Protons of 200 MeV incident on ^{12}C. II. Quasifree proton knockout

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The validity of the distorted-wave impulse approximation treatment has been investigated for $^{12}C(p,2p)^{11}B$ knockout at an incident energy of 200 MeV for coplanar geometries which are very different from those at which quasifree knockout is usually studied. Good agreement in shape has been found between the calculated and measured energy-sharing distributions over a wide range of kinematic conditions. Except at very forward symmetric angles, the distorted-wave impulse approximation treatment was found to be insensitive to the choice of the initial- or final-energy prescriptions for the two-body scattering approximation. An average spectroscopic factor of 1.1 ± 0.3 was extracted.

I. INTRODUCTION

A number of studies[1–4] of coincident proton emission from the continuum induced by protons of 100- and 200-MeV incident energy, have indicated that the reaction mechanism is dominated by an initial nucleon-nucleon interaction of the incident projectile with a nuclear constituent. Our experiment on $^{12}C(p,p'p'')$ at 200 MeV reported in the preceding paper[5] (hereafter referred to as I) has confirmed that the initial nucleon-nucleon interaction is followed by the further interaction of the struck nucleon with the rest of the nucleus. A quantitative appraisal requires information on the reliability of the various components of the model. In particular, the treatment in distorted-wave impulse approximation (DWIA) of the important first step in the reaction as a quasifree process needs to be investigated.

In nucleon knockout reactions, the range of validity of the factorized DWIA is understood reasonably well,[6] and therefore experimental studies of that type are usually performed under carefully selected kinematic conditions. Examples of these for $^{12}C(p,2p)^{11}B$ are Refs. 7 and 8 at 100 MeV and Ref. 9 at 150 MeV. In the calculations performed in I, however, a more extensive region of kinematic phase space contributes, and it is essential to establish the range over which the DWIA is reliable.

Quasifree knockout by means of nucleons is, of course, also a reaction of interest in its own right. Even though it is generally recognized that knockout reactions induced by high-energy electrons have distinct advantages over those initiated with nucleons in nuclear structure studies, these reactions nevertheless complement each other. In the present investigation, the reaction mechanism itself is of primary interest.

The experimental data presented here were measured concurrently with those reported in I. Energy-sharing distributions were obtained for $^{12}C(p,2p)^{11}B$ in coplanar geometry with one ("primary") angle at $-20°$ (and $-45°$) and the angle of coincidence ("secondary") at 20°, 45°, 70°, 95°, 120°, and 145° (35°, 85°, and 135°). Thus these data include conditions of more extreme angular as well as energy asymmetry than previous studies, in addition to some angle pairs where the DWIA is known to be a reasonable treatment. A preliminary account of some of the present results and conclusions has been presented elsewhere.[10]

II. EXPERIMENTAL DETAILS

Most of the experimental details are as described in I. In order to extract energy-sharing distributions from the knockout to ^{11}B, spectra of total energy versus energy of one proton were generated (see Fig. 1). As shown in Fig. 2, projection onto the total energy axis allows the extent of the knockout locus to be clearly identified. However, the observed missing mass resolution of 4-MeV results in the inclusion of yield due to some of the excited states in ^{11}B. Knockout to these states is known from work[8] at 100 MeV to have the same distorted momentum distributions as the knockout to the dominant ground state of ^{11}B, with a contribution of $\sim 10\%$ from the state at 2.13 MeV accounting for almost all of the remaining yield.

III. THEORY

The DWIA formalism of Chant and Roos[11] is used in the present study for determining the cross sections for the quasifree knockout interaction. This treatment considers the knockout reactions $A(a,a'b)B$, where $A=B+b$, b is the emitted nucleon or cluster, and the prime indicates the particle a in the exit channel. The differential cross section for specific values of orbital angular momentum L (projection Λ) and total angular momentum J is written as

$$\frac{d^3\sigma^{LJ}}{d\Omega_{a'}d\Omega_b dE_{a'}} = C^2|[\bar{t}]|^2 S_{LJ}\left\{\frac{E_a E_{a'} E_b}{(2\pi)^5(\hbar c)^7}\frac{P_{a'}P_b c}{P_a} \times \frac{1}{1+(E_b/E_B)[1-(P_a/P_b)\cos\theta_{ab}+(P_{a'}/P_b)\cos\theta_{a'b}]}\right\}\sum_{\Lambda}|T_{BA}^{aL\Lambda}|^2 , \quad (1)$$

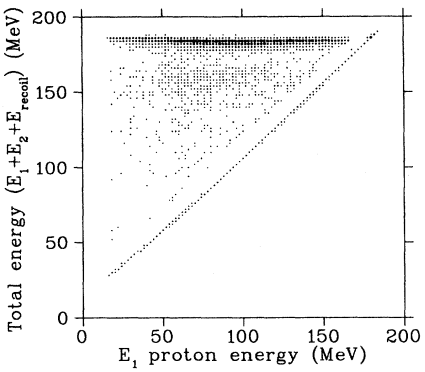

FIG. 1. Density plot of reaction-product summed energy vs. E_1.

