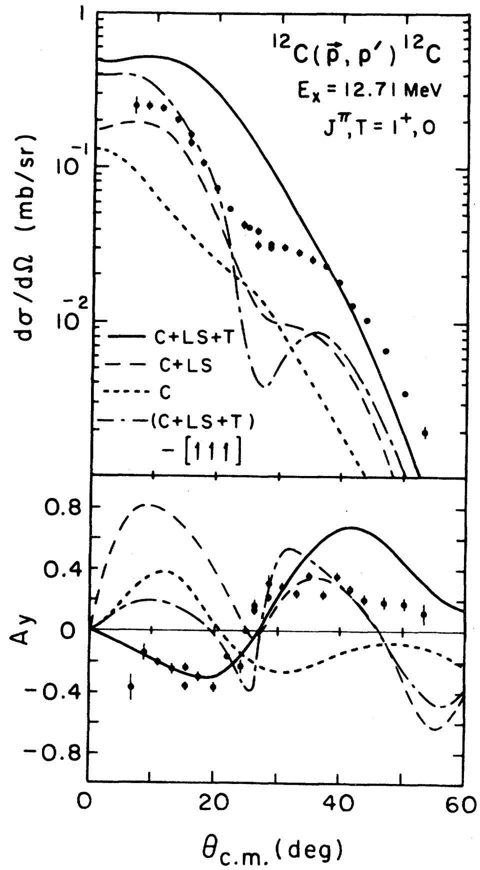

FIG. 11. DWIA calculations for the 12.71-MeV state of ^{12}C. See also the caption for Fig. 5.

This result is in contrast to the 120-MeV case[2] where the data and calculations had opposite signs.

In view of the known sensitivity to the tensor-exchange interaction,[1,2,5] DWIA calculations were also made with the abnormal-parity [111] term removed from the CKWF. The final result is also shown in Fig. 11. The cross sections have dropped substantially in the intermediate-angle range. Since a minimum has formed near 27°, where the data only have a shoulder, it is clear that this modification is too extreme. In this case, the minimum is brought about by interference of the central and spin-orbit terms and is not modified significantly by the tensor interaction. The analyzing powers are changed substantially, especially at forward angles, and are in poor agreement with the data.

2. *The 11.83-MeV state*

The transition to the 2^-, $T=0$ state at 11.83 MeV has a number of similarities with that to the 2^-, $T=1$ state at 16.58 MeV. The differential cross sections and analyzing powers are qualitatively similar. The MKWF amplitudes for the transitions are also similar and, even though very different parts of the effective interaction contribute to the two transitions, the DWIA calculations are similar. The results for the 11.83-MeV state are shown in Fig. 12 where the theoretical cross sections have been reduced by a factor of 6. Finally, like the 16.58-MeV transition, removal of the [213] amplitude has very little effect on the theoretical results.

VI. OTHER TRANSITIONS

Several other transitions were observed in the $(\vec{p},p')$ reaction but most of them were not analyzed in the DWIA. Those below 15 MeV have known quantum numbers[34] while the pair between 19 and 20 MeV do not. Reliable wave functions are not necessarily available for most of these states and an empirical analysis did not appear to be very useful, especially in view of the uncertainties of the DWIA. The data for these transitions are shown in Figs. 2 and 3. Although the 19–20 MeV region is espe-

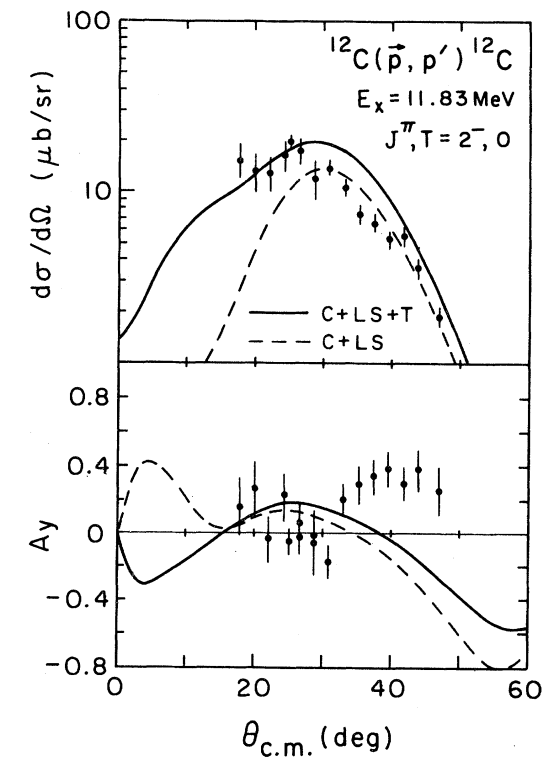

FIG. 12. DWIA calculations for the 11.83-MeV state of ^{12}C. See also the caption for Fig. 5.

cially interesting in terms of possible isospin mixing in inelastic scattering,[36] little can be added to the issue from this experiment. It should be recognized that the two observed structures near 19.2 and 19.7 MeV overlap substantially and that the division of the region into two states of equal widths is somewhat arbitrary.

