# The ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p}){ }^{11} \mathrm{~B}$ Reaction at $100 \mathrm{MeV}^{*}$ 

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## Abstract

The ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p}){ }^{11} \mathrm{~B}$ reaction has been measured at 100 MeV in both symmetric and asymmetric geometries. Distorted wave impulse approximation calculations were used to obtain spectroscopic factors for all states of ${ }^{11} \mathrm{~B}$ below 7 MeV excitation. From these spectroscopic factors and the shapes of the measured angular correlations, it is concluded that (i) no large if components are present in the wavefunction of the ground state of ${ }^{12} \mathrm{C}$ and (ii) this experiment gives no evidence for the formation of giant resonances as the intermediate step in multistep reaction processes to the 4.44 MeV $\left(5 / 2^{-}\right)$and $6.74 \mathrm{MeV}\left(7 / 2^{-}\right)$states of ${ }^{11} \mathrm{~B}$.

## 1. Introduction

The availability of high resolution, high duty factor, intermediate energy light ion beams from the Indiana University Cyclotron Facility (IUCF) is making possible the extension of detailed nuclear spectroscopic studies into the $100-200 \mathrm{MeV}$ proton energy range. Such studies have heretofore been possible with lower energy accelerators, but are now being reported at intermediate energies (Adams et al. 1977; Henderson et al. 1979, present issue pp. 411-14).

In the past there has been some tendency to assume that the standard reaction analysis codes used at lower energies would be applicable at the higher energies now available from the IUCF, after proper modification to include more partial waves. However, these codes, notably distorted wave Born approximation (DWBA) formulations, are based on several approximations, the validity of which at higher energies has not been established. Even reaction mechanism formulations which are believed to be useful at intermediate energies, such as the distorted wave impulse approximation (DWIA), have not been rigorously tested (Chant and Roos 1977). Implicit in these formulations is the restriction that the transition from a particular initial state to a particular final state proceeds only by means of a single reaction channel. This restriction is relaxed somewhat by the use of a coupled channels Born approximation (CCBA) (Iano and Austern 1966).

The importance of two-step processes in direct reactions has long been recognized (Penny and Satchler 1964). However, the energy dependence of such processes is not clear. A priori one would expect that, as the bombarding energy is increased, the

[^0]reaction mechanism would tend more and more closely to a direct reaction; that is, two-step processes should decrease in importance. However, some evidence from single-nucleon transfer reactions (Källne and Obst 1977) suggests that two-step processes may actually become more important with increasing energy. This effect may be simply a consequence of momentum matching requirements rather than an indication of the energy dependence of two-step processes (Redish 1977).

Several recent studies, analysed using CCBA, have achieved a degree of success in understanding two-step processes (Kunz and Rost 1974; Didelez et al. 1976; Burch et al. 1978). The strong absorption of, and the possibility of excitation of, the composite particles used in these studies make the interpretation of the CCBA calculations difficult. Problems of this sort can be avoided by using proton knockout as the spectroscopic probe. There exists, however, no general distorted wave code which includes two-step processes for the analysis of knockout reactions in analogy to the CCBA for transfer reactions.


Fig. 1. Energy levels of ${ }^{12} \mathrm{C}$ and ${ }^{11} \mathrm{~B}$ appropriate to the present discussion of the ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p}){ }^{11} \mathrm{~B}$ reaction.

Even though a quantitative assessment of the two-step component of a knockout reaction at intermediate energies is currently not possible, it is possible to seek insight into the nature of the intermediate states by varying the kinematic conditions of that reaction. A unique property of the knockout reaction is that the energy of one outgoing particle and the overall momentum transfer $p_{3}$ to the residual nucleus may be varied independently over a wide range, including $p_{3}=0$. In addition, for the high resolution work described in this paper, the DWIA can be applied to the angular correlations of outgoing protons leaving the residual nucleus in various excited states to extract spectroscopic factors which can be compared with different model calculations.