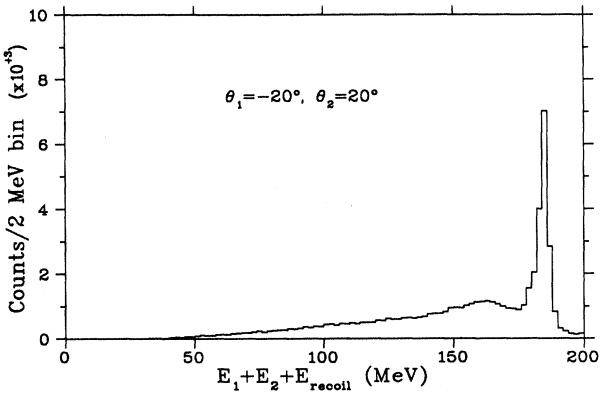

FIG. 2. Binding energy spectrum obtained from a projection of the data shown in Fig. 1 onto the total energy axis. Note that the arbitrary cross-section scale contains an implicit energy dependence due to experimental thresholds on proton energies.

where the momenta P_i, energies E_i and angles θ_{ij} refer to the different particles.

The quantity $T_{BA}^{\alpha L\Lambda}$ is expressed in terms of distorted waves χ for incident and emitted particles and the bound-state wave function $\phi_{L\Lambda}^{\alpha}(r)$ describing the motion of the center of mass of B, as

$$T_{BA}^{\alpha L\Lambda}=\frac{1}{(2L+1)^{1/2}}\int \chi_{aB}^{(-)*}(\mathbf{k}_{aB},\mathbf{r})\chi_{bB}^{(-)*}(\mathbf{k}_{bB},\mathbf{r})\chi_{aA}^{(+)}(\mathbf{k}_{aA},\gamma\mathbf{r})\phi_{L\Lambda}^{\alpha}(\mathbf{r})d\mathbf{r}\ , \tag{2}$$

where

$$\mathbf{r}_{aB}=\mathbf{r}_{ab}+\mathbf{r}_{bB}\ , \tag{3}$$

$$\mathbf{r}_{aA}=\mathbf{r}_{ab}+\gamma\mathbf{r}_{bB} \tag{4}$$

and

$$\gamma=\frac{B}{(B+b)}\ . \tag{5}$$

All quantum numbers of the bound state other than L,J, and their projections Λ and M are included in α.

If one assumes that $T_{BA}^{\alpha L\Lambda}$ is independent of α, the spectroscopic factor S_{LJ} is defined as

$$S_{LJ}=\left|\sum_{\alpha} S_{\alpha LJ}^{1/2}\right|^2\ , \tag{6}$$

where C is the isospin coupling (Clebsch-Gordan) coefficient. The two-body t matrix can be shown to be

$$|[\bar{t}]|^2=(2\pi\hbar^2c^2)^2\frac{P_i^{\text{c.m.}}E_{\text{c.m.}}^2}{P_f^{\text{c.m.}}E_aE_{b'}E_{a'}E_b}\frac{d\sigma(E_{\text{c.m.}},\theta_{\text{c.m.}})}{d\Omega}\ , \tag{7}$$

where $P_i^{\text{c.m.}}$, $P_f^{\text{c.m.}}$, $E_{\text{c.m.}}$, and $\theta_{\text{c.m.}}$ are the initial momentum, final momentum, total energy, and scattering angle in the $a'+b$ center-of-mass system. E_j is the laboratory energy of particle j, and $E_{b'}$ is the laboratory energy for the virtual particle b' where

$$E_{b'}=m_Ac^2-E_B\ . \tag{8}$$

Finally, to evaluate the "half-off-mass-shell" two-body cross section $d\sigma(E,\theta)/d\Omega$, Chant and Roos use an on-shell amplitude interpolated from available phase shifts for free $a+b$ scattering. This is done with two different prescriptions for E. In the final-energy prescription (FEP) approximation, E is taken to be the relative center-of-mass energy of the emitted particles in the exit channel, whereas in the initial energy prescription (IEP) approximation, E is the relative center-of-mass energy of the incident and struck particles in the entrance channel.

In the above treatment spin-orbit effects are ignored. It has been suggested[12] that such effects could, in principle, be profound. Chant and Roos have extended the above treatment[13] by including such spin-orbit terms in the distorting potentials, and replacing the explicit calculation of angular momentum coupling coefficients by a numerical integration technique. Applying their results to $(p,2p)$ reaction data at 150 MeV, they found major differences for some polarization analyzing powers involving a range of residual nucleus recoil momenta, but no major qualitative changes were found in the predicted differential cross sections compared with calculations in which the spin-orbit effects were neglected.

IV. RESULTS AND DISCUSSION

A. Experimental results and calculations

The measured cross sections for the knockout of p-state protons from ^{12}C by 200-MeV incident protons are plotted in the energy-sharing distribution of Figs. 3 to 5. These show the cross sections extracted from the p-state knockout locus in the summed energy spectra for coincident protons (see Fig. 1) at the nine pairs of angles—six secondary angles θ_2 at the primary angle θ_1 of $-20°$ and

three secondary angles at the primary angle of $-45°$. The extracted cross sections are plotted with associated statistical error bars, as a function of the laboratory kinetic energy E_1 of the proton detected at the primary angle.

