Two-step processes and short-range correlations in the reaction $^{12}C(\gamma,p)$

G. van der Steenhoven[(1)] and H. P. Blok[(1,2)]
[(1)]Nationaal Instituut voor Kernfysica en Hoge-Energiefysica, sectie K (NIKHEF-K), P.O. Box 4395, 1009 AJ Amsterdam, The Netherlands
[(2)]Department of Physics and Astronomy, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
(Received 25 April 1990)

One-nucleon knockout calculations have been performed for the reaction $^{12}C(\gamma,p)^{11}B$ at incident photon energies of 60, 80, and 100 MeV. Both two-step processes and high-momentum components in the single-nucleon wave function due to short-range correlations have been included. It is shown that direct knockout leading to the ^{11}B ground state followed by inelastic excitation of the $\frac{7}{2}^-$ state at 6.743 MeV in ^{11}B exceeds the direct excitation of this state by 1 to 2 orders of magnitude. For the ground-state transition the influence of high-momentum components becomes increasingly important going from $E_\gamma=60$ to 100 MeV. Constraining the parameters entering the calculation by recently measured quasielastic $^{12}C(e,e'p)^{11}B$ data a discrepancy is found between the calculations and the data, particularly at low photon energies, which is attributed to exchange currents and random-phase approximation correlations.

I. INTRODUCTION

Quasielastic knockout reactions such as the electron-induced proton knockout reaction $(e,e'p)$ have provided detailed quantitative information on the wave functions of individual nucleons inside the nucleus.[1] Experiments on a fairly large range of nuclei[2-5] have mapped the momentum distributions of valence protons up to the Fermi momentum k_F. These distributions are well described using simple single-particle wave functions, lending support to the concept of a nuclear mean field. However, the spectroscopic factors derived from such analyses are significantly smaller than expected from mean-field calculations.[1] Moreover, unexpected strength is found at large values of the missing-energy parameter ($E_m > 60$ MeV), which cannot be due to a single-particle knockout.[6,7] It is believed that these observations are due to correlations between nucleons in the nuclear ground state, which should also yield additional strength in the proton momentum distributions beyond k_F. Presently, this part of the momentum distribution cannot be investigated with the $(e,e'p)$ reaction due to the limited duty factor available at existing intermediate-energy electron accelerators.

The photon-induced knockout reaction (γ,p) at photon energies $E_\gamma=60-100$ MeV is sensitive to initial proton momenta beyond k_F, as the mismatch between the momentum transfer ($=E_\gamma$ in this case) and the momentum of the knocked-out proton is quite large. Hence, such (γ,p) experiments could yield complementary information on the aforementioned nucleon-nucleon (NN) correlations. However, in this energy domain there are considerable uncertainties regarding the mechanism of the (γ,p) reaction. The relative importance of a quasifree direct knockout process with[8] or without[9] exchange currents and the so-called quasideuteron mechanism[10] is still under debate.[11,12] It goes beyond the scope of the present paper to resolve this issue, but it is of importance to establish which part of the (γ,p) cross section can be expected on the basis of knowledge from existing $(e,e'p)$ data. Possible differences can then be attributed to processes that do not (significantly) contribute to the $(e,e'p)$ cross section below k_F, such as meson-exchange currents, initial-state correlations due to the short-range part of the NN interaction, and final-state correlations between the continuum proton and individual hole states in the residual nucleus (random-phase-approximation-type correlations). It is the aim of this paper to employ all ingredients entering the analysis of modern $(e,e'p)$ data in calculating (γ,p) cross sections. Both the effects of two-step processes and of short-range correlations are considered. We have chosen ^{12}C as the subject of our studies in view of the high-resolution $(e,e'p)$ and (γ,p) data[2,3,13-15] that have recently become available. Particular attention will be given to the $(\frac{1}{2}^+,\frac{7}{2}^-)$ doublet at $E_x=6.8$ MeV in ^{11}B, which was excited with unexpected strength in a recent $^{12}C(\gamma,p)$ experiment.[14,15]

II. CONSISTENT $(e,e'p)$ AND (γ,p) CALCULATIONS

Previously there have been several attempts to obtain consistent descriptions of quasielastic $(e,e'p)$ data and (γ,p) data above the giant resonance region. Findlay and Owens[16] transformed $^{12}C(\gamma,p)$ and $^{12}C(e,e'p)$ cross sections to a plane-wave impulse approximation momentum distribution using a crude description of the final-state interaction. While assuming a factorized cross section for both reactions, and thus neglecting the spin-orbit interaction, they found a single curve describing both data sets. However, deviations of up to a factor of 2 remained between the curve and single data points, especially for the $(e,e'p)$ data at low momenta, i.e., below 120 MeV/c.