The ${ }^{12} \mathrm{C}$ nucleus is attractive to use as a target for studies of two-step mechanisms in knockout reactions for several reasons. It has well-known and well-separated discrete states (Ajzenberg-Selove 1975); see Fig. 1. Its low-lying states are well
reproduced by shell model calculations (see e.g. Cohen and Kurath 1967); indeed, nuclei in this mass region are light enough for extended shell model calculations to be carried out. The odd-parity states of the residual nucleus ${ }^{11} \mathrm{~B}$ are fairly well understood in terms of the unified model (Cavaignac et al. 1975; see also Fig. 1). Of these odd-parity states, the states at $4.44 \mathrm{MeV}\left(5 / 2^{-}\right)$and $6 \cdot 74 \mathrm{MeV}\left(7 / 2^{-}\right)$cannot be excited in a one-step reaction process (see the fuller discussion in Section 3 below). On the other hand, all states that can be formed by direct one-step proton knockout can also be formed through a variety of multistep mechanisms.

A high resolution measurement of the ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p})^{11} \mathrm{~B}$ reaction has been made at 50 MeV bombarding energy by Pugh et al. (1967). This experiment, carried out in symmetric coplanar geometry, showed strong population of the $4.44 \mathrm{MeV}\left(5 / 2^{-}\right)$ state; in magnitude this population was comparable with that of the 'allowed' 5.02 $\mathrm{MeV}\left(3 / 2^{-}\right)$state. Unfortunately, the angular correlations reported for the 4.44 MeV $\left(5 / 2^{-}\right)$and $5.02 \mathrm{MeV}\left(3 / 2^{-}\right)$states were obtained by summing over all the available phase space, and therefore are not directly comparable with those of other states. A repetition of this symmetric geometry experiment (for which $E_{1}=E_{2}$ ) at 100 MeV with resolution good enough to separate the 4.44 and 5.02 MeV final states yields qualitative information on the energy dependence of the two-step processes involved. Further, by making this measurement also in an asymmetric mode (for which $E_{1} \ll E_{2}$ ) it should be possible to deduce some features of the one-step to two-step reaction mix.

This paper reports the results of measurements such as those just described, in both symmetric and asymmetric geometries. The experimental details are given in Section 2, a fuller discussion of the interrelationship between nuclear structure and the reaction mechanism is included in Section 3, and the results are presented and discussed in Sections 4 and 5.

## 2. Experimental Details

A $98.7 \pm 0 \cdot 2 \mathrm{MeV}$ proton beam from the Indiana multistage separated sector cyclotron was directed onto $2 \cdot 1 \mathrm{mg} \mathrm{cm}^{-2}$ self-supporting natural carbon foils in the 60 cm QDDM-spectrograph scattering chamber. The momentum-analysed beam was focused to a 1.5 by 2 mm spot at the target, and had an energy resolution of about 80 keV , as deduced by scattering from a thin CH foil. Beam currents varied from 50 to 300 nA .

The outgoing protons were detected in coincidence in a coplanar geometry by the spectrograph-focal-plane system (Officer et al. 1975) in one arm and by a detector telescope in the other. Details of the detection system have been given elsewhere (Friesel et al. 1977a, 1977b). In the symmetric geometry, with the spectrograph angle $\theta_{\mathrm{s}}$ and telescope angle $\theta_{\mathrm{t}}$ given by $\theta_{\mathrm{s}}=\theta_{\mathrm{t}}=\theta$, data were taken at $\theta=30^{\circ}, 40^{\circ}, 47^{\circ}$, $55^{\circ}$ and $65^{\circ}$. For this case the spectrograph was set to detect protons of energy $E_{\mathrm{s}}=41 \cdot 35 \pm 1 \cdot 25 \mathrm{MeV}$. In the asymmetric geometry $\theta_{\mathrm{s}}$ was fixed at $25^{\circ}$ and data
were taken were taken at $\theta_{\mathrm{t}}=30^{\circ}, 45^{\circ}, 66^{\circ}, 75^{\circ}$ and $90^{\circ}$. For this case the spectrograph was set to detect protons of energy $59 \cdot 5 \pm 1 \cdot 8 \mathrm{MeV}$. In both cases the detector solid angles were $\theta_{\mathrm{s}}=2.1 \mathrm{msr}$ and $\theta_{\mathrm{t}}=3.5 \mathrm{msr}$ for the spectrograph and detector telescope respectively. The horizontal and vertical acceptance angles, were for the telescope, $\theta_{\mathrm{tH}}=4.5^{\circ}$ and $\theta_{\mathrm{tV}}=4^{\circ}$ and, for the spectrograph, $\theta_{\mathrm{sH}}=2 \cdot 4^{\circ}$ and $\theta_{\mathrm{sV}}=4^{\circ}$. The effect of momentum averaging, because of the finite angular openings, was calculated using the computer program момrath (P. G. Roos, personal communication) and
found to contribute less to the overall resolution than other effects. The contributions to the resolution obtained in the summed energy spectrum were as follows.