Results of DWIA calculations performed with the aid of the computer program THREEDEE (Ref. 14) are also shown in Figs. 3 to 5. The continuous curves are the results from calculations in which the FEP was employed in the approximation for the two-body scattering amplitudes, whereas the dashed curves are the results obtained for the IEP. Two graphs are plotted for each angle pair, one for the DWIA calculations performed with average energy optical potentials[15] at 100 MeV for the outgoing particles, and the second with a more realistic energy-dependent set[16,17] of potentials. For the incident scattering a potential set at 200 MeV (Ref. 18) was used.

The separation energy of the knocked-out proton was taken as 15.9 MeV. A Woods-Saxon optical potential with geometrical parameters[7] of $r_0=1.64$ and $a=0.65$ was used and the well depth was adjusted to give an appropriate bound-state wave function. The spectroscopic factors obtained by normalizing the theory are also shown on each of the graphs in Figs. 3 to 5. These spectroscopic factors correspond to the C^2S_{LJ} factor in Eq. (1) for the differential cross section.

The shapes of the DWIA curves are in reasonable agreement with the measured cross sections. For the pri-

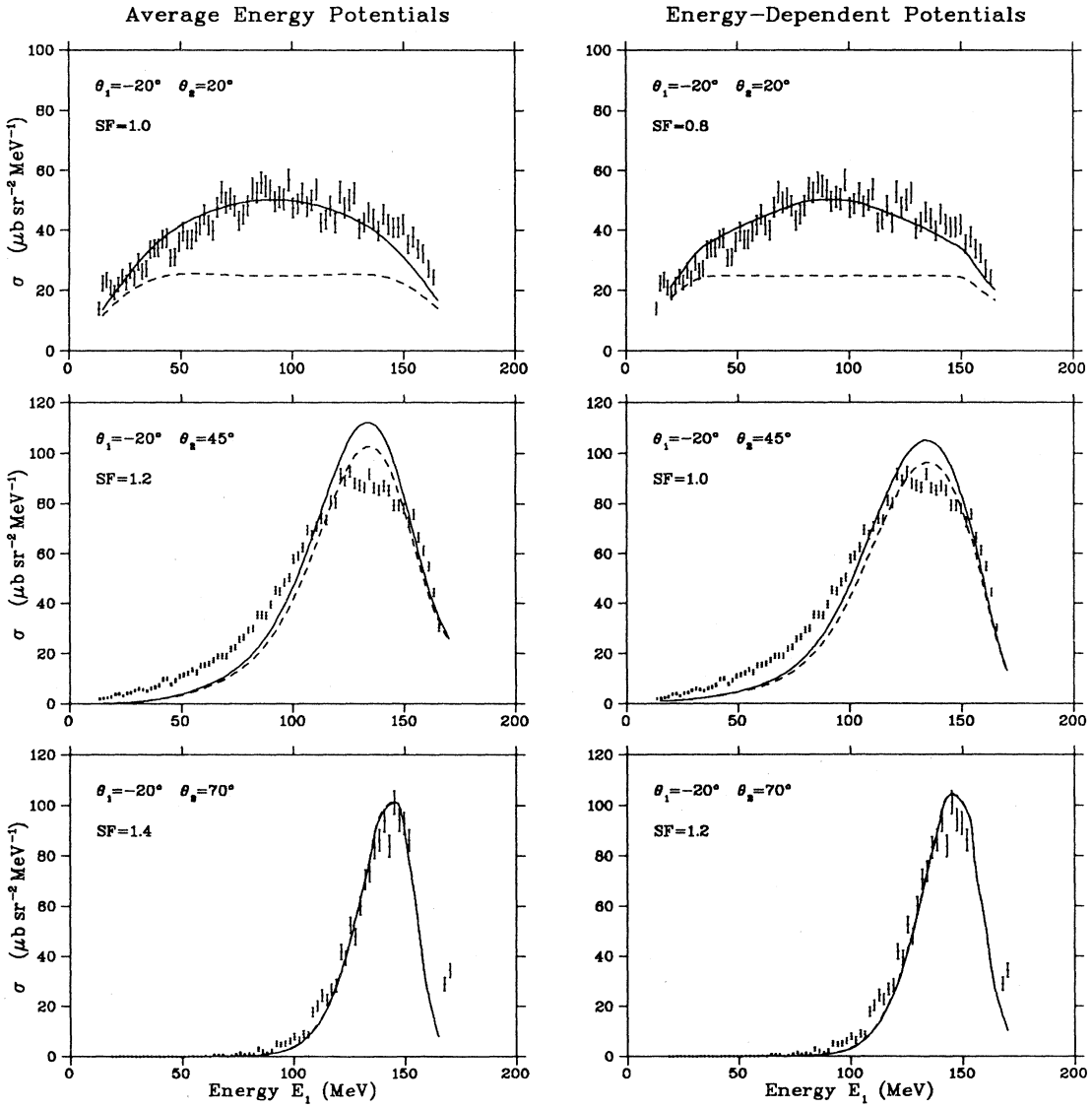

FIG. 3. Energy-sharing distributions for knockout of p-state protons from ^{12}C by incident protons of 200 MeV. Measured cross sections are shown with statistical error bars. DWIA calculations are drawn as continuous curves (FEP) and dashed curves (IEP). Spectroscopic factors are indicated. Calculations with average-energy potentials and energy-dependent potentials are shown.