Boffi *et al.*[9] developed rather sophisticated direct-knockout codes for both (γ,p) and $(e,e'p)$. Their (γ,p) code[17,18] includes corrections for three effects that are thought to be negligible in $(e,e'p)$: (i) orthogonality of the initial-state and final-state wave functions, (ii) antisymmetrization of the initial-state and final-state nuclear wave functions under the exchange of any pair of nucleons, and (iii) coupling of the photon to the recoil nucleus. The resulting calculated (γ,p) cross sections are relatively close to the ^{12}C data, but the bound-state and continuum wave functions employed are not consistent with more recent (e,e') and $(e,e'p)$ data.[2] Their $(e,e'p)$ code has recently been modified[19] such that the distortion of the electron waves in the Coulomb field of the nucleus is treated in the first-order eikonal approximation. Using this Coulomb distorted-wave impulse approximation (CDWIA) code with properly checked bound-state and continuum wave functions good descriptions of recently measured $(e,e'p)$ cross sections are obtained for various nuclei.[1-4]

A third approach is due to Cavinato *et al.*[20] and Ryckebusch *et al.*,[21] who performed random-phase approximation (RPA) calculations for the (γ,p) and $(e,e'p)$ reactions on ^{12}C, ^{16}O, and ^{40}Ca. These calculations, which effectively encompass the aforementioned final-state (or RPA-type) correlations, exchange currents, and some multistep processes in the final state, describe the various (γ,p) data with a reasonable degree of success and give a fairly good account of the $(e,e'p)$ data. Compared to the Boffi approach the RPA calculations have the advantage of including the effect of giant-resonance-like proton emission processes, which is especially important in (γ,p) with its relatively low energy transfer. However, more complicated *np-nh* excitations $(n \geq 2)$ that are effectively included in the Boffi calculations through the imaginary part of the optical potential are not included in these RPA calculations, thereby leaving out an important part of the final-state interaction. Hence, there is a fundamental uncertainty in the overall normalization of the calculations with respect to the data.

The present calculations have been carried out using Boffi's (γ,p) code.[18] Compared to previous ^{12}C(γ,p) calculations with this code[18] we now have the advantage of having the results of a high-resolution ^{12}C$(e,e'p)$ experiment available.[2,3] These $(e,e'p)$ data have been analyzed with the aforementioned CDWIA code,[19] yielding a good description of the cross sections. From this analysis we take the parameters of the bound-state wave function ($r_0=1.3511$ fm, $a_0=0.65$ fm, $\lambda=25$, $r_c=1.20$ fm and a nonlocality range $\beta=0.85$ fm) and the spectroscopic factor for the transition to the ^{11}B ground state ($S_{\mathrm{g.s.}}=1.72$). The root-mean-square (rms) radius of the $1p_{3/2}$ wave function thus calculated (2.780 fm) is in agreement with rms radii obtained in magnetic elastic electron scattering off neighboring nuclei.[2] The parameters of the optical potential have been interpolated from the results of Comfort and Karp,[22] who analyzed ^{12}C(p,p) data over a wide energy range (12–183 MeV). The same method was used to obtain the optical model parameters for the $(e,e'p)$ analysis. Thus a new aspect of the present (γ,p) calculations is that they are fully consistent with existing (e,e), (p,p) and $(e,e'p)$ data.

We note that contrary to the $(e,e'p)$ analysis in the present calculation *no* nonlocality correction was applied to the proton continuum wave function. The reason for this was explained by De Forest,[23] who pointed out that the orthonormality condition between two wave functions that are solutions of an energy-dependent potential corresponds to a nonlocality correction. Hence, application of both an orthogonality correction [as is done in the (γ,p) code] and a nonlocality correction [as is done in the $(e,e'p)$ code] would amount to double counting (also see Ref. 17). This point is illustrated in Fig. 1, where two calculations of the ^{12}C(γ,p) angular distribution at $E_\gamma=80$ MeV are shown. The solid line includes corrections for orthogonality, antisymmetrization and recoil effects, while no nonlocality correction was applied to the proton continuum wave function. The dashed line was obtained with the same bound-state wave function and optical model, but none of the aforementioned corrections were applied except for a nonlocality correction of the outgoing proton wave using a range parameter $\beta=0.85$ fm. The similarity of the curves at forward proton angles confirms the assumed equivalence of orthogonality and nonlocality corrections. The difference between the two calculations at backward proton emission angles is due to the coupling of the photon to the recoil nucleus. This contribution depends on the form factor of the residual $A-1$ nucleus and therefore is relatively large in (γ,p), since the momentum transfer in this reaction is relatively small.

III. TWO-STEP PROCESSES

Two-step processes were shown to be of importance in the analysis of the ^{12}C$(e,e'p)$ experiment,[2] in particular for transitions involving knockout from an orbital above the Fermi level.[3] In the past Haider and Londergan[24]