Two states, however, were sufficiently interesting that DWIA calculations could be considered for them. Although the 18.4- and 20.54-MeV states appear at energies where other experiments have suggested several different J^π assignments, it appeared that the present data could help in clarifying the features of ^{12}C at high excitation energy.

A. The 18.4-MeV state

The 18−19 MeV region of ^{12}C is very complex and many states have been suggested for it.[34] A 3^-, $T=1$ state seems to dominate proton-transfer experiments,[34,37] but other states are indicated from other sources. Buenerd *et al.* found evidence for both a 2^+, $T=0$ state and a 3^-, $T=1$ state near 18.4 MeV from (p,p') and (α,α') reactions.[35] Nuclear models also predict many states for the region.[6,21]

Four options were considered for the observed group near 18.4 MeV excitation in ^{12}C. These are (1) the third 2^+, $T=0$ state of the CKWF, predicted at 18.13 MeV; (2) the lowest 3^-, $T=1$ state of the MKWF, predicted at 18.63 MeV; (3) the second 2^-, $T=0$ state of the MKWF, predicted at 16.98 MeV; and (4) the second 2^-, $T=1$ state of the MKWF, predicted at 19.13 MeV. The results of DWIA calculations for the first three cases are shown in Fig. 13. The results of the two 2^- calculations are not very different.

The theoretical 2^+ cross sections fall substantially below the data and do not reproduce the experimental shape very well. The experimental analyzing powers do not have the characteristic pattern usually associated with the isoscalar natural-parity excitations (see Sec. V A) nor are they well represented by the 2^+ calculations. The 3^- transition is dominated by the $p_{3/2}\rightarrow d_{5/2}$ amplitude and the calculations are similarly very unsatisfactory. In contrast, the 2^- calculations, either $T=0$ or $T=1$, obtain all of the basic features of the data. Although this transition has all of the same components as the ones at 11.83 and 16.58 MeV, the phasing between the dominant $p_{3/2}\rightarrow s_{1/2}$ and $p_{3/2}\rightarrow d_{5/2}$ components is reversed. This produces the large cross section at relatively small angles. Small adjustments of the amplitudes could reduce the forward-angle cross sections and give a very good fit to the data.

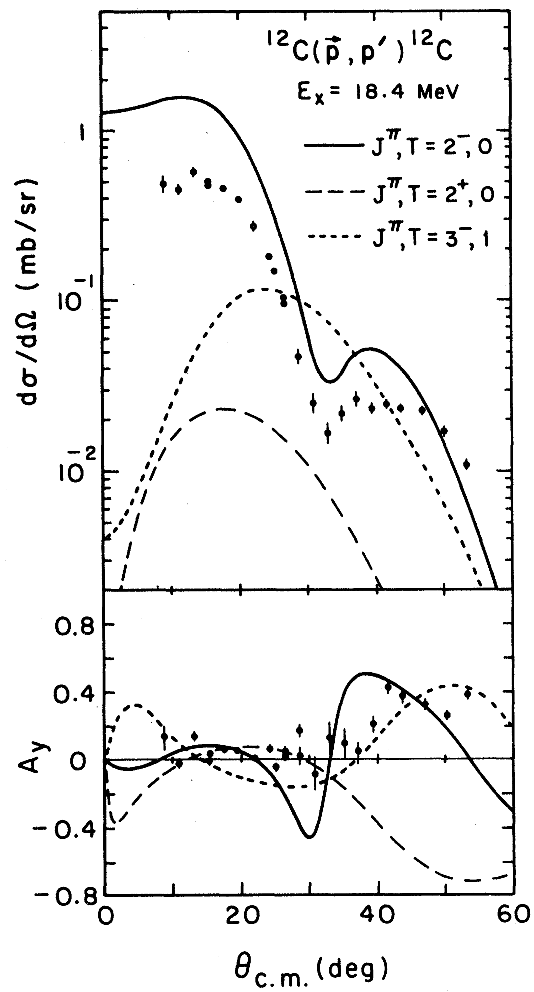

FIG. 13. DWIA calculations for the 18.4-MeV state of ^{12}C with three choices for the J^π, T of the state.

Although the presence of more than one state cannot be excluded, the data seem to agree best with the 2^- assumption. The structure near 30° would otherwise be very difficult to reproduce. Unlike the behavior at 800 MeV,[38] where A_y for the same transition agreed with the systematics of $T=0$ excitations, no distinction between $T=0$ and $T=1$ can be made at 200 MeV.