| Beam energy spread | 80 keV |
| :--- | ---: |
| Momentum averaging | 50 keV |
| Target thickness | 300 keV |
| Energy summing procedure | 100 keV |
| Electronic noise | 30 keV |
| Overall resolution | 330 keV |



Fig. 2. Summed energy spectrum of protons from the ${ }^{12} C(p, 2 p){ }^{11} B$ reaction at a proton bombarding energy of 100 MeV . The asymmetric angles were $\theta_{\mathrm{s}}=25^{\circ}$ and $\theta_{\mathrm{t}}=75^{\circ}$.

A characteristic summed energy spectrum is shown in Fig. 2. This spectrum was taken at the asymmetric angle pair $\theta_{\mathrm{s}}=25^{\circ}$ and $\theta_{\mathrm{t}}=75^{\circ}$. Background subtraction, pulse height to energy conversion, recoil energy calculation and energy summing were done on-line using the data acquisition system GENPRP (Devins 1977). The intrinsic resolution of the experimental arrangement was measured, using the summed energy peak for scattering from hydrogen in a thin CH target, to be 152 keV . The resolution in the spectrum of Fig. 2 is 330 keV , the difference in these resolution values showing the effects primarily of target thickness and a three-point smoothing
of the data. The several small peaks in the figure are caused by $(p, 2 p)$ reactions in the contaminants ${ }^{16} \mathrm{O}$ and ${ }^{13} \mathrm{C}$, event loss by inelastic excitations in the silicon counters (Makino et al. 1970) and the residue from background subtraction.

Dead-time effects were monitored in part by a pulser system, and in part by observation of zero contents in one or more ADCs for coincident events. This is possible because the coincidences are determined before the event pulses reach the ADCs. If one particular pulse does not reach the appropriate ADC because of dead-time effects, then that ADC records an event in channel zero. The correction factors for dead time averaged $1 \cdot 33$ and never exceeded $1 \cdot 45$.

## 3. Relationships between Reaction Mechanism and Nuclear Spectroscopy

In discussing the experimental data, we shall consider as final states only those levels of ${ }^{11} \mathrm{~B}$ shown in Fig. 1. Of these states, the ground state $\left(3 / 2^{-}\right)$and the states at $2 \cdot 12 \mathrm{MeV}\left(1 / 2^{-}\right), 5 \cdot 02 \mathrm{MeV}\left(3 / 2^{-}\right)$and $6.79 \mathrm{MeV}\left(1 / 2^{+}\right)$may be populated by direct one-step knockout of a proton from the ground state of ${ }^{12} \mathrm{C}$. For the odd-parity states, this statement is based on the 1 p shell calculations of Cohen and Kurath (1967). For the $6 \cdot 79 \mathrm{MeV}\left(1 / 2^{+}\right)$state, the relevant results are those of Teeters and Kurath (1977) which indicate that this state has of the order of $10 \%$ (in intensity) of the configuration ' $1 \mathrm{~s}_{1 / 2}$-hole coupled to the ${ }^{12} \mathrm{C}$ ground state'.

The other two states noted in Fig. 1, namely those at $4.44 \mathrm{MeV}\left(5 / 2^{-}\right)$and 6.74 $\mathrm{MeV}\left(7 / 2^{-}\right)$, cannot be reached by one-step knockout reactions, according to the Cohen and Kurath (1967) calculations for those states and the ${ }^{12} \mathrm{C}$ ground state. However, these latter calculations were confined to the 1 p shell but the projected Hartree-Fock calculation of Bouten et al. (1967) gave admixtures of 1d and 1f orbitals in the ${ }^{12} \mathrm{C}$ ground state wavefunction, 'these admixtures representing some $25 \%$ of the total wavefunction'. The calculation of Bouten et al. obtained approximately the correct value for $B(\mathrm{E} 2)$ for the $4.44 \mathrm{MeV}\left(2^{+}\right)$state of ${ }^{12} \mathrm{C}$, by the inclusion of these large higher configuration admixtures in the ground state of ${ }^{12} \mathrm{C}$. It is of interest to observe whether or not the ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p})^{11} \mathrm{~B}$ reaction can validate this method of accounting for the collective properties of the $2^{+}$state of ${ }^{12} \mathrm{C}$.