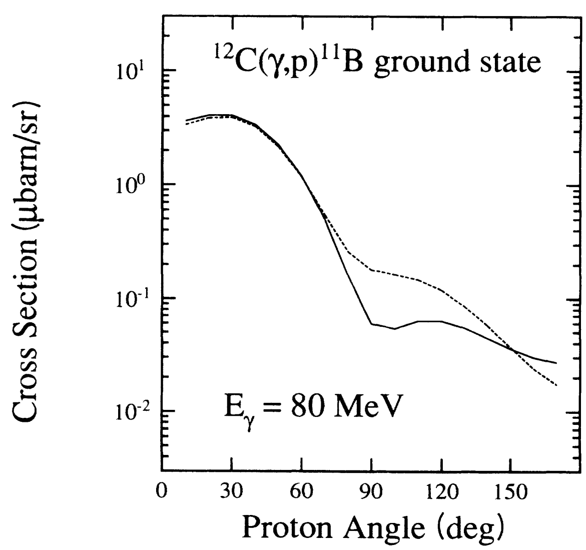

FIG. 1. Calculations of the ^{12}C(γ,p) angular distribution at $E_\gamma=80$ MeV. The solid line includes corrections for orthogonality, antisymmetrization, and c.m. recoil effects, while no nonlocality correction was applied to the proton continuum wave function. The dashed line has been obtained without the aforementioned corrections except for a nonlocality correction.

considered the effect of channel couplings in (γ,p) and (π,p) reactions in a schematic analytic approach. Although no comparison to the data could be made, they concluded that channel-coupling effects could be large even at high photon energies (200 MeV). In this paper we will use the method (outlined in Ref. 25) that was used to evaluate the effect of channel couplings in $(e,e'p)$. In this approach the $(e,e'p)$ reaction [or equivalently the $(\dot{\gamma},p)$ reaction] is simulated by a proton-pickup reaction for a very light (fictitious) particle.

The calculations have been performed with the computer code CHUCK.[26] The coupling scheme is identical to the one used in Ref. 3 and is shown in Fig. 2. It involves direct knockout from ^{12}C leading to the ^{11}B ground state followed by an inelastic excitation leading to either the $\frac{5}{2}^-$ state at 4.445 MeV or the $\frac{7}{2}^-$ state at 6.743 MeV in ^{11}B. Direct knockout of a $1f$ proton leading to either one of these states is also included. Whereas the amplitude of the $1f_{7/2}$ transition could be determined from a fit of the $(e,e'p)$ data,[3] the amplitude of the $1f_{5/2}$ transition was taken from a shell-model calculation,[27] because no measurable strength for the $\frac{5}{2}^-$ state was found in the $(e,e'p)$ experiment. The radial shape of the $1f_{5/2}$ and $1f_{7/2}$ bound-state wave functions has also been taken from Ref. 3 ($a_0=0.65$ fm, $\lambda=25$, $r_c=1.20$ fm, $\beta=0.0$ fm with $r_0=2.4840$ fm for the $1f_{5/2}$ orbital and $r_0=2.3904$ fm for the $1f_{7/2}$ orbital.[28])

The coupled-channels (CCIA) cross sections evaluated with CHUCK cannot be directly compared to measured cross sections, since the factorization (introduced by using CHUCK) is known to be a bad approximation for the (γ,p) reaction.[17] Consequently both CCIA and standard single-channel (DWIA) calculations have been carried out with CHUCK. The results found with Boffi's unfactorized (γ,p) code[18] were multiplied by the ratio of these CCIA and DWIA calculations in order to get unfactorized cross sections that include the effects of channel couplings.

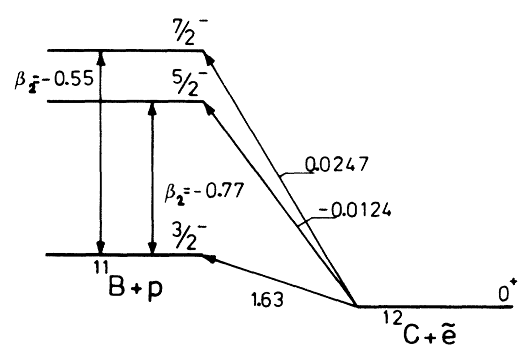

FIG. 2. Coupling scheme for the CCIA calculations of the ^{12}C(γ,p) reaction. The coupling amplitudes are indicated in the figure. The amplitude for the transition to the ^{12}C$_{g.s.}$ has been increased compared to the spectroscopic factor mentioned in the text in order to account for all knockout strength to low-lying $1p$ states in ^{11}B (see Ref. 3).

IV. SHORT-RANGE CORRELATIONS

One of the reasons for our interest in low-energy (γ,p) data stems from the possible sensitivity of this reaction to nucleon momenta beyond k_F. The influence of additional high-momentum components in the single-nucleon wave function was studied in two different approaches. The first approach involves the analysis of a recent elastic magnetic electron scattering experiment off ^{15}N at high momentum transfer.[29] The ^{15}N(e,e) data were described using a coherent sum of five $l=1$ harmonic-oscillator wave functions with different main quantum numbers. The corresponding $1p_{3/2}$ wave function for ^{12}C was obtained from the same set of harmonic oscillator wave functions, but with a different oscillator parameter b and a different overall normalization. Both parameters have been determined from a fit to the low-momentum (<340 MeV/c) part of the bound-state wave function $\phi_{1p3/2}$ used in the analysis of the ^{12}C$(e,e'p)$ experiment. The resulting overlap function $|\langle\Psi_{A-1}|\Psi_A\rangle|^2$ for the reaction ^{12}C$(\gamma,p)^{11}$B$_{g.s.}$ is displayed in Fig. 3 (dashed curve labeled $1p_{3/2}$).