mary angle of $-20°$ and at large secondary angles ($\Delta\theta=|\theta_1-\theta_2|>110°$), the peak of the calculated yield shifts to an energy higher than that of the measured yield, and this difference increases with secondary angle ($\Delta E=\sim 6$ MeV at $\Delta\theta=115°$ and $\Delta E=\sim 19$ MeV at $\Delta\theta=140°$). For the primary angle of $-45°$, no similar shift in the peak of the calculated yield with respect to the measured yield is present at $\Delta\theta=130°$. It should be noted that experimental data for secondary angles θ_2 of 135° and 145° are probably[19] dominated by sequential decay of states in ^{12}C which are inelastically excited. In fact, the peaks that are observed at those angles also appear without kinematic shift at other angles and the energies are reasonably consistent with a high-resolution study[20] of the excitation of resonant states in ^{12}C.

B. Sensitivity to distorting and bound-state potentials

DWIA calculations performed with the average energy and energy-dependent potential parameter sets result in curves of very similar shape, with relatively minor changes in magnitude (the largest difference being approximately 20% in the $-20°$,20° case). This apparent insensitivity to reasonable changes in the optical-model parameters has been found by other workers for the same reaction at lower incident energy. For example, in their DWIA treatment of the ^{12}C$(p,2p)$ reaction at an incident proton energy of 100 MeV, Bhowmik *et al.*[7] studied the sensitivity of their calculations to the optical potential parameters and the bound-state wave functions. They reported that the distorted momentum distributions were