If the $5 / 2^{-}$and $7 / 2^{-}$states of ${ }^{11} \mathrm{~B}$ are not populated by direct knockout from such 1f components, the only other possibility is that they are reached via multiple-step reaction mechanisms. There are two such mechanisms discussed in the literature. Firstly, Pugh et al. (1967) postulated that the excitation of the $4 \cdot 44 \mathrm{MeV}\left(2^{+}\right)$state of ${ }^{12} \mathrm{C}$ is followed by proton knockout from that state. This mechanism allows population of final states with spins and parities from $1 / 2^{-}$to $7 / 2^{-}$. Secondly, Geramb and Eppel (1973), in a calculation of the angular correlation of the protons from the ${ }^{16} \mathrm{O}(\mathrm{p}, 2 \mathrm{p}){ }^{15} \mathrm{~N}$ reaction at 45 MeV , postulated that the direct one-step process was accompanied by a two-step process involving core excitation which virtually excited the E1, E2 and E3 giant resonances. Such a reaction mechanism could, via one or other of the giant resonances, lead to population of final states with spins and parities up to $7 / 2^{-}$or $9 / 2^{+}$.

Thus, one cannot distinguish between the two-step reaction mechanisms discussed above on the basis of which states are, or are not, populated. A calculation including both direct and two-step reaction mechanisms may possibly show up this difference. However, no such calculation in a distorted wave formalism has been possible as yet.


Fig. 3. Experimental results for the angular correlations of the two protons from the ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p}){ }^{11} \mathrm{~B}$ reaction at 100 MeV for the (a) symmetric and (b) asymmetric geometry experiments. Also shown are the curves from the DWIA calculations of the angular correlations which gave the spectroscopic factors listed in Table 2. The full curves in both figures are for $l=1$ knockout, while the dashed curve in (b) is for $l=3$ knockout.


Fig. 3b

Table 1. Optical model parameters used in DWIA calculations of angular correlations
Parameters other than those shown were $R_{\text {Coul }}=1.2 \mathrm{fm}$ and, for the bound state, $R_{0}=1.36 \mathrm{fm}$,

| $E(\mathrm{MeV})$ | $V(\mathrm{MeV})$ | $r(\mathrm{fm})$ | $a(\mathrm{fm})$ | $W_{\text {d }}(\mathrm{MeV})$ | $W(\mathrm{MeV})$ | $r^{\prime}(\mathrm{fm})$ | $a^{\prime}$ (fm) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $100 \cdot 0$ | 19.5 | 1.02 | $0 \cdot 15$ | 0 | $6 \cdot 66$ | 1.70 | 0.216 |
| $58 \cdot 0$ | $33 \cdot 0$ | 1.08 | 0.689 | 1.0 | $5 \cdot 0$ | $1 \cdot 25$ | 0.533 |
| $42 \cdot 0$ | $40 \cdot 0$ | 1.08 | 0.689 | 3.0 | $5 \cdot 0$ | $1 \cdot 25$ | 0.533 |
| $24 \cdot 7$ | $50 \cdot 0$ | 1.08 | 0.689 | 11.0 | 0 | 1.25 | 0.533 |

## 4. DWIA Calculations

The results of DWIA calculations of the angular correlations of the two protons for both the symmetric and asymmetric geometry experiments are shown, along with the data, in Figs $3 a$ and $3 b$ respectively. The parameters used in the calculations are given in Table 1. No systematic search was attempted, as this has already been done by Bhowmik et al. (1976) at 100 MeV . We did, however, confirm the lack of sensitivity of the calculation to the incident channel parameters. The effect of varying the exit channel parameters was to make little variation in the general shape of the calculated angular correlation, although shifts in the overall magnitude did occur. These shifts in magnitude lead directly to changes in the extracted spectroscopic factors, and these are reflected in the errors assigned to the derived spectroscopic factors, which are displayed in Table 2. These errors were estimated by observation of the extent to which the normalization could be changed without seriously degrading the fit to the experimental points.