In the second approach we added a high-momentum tail to the aforementioned bound-state wave function $\phi_{1p3/2}$ that gives a good account of the ^{12}C$(e,e'p)^{11}$B$_{g.s.}$ data:

$$|\langle\Psi_{A-1}|\Psi_A\rangle|^2=(1-\varepsilon_s)|\phi_{1p3/2}(p)|^2+\varepsilon_s N(p) ,$$

where the parameter ε_s determines the contribution of

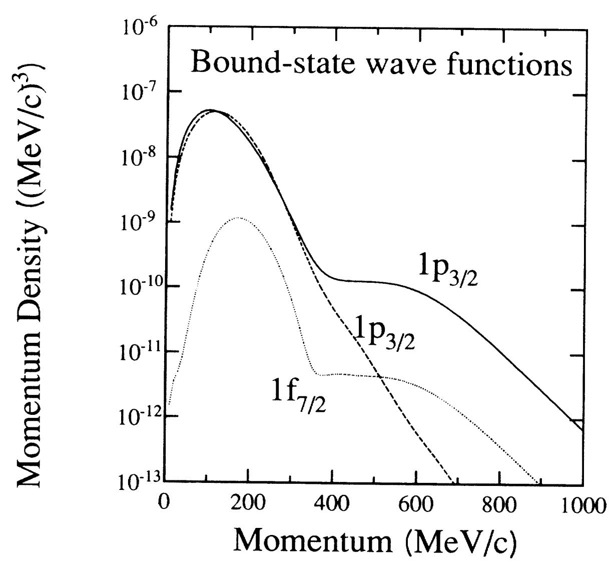

FIG. 3. Overlap of the initial and final nuclear states used in our ^{12}C(γ,p) calculations. The curves essentially represent the square of the wave function in momentum space, and thus correspond to the PWIA momentum distribution. The dashed curve was derived from the analysis of a recent ^{15}N(e,e) experiment (see Ref. 29). The low-momentum part of both the solid and dotted curves (representing the $1p_{3/2}$ and $1f_{7/2}$ wave functions, respectively) is identical to the square of the bound-state wave function used in the ^{12}C$(e,e'p)$ analysis[2,3] of each of these states, while the high-momentum part has been taken from Ref. 30.

the high-momentum tail $N(p)$ to the total overlap function. For $N(p)$ we used a simple description of nucleon high-momentum components due to short-range correlations as given by Malecki *et al.*[30] This description parametrizes results obtained by Malecki and Picchi[31] with the Jastrow correlation model. In the present calculations we used the parameters obtained by Malecki *et al.*[30] for ^{16}O ($\varepsilon_s=0.095$, $x_s=0.69$ fm, and $\gamma_s=0.15$ fm), which except for a slightly smaller value of ε_s are the same for ^{4}He. The results for both the $1p_{3/2}$ (solid curve) and the $1f_{7/2}$ (dotted curve) orbital are shown in Fig. 3. As expected the resulting wave functions only start to deviate from the pure single particle wave functions beyond 350 MeV/c. Hence, these tails do not affect the description of the $(e,e'p)$ experiment, in which only data below 230 MeV/c were obtained. We also conclude from Fig. 3 that the Malecki approach presumably overestimates the effect of short-range correlations on the overlap function.

In order to incorporate the additional high-momentum components in our DWIA calculations we have transformed the momentum-space representation of the wave functions shown in Fig. 3 to r space. The transformation is trivial for the overlap function derived from the ^{15}N(e,e) data. For the Malecki approach this has been done by expanding the total overlap function in terms of a coherent sum of 8 harmonic oscillator wave functions of the same orbital quantum number, but of different main quantum numbers.

V. RESULTS

The results of the ^{12}C(γ,p) calculations are shown in Figs. 4–7. Angular distributions are plotted for the transition to the ^{11}B ground state, the $\frac{5}{2}^-$ state at 4.445 MeV, and the $\frac{7}{2}^-$ state at 6.743 MeV. In each case calculations have been performed for three values of the incident photon energy: 60, 80, and 100 MeV. The solid curves represent direct knockout DWIA calculations using Woods-Saxon-type bound-state wave functions derived from (e,e') data, the dotted curves are calculations using overlap functions that include the effects of short-range correlations, the dot-dashed curves correspond to the CCIA calculations, while the dashed curves represent calculations that include both the effects of channel couplings and of short-range correlations. We will now discuss the three transitions separately.