B. The 20.54-MeV state

The 20-MeV region of ^{12}C is also very complex.[34] The $(^3He,p)$ reaction gives a clear indication of a 3^+, $T=1$ state near 20.6 MeV.[39,40] Information on the analog states in ^{12}B indicates that a 3^-, $T=1$ state should be present near the same energy.[34,41] However, the (d,α) reaction strongly populates a level that must be assigned $T=0$.[42,43] A state at 20.6 MeV has been observed in the (p,p') reaction at 45 and 155 MeV, but not in the (α,α') reaction at 60 MeV.[35] Distorted-wave calculations for the (p,p') reaction, assuming the state has $J^\pi=3^-$, $T=1$, gave reasonable agreement with the data.[35] However, the observation of a state near 20.6 MeV in (d,d') reactions,[44] and the absence in (α,α'),[35] is consistent with the population of an unnatural-parity state with $T=0$.

DWIA calculations for the 20.54-MeV transition are compared with the data in Fig. 14. For the 3^+, $T=1$ calculation, the CKWF corresponding to a state at 19.6 MeV are used. For the 3^-, $T=1$ calculation, a pure $p_{3/2}\rightarrow d_{3/2}$ transition is assumed as in Ref. 35. The theoretical cross sections in both cases have been rescaled to match the data near the maximum. The renormalization is large for the 3^- case, but the assumption of a pure configuration is perhaps extreme.

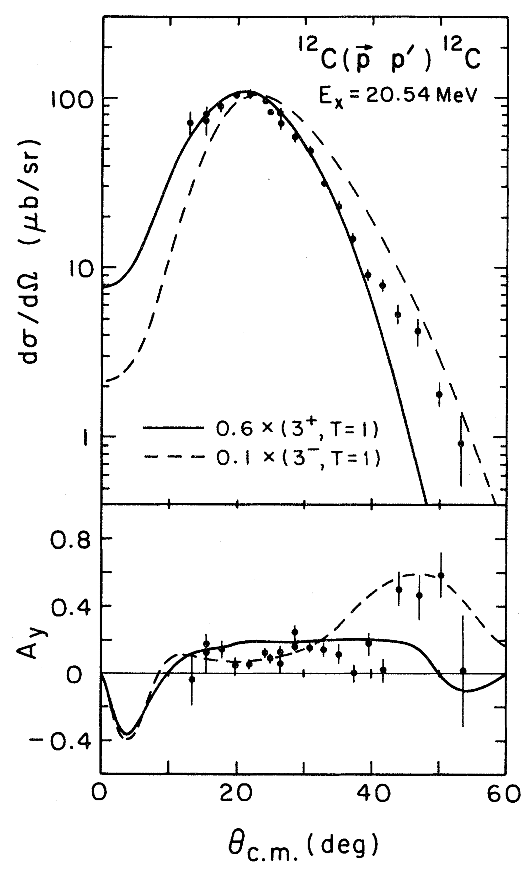

FIG. 14. DWIA calculations for the 20.54-MeV state of ^{12}C with two choices of J^π for the state. The theoretical cross sections have been rescaled by the factors indicated.

It seems difficult to choose between the two calculations. Discrepancies with the angular scale of the differential cross sections for the 3^- case can be partly removed by an adjustment of the size parameter b. A distinction between the two analyzing-power curves occurs in the region near 50° where the theoretical results may not be entirely reliable. In this comparison, the 3^- calculation appears to do somewhat better. However, the existence of a 3^+, $T=1$ state near 20.6 MeV cannot be ignored. The calculation for it alone, based on the CKWF, seems to be no worse than for the other unnatural-parity $T=1$ states at 15.11 and 16.58 MeV. The 3^+ transition proceeds through a "stretched" configuration and the renormalization for it is consistent with other isovector transitions of this type.[24]

VII. DISCUSSION AND SUMMARY

The spin, parity, and isospin quantum numbers for most of the states of ^{12}C observed in the (p,p') reaction at 200 MeV are known from the literature.[34] For some of the excitations considered, many states are known within the region of an observed peak. Evidence was given that the observed structure near 18.4 MeV is predominantly a 2^- state, probably with isospin $T=0$.[38] The 2^+, $T=0$ and 3^-, $T=1$ combination that has been suggested in the case of inelastic-scattering reactions[35] appears to be unsatisfactory. The region near 20.5 MeV is more ambiguous. Both a 3^+, $T=1$ and a 3^-, $T=1$ calculation appear to give results that are as good as for other transitions. A state of each type should be present in addition to other $T=0$ states at this excitation.[34,40]