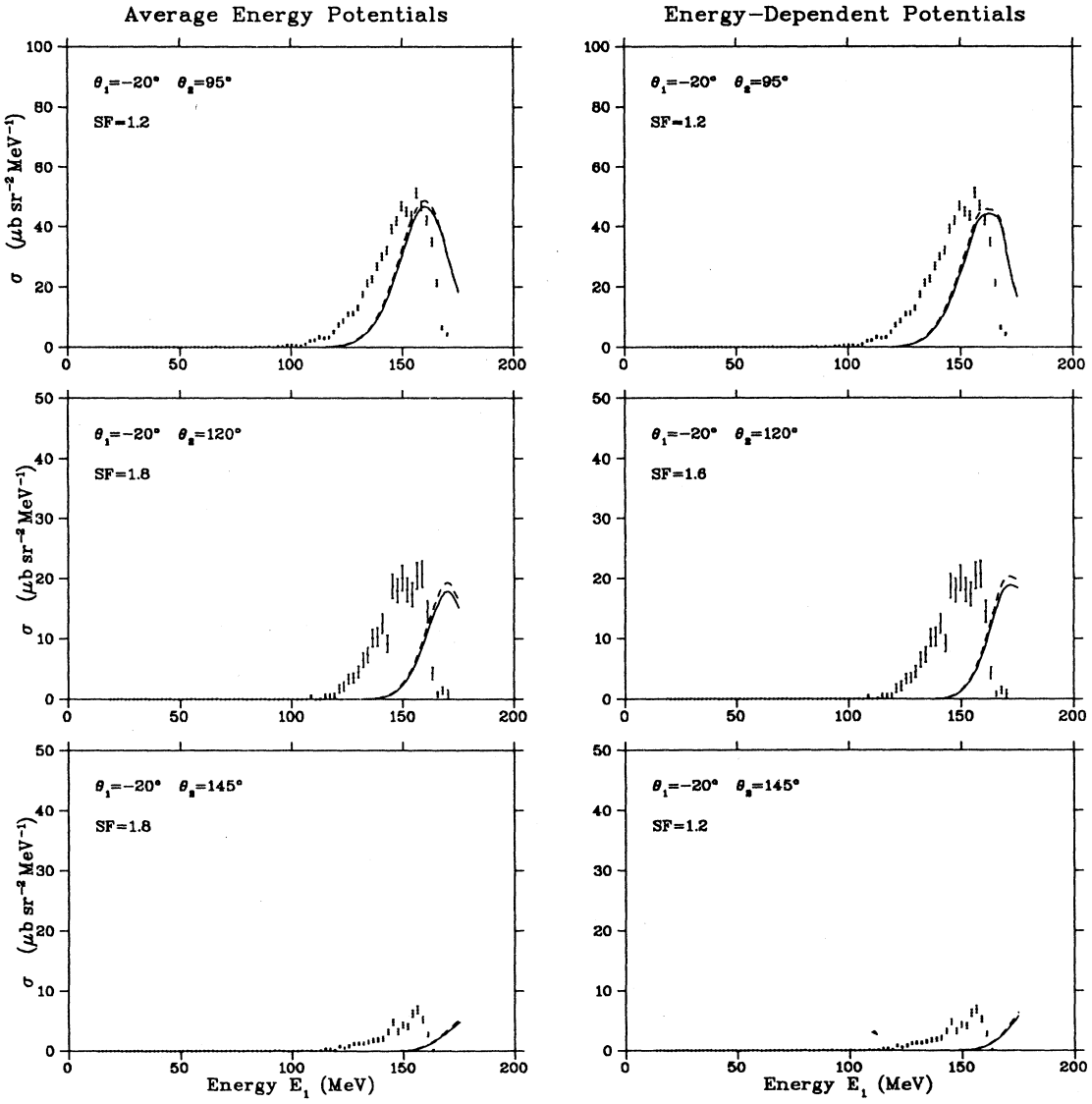

FIG. 4. Energy-sharing distributions for knockout of p-state protons from ^{12}C by incident protons of 200 MeV. See caption to Fig. 3.

independent of the optical potentials used for the incident channel and that, whereas the choice of potential for the outgoing channels affected the absolute magnitude, the qualitative shapes did not alter. In addition, they tested whether the use of ^{12}C parameters for the residual ^{11}B nucleus was reasonable by allowing parameters of the potential well for the outgoing channel to vary. It was found that variations of up to 25% in these parameters did not change the momentum distribution by more than 10%. In another experiment also at 100-MeV incident energy, Devins *et al.*[8] confirm this lack of sensitivity of the DWIA calculations to the incoming and outgoing channel parameters.

In the comparison of our spectroscopic factors with those from other work, to follow in Sec. IV E, the sensitivity to the bound state also has to be considered. For example, use of Elton and Swift[21] bound-state parameters changes the spectroscopic factor for $-45°,35°$ from 1.0 to 1.4 for the calculation with the average energy potentials. Therefore, due to our specific choice of bound-state parameters, we may expect values of spectroscopic factors $\sim 30\%$ lower than those which are based on parameters with an rms radius more consistent with the work of Elton and Swift.

C. Sensitivity to on-shell assumption

In the present study, differences between calculations performed with the IEP and FEP approximations for the two-body amplitudes are negligible, except at $-20°,20°$ where the spectroscopic factors differ by almost a factor of 2. Here the FEP approximation produces a shape giv-