Ground-state transition. The ^{12}C(γ,p) data in Figs. 4 and 5 are due to Matthews *et al.*[32] From a comparison of the solid and dot-dashed curves we conclude that channel couplings of the type depicted in Fig. 2 do not strongly affect the cross sections in the energy range between 60 and 100 MeV. Coupled-channel calculations for the ^{12}C$(e,e'p)$ reaction also revealed relatively small effects for the ground-state transition.[2] However, we observe a large discrepancy between the CCIA calculation and the experimental data at all three energies, while the corresponding CCIA calculation gave a very nice account

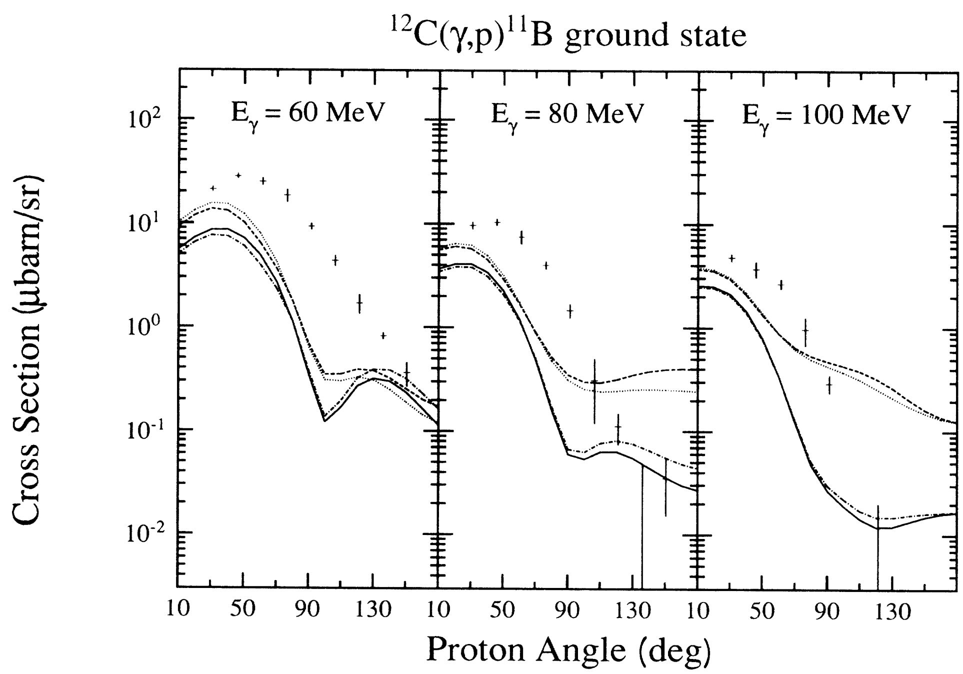

FIG. 4. Angular distributions of the reaction ^{12}C$(\gamma,p)^{11}$B$_{\rm g.s.}$ for three values of the incident photon energy 60, 80, and 100 MeV. The solid curves represent direct knockout DWIA calculations using the bound-state wave functions derived from $(e,e'p)$, the dotted curves are calculations using overlap functions that include the effect of short-range correlations [as derived from ^{15}N(e,e) data], the dot-dashed curves correspond to the CCIA calculations, while the dashed curves represent calculations that include both the effect of channel couplings and of short-range correlations.

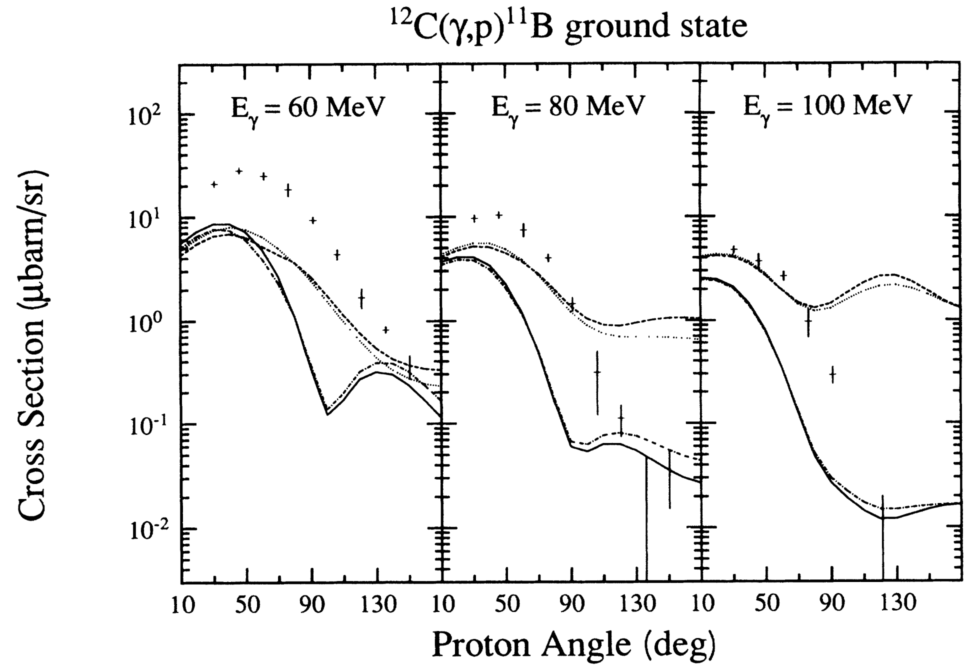

FIG. 5. Angular distributions of the reaction $^{12}C(\gamma,p)^{11}B_{g.s.}$ The curves have the same meaning as in Fig. 4, but now the Malecki approach was used to incorporate the effect of short-range correlations.