Table 2. Spectroscopic factors obtained from DWIA calculations for ${ }^{11} B$ states populated in ${ }^{12} C(p, 2 p){ }^{11} B$

| State <br> of ${ }^{11} \mathrm{~B}$ |  | Spectroscopic factors $C^{2} S$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Experimental geometry |  | Theoretical results ${ }^{\text {A }}$ |  |  |
| $E_{\text {x }}(\mathrm{MeV})$ | $J^{\pi}$ | Symmetric | Asymmetric | CK | S | K |
| g.s. | 3/2- | $2.0 \pm 0.2$ | $1 \cdot 0 \pm 0.2$ | $2 \cdot 85$ | $3 \cdot 27$ | 2.79 |
| $2 \cdot 12$ | 1/2- | $0.33 \pm 0.06$ | $0.20 \pm 0.05$ | $0 \cdot 38$ | $0 \cdot 60$ | 0.79 |
| 4.44 | 5/2- | $0 \cdot 10 \pm 0.05$ | $0 \cdot 11 \pm 0.04$ | - | - | $0 \cdot 0005^{\text {B }}$ |
| 5.02 | 3/2- | $0 \cdot 33 \pm 0 \cdot 1$ | $0.13 \pm 0.03$ | 0.75 | $0 \cdot 12$ | 0.345 |
| $6.74{ }^{\text {c }}$ | 7/2- | $0.06 \pm 0.03$ | $0 \cdot 12 \pm 0.04$ | - | - | $0.035^{\text {B }}$ |
| $6.79{ }^{\text {c }}$ | $\left.1 / 2^{+}\right\}$ | $0.05 \pm 0.02$ |  |  |  |  |

A Results from: CK, intermediate coupling calculation of Cohen and Kurath (1967); S, Singh et al. (1973); K, Kurath (1968).
${ }^{\text {B }}$ These calculations assumed f-wave knockout.
${ }^{\text {c }}$ These states were not resolved; see the text for the method of estimating their separate contributions.
In all cases, except for the 6.7 MeV peak observed in the symmetric geometry experiment, the DWIA calculation is for $l=1$ knockout. In all calculations for the symmetric geometry, the calculation consistently overestimates the size of the lefthand peak. This effect has been observed before (Bhowmik et al. 1976) and is presumed to result from the failure of the calculation to use a $t$-matrix which correctly describes the off-shell behaviour of the two-nucleon interaction (McCarthy 1976). There is no suggestion that this phenomenon depends on the orbital angular momentum of the ejected proton.

## 5. Discussion

The fact that an $l=1$ knockout calculation provides a reasonable fit for all the angular correlations (except that for the 6.7 MeV peak in the symmetric geometry experiment-to be discussed below) gives insight into the reaction mechanism. The $4.44 \mathrm{MeV}\left(5 / 2^{-}\right)$and $6.74 \mathrm{MeV}\left(7 / 2^{-}\right)$states of ${ }^{11} \mathrm{~B}$ cannot be formed by the direct $l=1$ knockout presumed in the DWIA calculation.

A direct $l=3$ knockout could populate the 4.44 and 6.74 MeV states if there is a 1 f component in the ${ }^{12} \mathrm{C}$ ground state. The angular correlation for such an $l=3$ knockout is shown by the dashed curve in Fig. 3b. Its shape is clearly inappropriate,
although a small contribution from this direct process cannot be ruled out. However, this result does indicate that large admixtures of 1 f configurations are not present in the ${ }^{12} \mathrm{C}$ ground state wavefunction. Thus these two states may be formed by, at best, a two-step process involving excited states of the target and residual nuclei. The reasonable $l=1$ DWIA fit indicates that, whatever the nature of the intermediate process, the overall angular correlation is dominated by an $l=1$ knockout.

The angular correlation for the 6.7 MeV peak in the symmetric geometry case (Fig. $3 a$ ) is fitted reasonably well by an incoherent sum of 1 p and 1 s knockout contributions in the DWIA calculation. This procedure is appropriate if both the 6.74 $\mathrm{MeV}\left(7 / 2^{-}\right)$and $6.79 \mathrm{MeV}\left(1 / 2^{+}\right)$states are assumed to be populated, but unresolved.

The angular correlation for the 6.7 MeV peak in the asymmetric geometry experiment does not appear to require a significant contribution from 1 s knockout. The curve shown for this peak in Fig. $3 b$ is for $l=1$ knockout only. This can be understood if it is assumed that the ratio of cross sections for forming the $6.74 \mathrm{MeV}\left(7 / 2^{-}\right)$and $6 \cdot 79\left(1 / 2^{+}\right)$states is different in the symmetric and asymmetric geometry experiments, the relative contribution of the 1 s knockout in the asymmetric geometry experiment being diminished by at least a factor of two. If this were the case, the contribution of 1 s knockout near the zero momentum transfer region, where it is most important, would be diminished to such an extent that it would be difficult to observe without significantly better statistical accuracy and more data points.