One aspect of the data from this experiment that is particularly noteworthy is the observation that the angular distributions cannot be immediately intepreted in terms of the dominant angular momentum transfer. The differential cross sections for the two 1^+ states at 12.71 and 15.11 MeV, for example, are not alike. Sometimes the differential cross sections may be similar, but the analyzing powers will be quite different as for the two 2^+ states at 4.44 and 16.11 MeV. Of course, many of the differences are directly related to the features of the effective interaction, particularly if the isospin quantum numbers are different. However, it is even more striking that transitions with the same quantum numbers can look totally unrelated. Such is the case for the apparent 2^- state at 18.4 MeV and either the 11.83-MeV or 16.58-MeV state. In both cases, the calculations are also dominated by $L=1$ transfer to the nucleus. The very distinctive differences in the differential cross sections is a direct reflection of the underlying microscopic configurations.

Another interesting aspect of the (p,p') reaction is that it seems to be more sensitive to particular structure amplitudes than are other probes. These are the abnormal-parity amplitudes which enter the (p,p') calculations through the knockon-exchange matrix elements. Those spectroscopic abnormal-parity amplitudes with $S=0$ give rise to the convection-current contributions to (e,e') reactions. Those with $S=1$ are not sampled in (e,e') reactions.

The effects of the abnormal-parity amplitudes with $S=1$ were considered for several transitions by comparing DWIA calculations with and without their presence. The removal of the $[LSJ]=[111]$ term converted the DWIA results for the 15.11-MeV transition from very poor to very good agreement with the A_y data. The removal of the large [112] amplitude for the 15.3-MeV transition substantially improved the agreement with the experimental analyzing powers, although the cross sections were then much too low. For other transitions, elimination of the abnormal-parity amplitudes either had little effect in the region where data were available, or gave slightly inferior results.

At this time it cannot be determined whether the difficulties that appear to be associated with the abnormal-parity terms are related to the nuclear structure or to the exchange features of the effective interaction. Although information is limited, there appears to be little reason from independent sources that these spectroscopic terms are erroneous. Useful insight might come from studies of other nuclei, especially those for which the abnormal-parity amplitudes are expected to be small, so that focus can be given to the effective interaction.

The use of the 210-MeV t matrix for the present 200-MeV data has given results that, on the whole, are about as good as those obtained at lower energies with a 140-MeV t matrix.[1,2,7] Comparisons with the data for some transitions were improved, while the results for others were worse. The largest changes involved the analyzing powers. The most significant deterioration was for the important 15.11-MeV state. It is most likely that the origin of the problem lies with some feature of the effective interaction since the characteristics of the data do not change much between 120 and 200 MeV.[7]

By way of summary, the 200-MeV results of this study may be compared with those of the lower energies,[1,2,7] for each of the following four classes of transitions.

(1) As has been clear from the discussion of the 15.11-MeV transition, the isovector unnatural-parity transitions are less well described at 200 MeV. The exchange features of the $V_{T\tau}$ term may be responsible for this, leaving the central $V_{\sigma\tau}$ term reasonably correct. The tensor exchange does not appreciably affect the 16.58-MeV transition. The angular patterns for this latter transition, which require a delicate balance of microscopic components, are very well reproduced, but the cross-section scale is substantially incorrect at all energies even when the CKWF are renormalized to match electron scattering.

(2) Although the theoretical cross-section scale for the isovector natural-parity transition to the 16.11-MeV state is not as good at 200 MeV as at lower energies, the results for the analyzing powers are much improved. The pion-exchange part of $V_{\sigma\tau}$ cannot contribute to this class and, once again, the tensor-exchange contributions seem be be weak. Hence, there is no evidence for serious problems with either V_τ or $V_{\sigma\tau}$ as applied to transitions of this class.

(3) The analyzing powers for isoscalar natural-parity transitions have a very characteristic pattern that is generally well reproduced by the DWIA calculations. When rescaled by the renormalization factors required for the (e,e') form factors, the cross section scales for both the 2^+ (4.44 MeV) and 3^- (9.63 MeV) (p,p') transitions are too large by roughly a factor of 2. Density dependent corrections to V_0 seem to be necessary for both transitions.[10] The V_{LS} term seems to be reasonably well described.

(4) Serious difficulties remain for the isoscalar unnatural-parity transitions. There appears to be some improvement at 200 MeV, especially for analyzing powers. Large abnormal-parity amplitudes for the 12.71-MeV transition produce significant contributions through exchange coupling to the isovector tensor interaction. The difficulties with the 12.71-MeV state are significantly reduced near 400 MeV (Ref. 45) and 800 MeV (Ref. 46).

ACKNOWLEDGMENTS

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*Present address: Department of Physics, Arizona State University, Tempe, AZ 85287.
†Present address: P. A. Inc., 9740 Tanner Road, Houston, TX 77041.

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