of the $^{12}C(e,e'p)$ data.[2] Hence, some mechanism contributes to the (γ,p) reaction that is absent in $(e,e'p)$. Meson-exchange currents, for instance, may be more important in (γ,p) than in $(e,e'p)$, since the former reaction is purely transverse, whereas the latter reaction is mainly longitudinal. In the standard CDWIA analysis of $(e,e'p)$ data neither exchange currents, nor final-state (RPA-type) correlations or initial-state (short-range) correlations are considered. Therefore we will consider these mechanisms as possible causes of the observed discrepan-

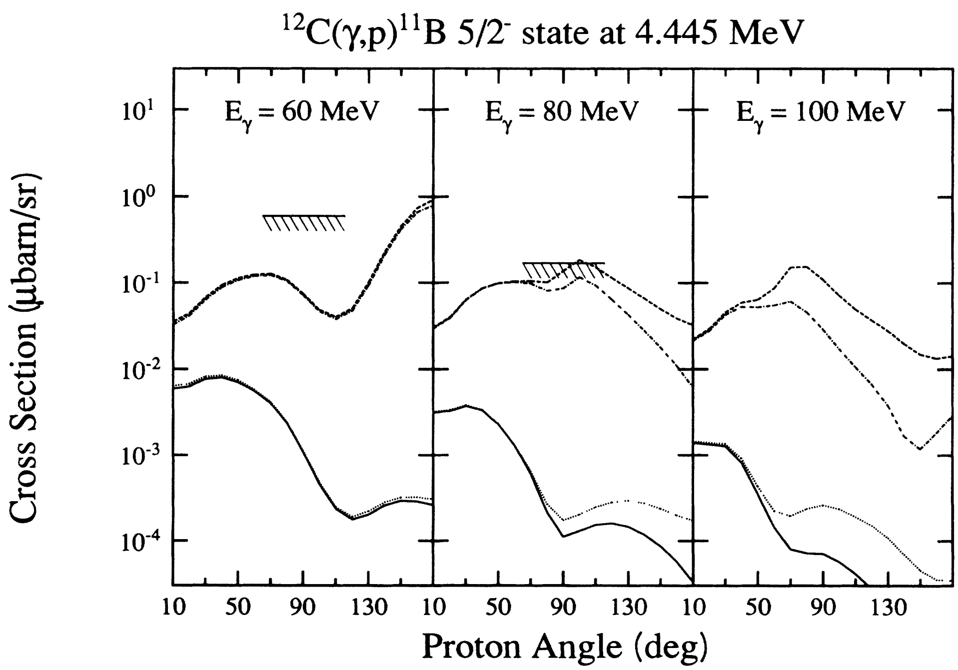

FIG. 6. Angular distributions of the reaction $^{12}C(\gamma,p)^{11}B$ leading to the $\frac{5}{2}^-$ state at 4.445 MeV in ^{11}B. The meaning of the curves is explained in the caption of Fig. 4. The Malecki approach was used to incorporate the effect of short-range correlations.

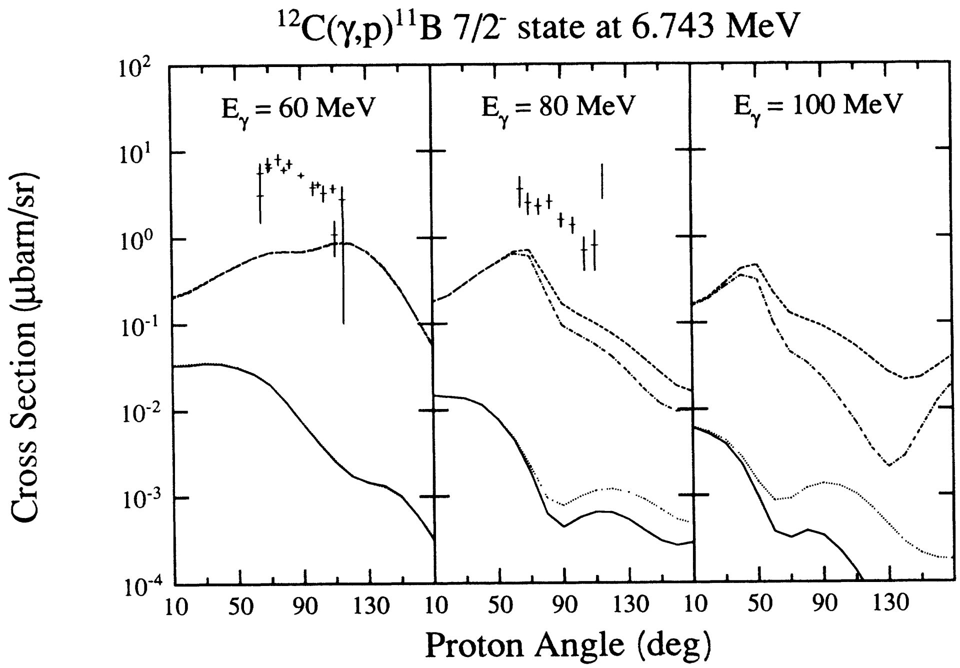

FIG. 7. Angular distributions of the reaction $^{12}C(\gamma,p)^{11}B$ leading to the $\frac{7}{2}^-$ state at 6.743 MeV in ^{11}B. The meaning of the curves is explained in the caption of Fig. 4. The Malecki approach was used to incorporate the effect of short-range correlations.

cy in the following paragraphs.