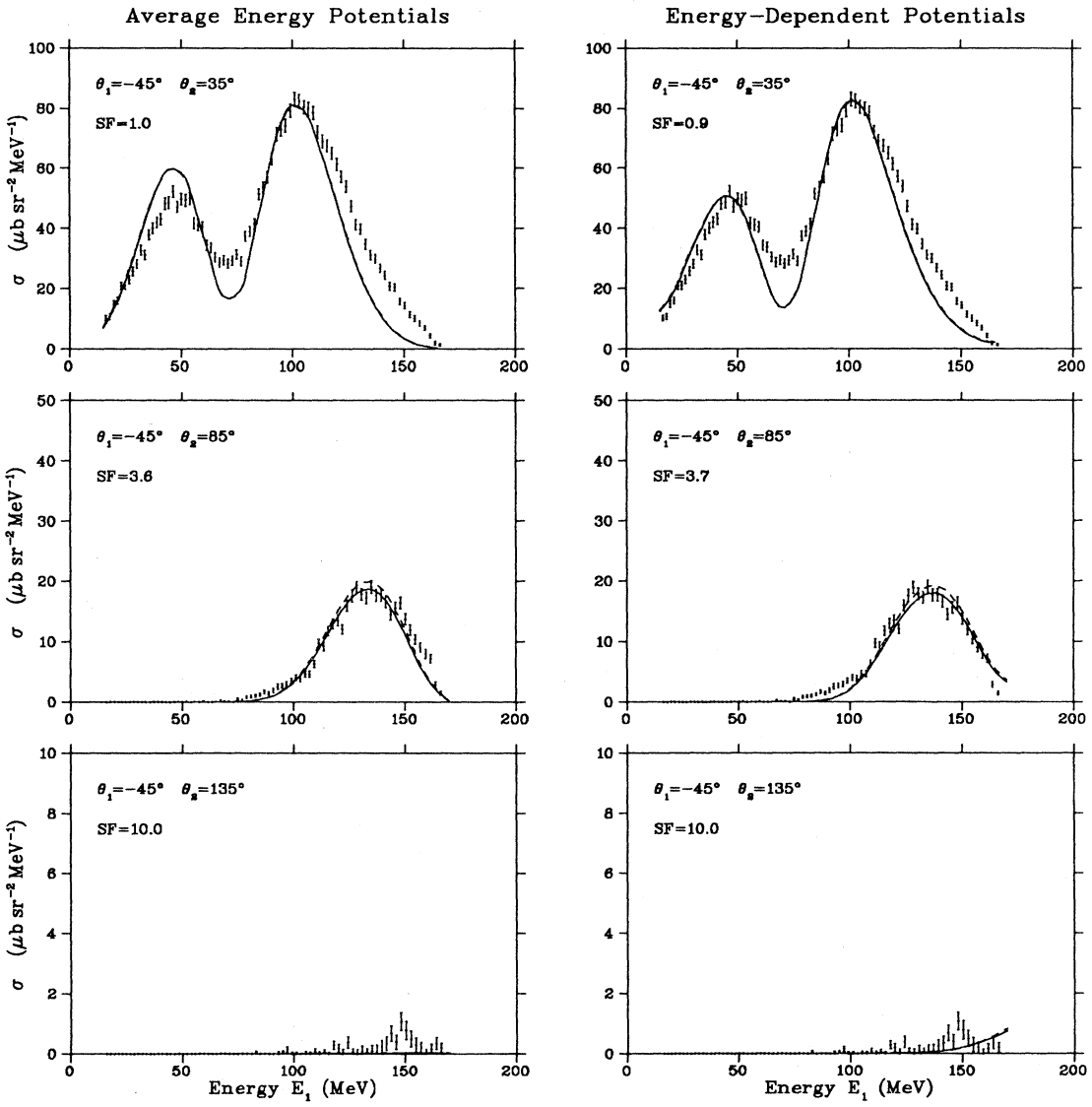

FIG. 5. Energy-sharing distributions for knockout of p-state protons from ^{12}C by incident protons of 200 MeV. See caption to Fig. 3.

ing a better fit to the measured data. This large difference in the predicted magnitudes at $-20°,20°$ could be an indication of the importance of the off-shell effects and the inadequacies[22] of the on-shell approximations for the two-body scattering in the DWIA treatment, particularly as the binding energy of the outer shell $1p_{3/2}$ proton in ^{12}C is relatively large (~ 16 MeV). The IEP and FEP approximations are believed[23] to represent the extreme cases, whereas a more accurate half-off-shell prescription is expected to lie between the two limits.

D. Corrections to the DWIA calculations

The implications of ignoring spin-orbit effects have been investigated in other studies[13,24] and we confirm that, except for $-20°,20°$, their inclusion does not affect our calculated cross sections appreciably, as may be seen by comparing the distributions of Figs. 3 to 5 with those of Fig. 6. However, even without inclusion of spin-orbit effects, the effective polarization[25] of the struck p-shell proton affects the cross sections by a factor[24] involving the product of this polarization and the two-body analyzing power. Our calculations indicate that the inclusion of this factor would change the cross sections by less than 5%.

Our investigation of nonlocality corrections was motivated by experimental studies of quasifree knockout in the ^{16}O$(p,2p)$ reaction. The extracted spectroscopic factor from the work performed at an incident energy of 200 MeV (Ref. 26) was found to be a factor of 2 smaller than that from the work performed at 100 MeV (Ref. 24). This discrepancy could not be fully explained with certainty. In the former (200 MeV) work, the factor was found to be 0.7 times that of the shell model expectation. In an attempt to resolve the problem of the DWIA-predicted cross sections being too large, Kitching *et al.*[26] considered the intrinsic nonlocality of the nucleon-nucleon potential by including a nonlocal component in the optical-model potential. This was parametrized by a range parameter in their DWIA code, and resulted in a reduction of the predicted $(p,2p)$ cross sections by between 20% and 50%. In this work, the DWIA calculations were repeated with the average-energy set of optical potentials and the inclusion of a nonlocal component (which had been neglected thus far in our previous calculations). In Fig. 6 the results of some of these calculations, in which a nonlocal range parameter of 1.15 fm was used, are compared with the experimental data. The value of the range parameter is somewhat larger than that normally employed (typically 0.85 fm), but was used in this study as it had been found to give a better fit to the 200 MeV ^{16}O$(p,2p)$ data.[27] In the kinematic region of interest in the continuum decay study of I, spectroscopic factors were found to vary by less than 20% for all the coincident angle pairs when the nonlocal component was included. Changes in the shape of the cross-section distributions were negligible. Consequently, based on a comparison of Figs. 3 to 5 with Fig. 6 it is estimated that