The calculations of s-state knockout assumed knockout of a $\mathrm{s}_{1 / 2}$ proton (consistent with the calculations of Teeters and Kurath 1977) rather than a $2 \mathrm{~s}_{1 / 2}$ proton, which would be possible if the ground state of ${ }^{12} \mathrm{C}$ contained substantial $2 \mathrm{~s}-1 \mathrm{~d}$ components. The angular correlation for knockout of a $2 \mathrm{~s}_{1 / 2}$ proton is shown by the dot-dash curve in Fig. 3a. This calculated angular correlation for knockout of a $2 \mathrm{~s}_{1 / 2}$ proton, when added to the $l=1$ knockout calculation, gave an inferior fit to the experimental data for the 6.7 MeV peak in the symmetric geometry (Fig. 3a). The extracted spectroscopic factor for $1 \mathrm{~s}_{1 / 2}$ proton knockout, which was $0.05 \pm 0.02$, is in fair agreement with the estimate of Teeters and Kurath (1977) of $0 \cdot 16$. This latter value was calculated on the basis that a significant component of the wavefunction of the $6 \cdot 79 \mathrm{MeV}\left(1 / 2^{+}\right)$state of ${ }^{11} \mathrm{~B}$ may be represented by a $1 \mathrm{~s}_{1 / 2}$ proton hole coupled to the ground state of ${ }^{12} \mathrm{C}$.

The use of a one-step DWIA calculation to extract spectroscopic factors for what is clearly, in some instances, a multistep process, may appear to be inappropriate. However, knockout to the $5 / 2^{-}$and $7 / 2^{-}$'two-step' states can be thought of as knockout from the ground state of ${ }^{12} \mathrm{C}$ modified by an intermediate step, either before or after the knockout process. Since the angular correlation shapes for these 'twostep' states are well fitted by 'one-step' calculations, the intermediate process does not appear to influence the angular correlation shape of the one-step knockout. Rather, it appears that the intermediate process acts only as an attenuator of the one-step knockout cross section. As has been noted in Section 3, the likely intermediate processes are excitations of states of the target and residual nuclei, and the models proposed look to low-lying collective states and/or giant resonance states.

Some more quantitative feeling that the intermediate states play little part in the two-step processes in this ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p}){ }^{11} \mathrm{~B}$ reaction may be gained from the simple process of overlapping the ground state wavefunction of ${ }^{12} \mathrm{C}$, less a 1 p proton, with the wavefunctions for the five lowest states of ${ }^{11} \mathrm{~B}$. A simple plane wave estimate of the transition amplitude for the ( $\mathrm{p}, 2 \mathrm{p}$ ) reaction, ignoring the possibility of multistep processes,
indicates that overlapping the wavefunctions, as described, should give to fair precision the relative spectroscopic factors for population of the five lowest odd-parity states of ${ }^{11} B$.

The ${ }^{12} \mathrm{C}$ ground state wavefunction was taken from the random phase approximation calculation of Agassi et al. (1969), and the wavefunctions for the five lowest states of ${ }^{11} \mathrm{~B}$ were taken from the Nilsson formulation given by Cavaignac et al. (1975). In performing the overlap calculation, we made the following assumptions:
(1) All the particles above the Fermi level in the ${ }^{12} \mathrm{C}$ ground state are in the $1 \mathrm{p}_{1 / 2}$ state. The calculation of Agassi et al. (1969) indicates that over $80 \%$ of them are, so that little error is introduced by this assumption.
(2) The ${ }^{12} \mathrm{C}$ ground state wavefunction is given in shell model terminology, while the ${ }^{11} \mathrm{~B}$ wavefunctions are written in terms of Nilsson wavefunctions. To make the overlap, it is assumed that the shell model $\left(1 \mathrm{p}_{1 / 2} 1 \mathrm{p}_{3 / 2}\right)_{J=2}$ can be equated with the Nilsson term $|2 x y\rangle$, where the angular momentum 2 is that of the core state and $x$ and $y$ are the projections on the nuclear symmetry axis of the hole angular momentum and the total nuclear angular momentum respectively.
(3) No knockout contribution leads to the $|4 x y\rangle$ components of the ${ }^{11} \mathrm{~B}$ state wavefunctions. Specifically, the $14 \cdot 08 \mathrm{MeV}\left(4^{+}\right)$state of ${ }^{12} \mathrm{C}$ does not participate in the reaction as an intermediate state.