Both Cavinato *et al.*[20] and Ryckebusch *et al.*[21] attributed their reasonably successful description of the 60-MeV $^{12}C(\gamma,p)^{11}B$ and $^{16}O(\gamma,p)^{15}N$ data respectively to a combination of final-state (RPA-type) correlations and exchange currents. A subtle interference between these RPA correlations and exchange currents is also thought[12] to be responsible for the rough equivalence of the (γ,p) and (γ,n) cross sections[33] on ^{12}C and ^{16}O at 60 MeV. Cavinato *et al.*[20] demonstrated in their continuum 1p-1h RPA calculations that the role of these effects in the reaction $^{12}C(\gamma,p)$ becomes less important with increasing photon energy. Hence, it is believed that the discrepancy between the $^{12}C(\gamma,p)$ data and the CCIA calculations of Fig. 4 at low E_γ is caused by a combination of RPA correlations and exchange currents, both of which are lacking in our approach.

The role of initial-state (short-range) correlations can be investigated in a more quantitative approach as was outlined in Sec. IV. In Fig. 4 the parametrization of high-momentum components derived from the $^{15}N(e,e)$ data was used, while in Fig. 5 the Malecki approach was used. In both cases (dotted and dashed curves in Figs. 4 and 5) it is seen that short-range correlations have their largest effect at high recoil momentum, i.e., large proton emission angle and/or high photon energy. As expected the Malecki parametrization overestimates the effect of short-range correlations, since the data are well below the dotted and dashed curves beyond 100° at 80 MeV and 70° at 100 MeV, both corresponding to a recoil momentum of roughly 340 MeV/c (cf. Fig. 3). Generally, however, the inclusion of short-range correlations brings the curves closer to the data.

Since no simple procedure exists to include the effects of RPA-correlations and exchange currents in low energy (γ,p) calculations of the type presented in this paper, we conclude that detailed comparisons between $(e,e'p)$ and (γ,p) data require a relatively high photon energy ($E_\gamma \geq 80$ MeV) in order to be able to derive quantitative information on short-range correlations in nuclei. In fact, by comparing Figs. 4 and 5 it is seen that the present data, in particular at large proton emission angles, already give significant constraints on the size of the high-momentum tail of the single-nucleon wave function. However, it cannot be excluded that a destructive interference between short-range correlations and any other of the aforementioned processes may complicate the interpretation of the high-momentum data.

Transition to the $\frac{5}{2}^-$ *state at 4.445 MeV.* As was mentioned before, in the $^{12}C(e,e'p)$ reaction no measurable strength was observed for the transition to this state.[3,34] Recently, high-resolution $^{12}C(\gamma,p)$ data have become available[14,15] that do not show a significant excitation of this $\frac{5}{2}^-$ state either. From these data[15] we derived an upper limit for the cross section of this transition at both 59.7 and 78.5 MeV. These upper limits are indicated in Fig. 6.

The meaning of the curves in Fig. 6 is the same as before. For the short-range correlations the Malecki approach was used. Whereas the influence of short-range correlations is only marginal, the effect of a two-step process involving direct proton knockout from ^{12}C followed by a secondary excitation of the ^{11}B ground state leading to the $\frac{5}{2}^-$ state is very large. This was also found in CCIA calculations[3,25] for the excitation of this state in the reaction $^{12}C(e,e'p)$.

The rise of the cross section at backward angles is an interesting feature of the 60 MeV CCIA calculations. The results of the *direct* knockout calculations depend globally on the value of the missing momentum $\mathbf{p}_m$, which explains the shape of the DWIA curves. In the *two-step* calculation two vectors, $\mathbf{p}_m$ and the momentum of the outgoing proton $\mathbf{p}'$, determine the cross section. However, in this case there is no simple rule telling how the cross section as a function of energy and angle of the outgoing proton should behave. This has also been observed in the $^{12}C(e,e'p)$ calculations discussed in Ref. 3 (Figs. 6 and 7) and Ref. 25 (Fig. 2), where especially for the $\frac{5}{2}^-$ state the cross sections are shown to be strongly dependent on the kinematics of the reaction.

The 60-MeV (γ,p) data of Fig. 6 are not inconsistent with our CCIA calculations. It should be possible to verify our CCIA predictions in a new high-resolution $^{12}C(\gamma,p)$ experiment with improved statistics.