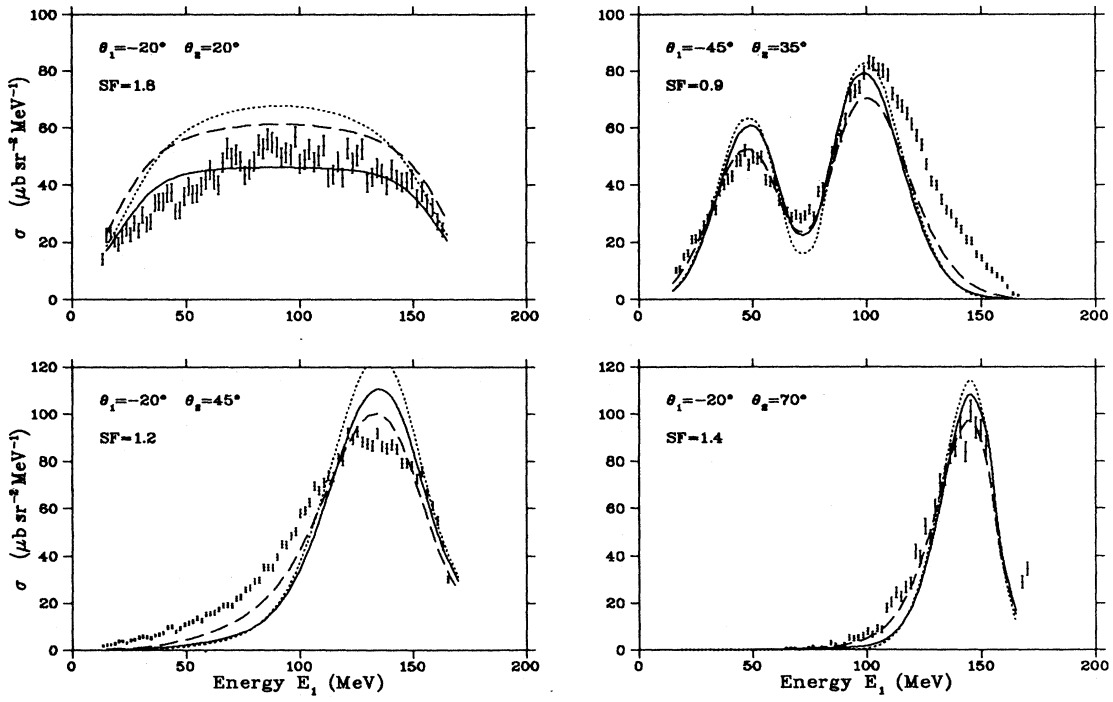

FIG. 6. Energy-sharing distributions for knockout of p-state protons from ^{12}C by incident protons of 200 MeV for some of the coincident angle pairs. Measured cross sections are shown with statistical error bars. The continuous curves are DWIA calculations for the FEP with the same average energy set of potentials as previously (Figs. 3 to 5) with both spin orbit and nonlocality included. Spin orbit only: dashed curves; nonlocality only: dotted curves. Spectroscopic factors are indicated.

neglect of spin orbit and nonlocality effects may result in an extracted spectroscopic factor which is lower by $\sim 10\%$, as the two effects mostly cancel.

E. Comparison of extracted spectroscopic factors

The extracted spectroscopic factors which were used to normalize the calculated cross sections to the data indicate a tendency to increase with the angle of the secondary proton. DWIA analyses of continuum yields from the inclusive $^{12}C(p,p')$ reaction at incident energies of 150 MeV (Ref. 17) and 90 and 200 MeV (Ref. 16) in which the calculated DWIA cross sections were integrated over the solid angle of the unobserved particle, also found an increasing trend in the value of the spectroscopic factors with scattering angle between 20° and 75°.

If we disregard the data at larger secondary angles ($\Delta\theta > 120°$), where the DWIA predictions appear to be less convincing, average values for the spectroscopic factors of 1.15 and 1.00 are obtained from calculations using the average energy and energy-dependent potential sets respectively (and the FEP approximation). These values are compared in Table I with results obtained from other experimental and theoretical work.

In a high-resolution measurement of the $^{12}C(p,2p)$ reaction at an incident proton energy of 100 MeV (overall summed proton energy resolution of 330 keV), Devins *et al.*[8] extracted spectroscopic factors from DWIA calculations for all states in the residual ^{11}B nucleus below 7-MeV excitation. They divided their data into two sets of five angle pairs each, the first set being for symmetric geometry ($\theta_1 = -\theta_2; E_1 = 41.35$ MeV) and the second for asymmetric geometry ($\theta_1 = 25°; \theta_1 \neq |\theta_2|, E_1 = 59.5$ MeV). It was found that for the symmetric geometry data, the summed spectroscopic factor for the $l=1$ states was equal to 2.66, while for the asymmetric data the sum was equal to 1.33. Most of the strength was due to the ground state ($\frac{3}{2}^-$) contribution (2.0 and 1.0, respectively), and the majority of the remainder to $l=1$ knockout to the 2.125 MeV ($\frac{1}{2}^-$) and 5.020 MeV ($\frac{3}{2}^-$) excited states. Devins *et al.* concluded that their results did not indicate large admixtures of $1f$ components in the ground-state wave function of ^{12}C, as had been previously postulated.[28] The difference in spectroscopic factors extracted from the symmetric and asymmetric sets was interpreted as a failure of the DWIA treatment to predict adequately the rapid falloff of the transition amplitude for single-step knockout. In the present study, the summed proton energy resolution was of the order of 4 MeV, thus knockout to the individual states in the residual nucleus could not be distinguished. Our average spectroscopic factors are reasonably close to the asymmetric values found by Devins *et al.*, but no clear difference is found within our own results for geometries which are asymmetric compared with those for approximately symmetric configurations.