Table 3. Comparison of relative spectroscopic factors for ${ }^{11} \mathrm{~B}$ states
The spectroscopic factors extracted from the symmetric geometry experiment are compared here with those given by the overlap calculation described in Section 5 The calculated value for the transition to the ground state was normalized to 2.0

| ${ }^{11} \mathrm{~B}$ final state |  | Relative spectroscopic factors |  |
| :--- | :---: | :---: | :---: |
| $E_{\mathrm{x}}(\mathrm{MeV})$ | $J^{\pi}$ | Symmetric geometry experiment | Overlap calculation |
| g.s. | $3 / 2^{-}$ | 2.0 | 2.0 |
| $2 \cdot 12$ | $1 / 2^{-}$ | 0.33 | 0.37 |
| 4.44 | $5 / 2^{-}$ | 0.1 | 0.15 |
| 5.02 | $3 / 2^{-}$ | 0.33 | 1.08 |
| 6.74 | $7 / 2^{-}$ | 0.06 | 0.25 |

The results of such a calculation are shown in Table 3. It is concluded that overlapping the wavefunctions as described does indeed give a fairly good representation of the relative spectroscopic factors. The exception is that for the 5.02 MeV state of ${ }^{11} \mathrm{~B}$; a possible explanation is that one-step and multistep mechanisms interfere destructively in the reaction leading to this state, but interfere constructively in populating the ground and $2 \cdot 12 \mathrm{MeV}$ states of ${ }^{11} \mathrm{~B}$.

If the preceding qualitative conclusion is accepted, then it follows that in the asymmetric geometry experiment the dominant effect is the reduction of the amplitude of the single-step direct knockout process relative to that given by the DWIA calculation. The reduction in spectroscopic factors, as deduced from the asymmetric geometry experiment, cannot then be due primarily to enhancement of the multistep processes. In particular, the reduction in the amplitude of the direct one-step knockout process must dominate over any enhancement of two-step processes involving excitation of giant resonances as the intermediate state.

## 6. Conclusions

In the present measurement of the ${ }^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p})^{11} \mathrm{~B}$ reaction at 100 MeV bombarding energy in both symmetric and asymmetric geometry, we have been able to resolve the $4 \cdot 44 \mathrm{MeV}\left(5 / 2^{-}\right)$'two-step' state from the $5 \cdot 02 \mathrm{MeV}\left(3 / 2^{-}\right)$'one-step' state, and have deduced spectroscopic factors for the six lowest states of ${ }^{11} \mathrm{~B}$ by means of DWIA calculations. All knockout processes, save that to the $6.79 \mathrm{MeV}\left(1 / 2^{+}\right)$state, are characterized by angular correlations whose shapes are consistent with $l=1$ knockout. For the $1 / 2^{+}$state, knockout of a $1 \mathrm{~s}_{1 / 2}$ proton is indicated, in agreement with the calculations of Teeters and Kurath (1977). In particular, large contributions from $l=3$ knockout leading to the $5 / 2^{-}$and $7 / 2^{-}$states of ${ }^{11} \mathrm{~B}$ are inconsistent with these results. It is therefore concluded that large admixtures of 1 f components are not present in the wavefunction of the ground state of ${ }^{12} \mathrm{C}$. This result is in disagreement with the calculation of Bouten et al. (1967).

The spectroscopic factors deduced for the final states in the asymmetric geometry experiment fall into two categories. Those states which can be reached by one-step knockout of a proton from the ${ }^{12} \mathrm{C}$ ground state were found to have spectroscopic factors which were 1.5-2 times smaller than those deduced from the symmetric geometry experiment. Those states of ${ }^{11} \mathrm{~B}$ which can be reached only by multistep processes were found to have approximately the same spectroscopic factors as were deduced from the symmetric geometry experiment. This result is interpreted as evidence that, in the $100 \mathrm{MeV}^{12} \mathrm{C}(\mathrm{p}, 2 \mathrm{p})^{11} \mathrm{~B}$ reaction leading to $1 / 2^{-}, 3 / 2^{-}$and $1 / 2^{+}$ final states, the transition amplitude for single-step knockout falls faster than is indicated by the DWIA calculations, and that no evidence exists in these experiments for giant resonance formation as the intermediate step of a two-step process.

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