In an earlier measurement of the $^{12}C(e,e'p)$ reaction Mougey *et al.*,[29] using a DWIA treatment, extracted spectroscopic factors of 2.5 and 1.0 for the knockout of a proton from the $1p_{3/2}$ and $1s_{1/2}$ orbitals respectively. A similar study of the same reaction by Ulmer *et al.*[30] found average occupation numbers of 4.04 and 1.28 for the p and s shells, respectively, although some doubt has been expressed[31] concerning the general applicability of these values due to the limited momentum region sampled in their experiment. In recent high-resolution $^{12}C(e,e'p)$ knockout measurements,[32] it was found that spectroscopic strengths were reduced by more than 40% compared with those predicted by the independent-particle model. In the latter, coupled-channel effects were included in the analysis of the experimental data, which resulted in summed spectroscopic factors for the three $l=1$ states of 2.18 (1.72 for the $\frac{3}{2}^-$ ^{11}B ground state). Several weak transitions to excited states consistent with direct knockout from orbitals above the $1p$ shell of ^{12}C were observed, but the extracted strengths are such that these are unimportant in the present study: fits to the data using DWIA calculations for $1f_{7/2}$ and $2s_{1/2}$ direct knockout gave spectroscopic factors of 3.8×10^{-3} and 8.1×10^{-3}, respectively, whereas a coupled-channel calculation resulted in a value of 6.1×10^{-4} for the $1f_{7/2}$ state (this discrepancy in the derived spectroscopic factors was attributed to interference between direct and two-step channels).

F. Applicability of DWIA to coincident continuum calculations

As pointed out previously, the primary interest in the $^{12}C(p,2p)$ quasifree knockout reaction in the present study is its role as the initial step in the assumed reaction mechanism for the production of the continuum yield. For the necessary calculations described in I to be performed, DWIA cross sections for $(p,2p)$ knockout were required for the proton detected at the primary angle with kinetic energies E_1 of 70, 100, and 130 MeV. From the fits to the data in Figs. 3 to 5 it can be seen that, at these energies, the DWIA calculations give good agreement with the shape and magnitude of the measured data

TABLE I. Spectroscopic factors.

Reaction	Reference	^{11}B(g.s.)$J^\pi=\frac{3}{2}^-$	^{11}B(2.12 MeV)$J^\pi=\frac{1}{2}^-$	Sum $\frac{1}{2}^-;\frac{3}{2}^-$
$(p,2p)$	This work			1.1
$(p,2p)$	8	2.0	0.33	2.33
$(p,2p)$		1.0	0.20	1.20
$(e,e'p)$	29			2.5
$(e,e'p)$	32	1.72	0.26	1.98
Theory	33	2.85	0.75	3.60

with a consistent value for the spectroscopic factor. The fact that the absolute value of the spectroscopic factor is lower than that which might be expected as a result of $^{12}C(p,2p)$ experiments performed at other energies should have no detrimental impact on the application of this DWIA treatment in an understanding of the coincident continuum yield reported in I. In those regions of this study where the DWIA calculations and spectroscopic factors are less satisfactory, the contribution of the quasifree knockout yield at the three energies of interest is negligible.

V. SUMMARY AND CONCLUSION

Coincident proton energy spectra were measured at a wide range of coincident angle pairs, covering a larger region of phase space than that usually selected in knockout studies, with a binding energy and energy resolution of approximately 4 MeV. The primary protons (that is, the protons assumed in I to be scattered without further secondary interactions) were observed at angles θ_1 of $-20°$ and $-45°$. The corresponding angles (θ_2) at which the coincident secondary protons were observed were 20°, 45°, 70°, 95°, 120°, and 145° (for $\theta_1 = -20°$), and 35°, 85°, and 135° (for $\theta_1 = -45°$).

As a test of the applicability of the DWIA treatment the kinematic regions of the coincident proton spectra corresponding to the knockout of protons mainly from the outer $1p_{3/2}$ orbital of ^{12}C were studied. The DWIA cross-section distributions were found to reproduce well the shapes of the experimental cross sections as a function of the energy of one of the quasifree protons, except that energy shifts between the two distributions were apparent at extreme geometries.

Normalization of the absolute magnitudes of the calculated distributions to the experimental energy-sharing distributions (disregarding the extreme geometry measurements) gave an average spectroscopic factor of 1.1 ± 0.3. This tends to be lower than the values of 1.2 and 2.3 obtained in a high-resolution $^{12}C(p,2p)$ measurement at 100-MeV incident energy by Devins *et al.*[8] for asymmetric and symmetric geometries, respectively, the values of 2.0 to 2.5 obtained in $^{12}C(e,e'p)$ knockout experiments[32,29] and the value of 3.6 from a shell model calculation.[33]

The present study found no significant differences (a maximum of approximately 20% for the $-20°,20°$ geometry case) in the predicted cross sections with two different realistic (average-energy and energy-dependent) optical potential parameter sets. In addition, the DWIA treatment was found to be insensitive to the choice of the initial or final energy prescriptions for the two-body scattering approximation, except in the $-20°,20°$ case.

The DWIA calculations were repeated with the inclusion of a nonlocal component and spin-orbit potentials. Changes in the shapes of the cross section distributions were found to be negligible, and absolute magnitudes were found to change by less than 20% in the kinematic region of interest to the continuum decay study of I.

The spectroscopic factors extracted from the experimental data for $(p,2p)$ knockout appear to be too low. Although the reasons for this are not immediately manifest, the range of extracted values is still reasonable. Furthermore, the fact that the trend of lower than anticipated spectroscopic factor was also found in other work at 200 MeV warrants further study.

It is concluded that the DWIA is reasonably consistent with the quasifree knockout data. This implies that it is indeed appropriate for modeling the initial quasifree nucleon knockout process as needed in I to account for the features of the continuum coincidence spectrum.

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