Transition to the $\frac{1}{2}^+,\frac{7}{2}^+$ *doublet at 6.8 MeV.* One of the most surprising observations in the new high-resolution $^{12}C(\gamma,p)$ experiments[14,15] using tagged photons is the unexpectedly strong excitation of this doublet containing both the $\frac{7}{2}^-$ state at 6.743 MeV and the $\frac{1}{2}^+$ state at 6.792 MeV. The corresponding cross sections are displayed in Fig. 7. In $(e,e'p)$ this doublet is also observed.[3]

Two-step processes are assumed to be much more important for the transition leading to the $\frac{7}{2}^-$ state compared to the transition to the $\frac{1}{2}^+$ state, since the former state is much more strongly excited in inelastic proton scattering off ^{11}B (see also Ref. 3). Therefore, the (γ,p) calculations in Fig. 7 only include the transition to the $\frac{7}{2}^-$ state. Inclusion of the $\frac{1}{2}^+$ transition in the CCIA (plus short-range correlations) calculations leaves the 100-MeV curve unchanged, has a minor effect on the 80-MeV curve below 40°, and leads to a relatively small increase ($<40\%$) in the 60-MeV curve below 50°.

As expected for knockout from an orbital above the Fermi level, the cross section for direct knockout from the $1f_{7/2}$ orbit in ^{12}C is very small: more than two orders of magnitude lower than the experimental data. Just as in the case of the $\frac{5}{2}^-$ state, discussed above, two-step processes lead to an enormous increase of the calculated cross section. However, there is still a factor of 5 between the calculations and the data, even when short-range correlations are incorporated in the calculations.

As there is no reason to believe why final-state (RPA-type) correlations or exchange currents act much differently for the transition to the $\frac{7}{2}^-$ state as compared to the ground-state transition, we think that the lack of these contributions in our calculations is again the most likely source of the remaining discrepancy. However, it should be pointed out that other channel couplings and a slightly different overlap wave function might also affect our results. Neither the coupling scheme, nor the wave function is very strictly constrained by the $(e,e'p)$ data in this case, as the $\frac{7}{2}^-$ state is only very weakly populated in the $(e,e'p)$ experiment.

In Ref. 14 the quasideuteron mechanism[10] was mentioned as a possible explanation of the strong excitation of the $\frac{7}{2}^-$ state in ^{11}B. At present no quantitative calculations exist that can either verify or falsify this statement. Results obtained within the quasideuteron model (QDM) need not be inconsistent with results obtained in the present approach as RPA correlations are effectively included in the QDM through an integral over the $A-1$ form factor. Moreover, exchange currents and short-range correlations are effectively included through the measured deuteron photodisintegration cross section (see Ref. 10). However, a consistent analysis of (γ,p) and $(e,e'p)$ data cannot easily be done within the QDM framework.

VI. CONCLUSIONS

Summarizing, we have calculated $^{12}C(\gamma,p)$ angular distributions for transitions leading to the ^{11}B ground state, the $\frac{5}{2}^-$ excited state at 4.445 MeV and the $\frac{7}{2}^-$ excited state at 6.743 MeV. Constraining our calculations by the results obtained in the analysis of recent $^{12}C(e,e'p)$ data, it was shown that short-range correlations give important contributions to the $^{12}C(\gamma,p)^{11}B_{g.s.}$ transition. At higher energies and backward proton emission angles the short-range correlations even dominate the cross section. Whereas two-step processes only play a minor role in the ground-state transition, they yield cross sections exceeding the direct knockout cross section by almost 2 orders of magnitude for the transitions to the $\frac{5}{2}^-$ and the $\frac{7}{2}^-$ states in ^{11}B. Remaining discrepancies between the data and the calculations are attributed to meson-exchange currents and final-state (RPA-type) correlations, in which the effect of giant-resonance-like proton emission processes is included.

In order to fully benefit from the complementary nature of (γ,p) and $(e,e'p)$ experiments, it is desirable to have high-resolution data for both reactions obtained at the same recoil momentum (or momentum mismatch p_m). This will soon be possible as 100% duty factor intermediate-energy electron accelerators come available at Mainz, MIT/Bates, and NIKHEF, where $(e,e'p)$ experiments can be carried out at $p_m > k_F$. The corresponding (γ,p) data should be taken at $E_\gamma \geq 80$ MeV (and backward angles) in order to reduce the influence of RPA correlations, which are difficult to calculate. In this way both reactions have a similar sensitivity to short-range correlations, while exchange currents will contribute to the purely transverse (γ,p) reaction but hardly to the $(e,e'p)$ reaction, which is mainly longitudinal. In this way a combined analysis of (γ,p) and $(e,e'p)$ experiments may yield quantitative information on short-range correlations and exchange currents in nuclei.

ACKNOWLEDGMENTS

We would like to thank Prof. S. Boffi, Dr. C. Giusti, and Dr. F. D. Pacati (Pavia) for making their DWIA (γ,p) codes available to us. It is gratefully acknowledged that Dr. D. Branford (Edinburgh) gave permission to use the new high-resolution $^{12}C(\gamma,p)$ data prior to publication. This work is part of the research program of the Foundation for Fundamental Research of Matter (FOM), which is financially supported by the Netherlands' Organization for Scientific Research (NWO).

[1]L. Lapikás, in *Proceedings of the Fourth Workshop on Perspectives in Nuclear Physics at Intermediate Energies, ICTP, Trieste, Italy, 1989* edited by S. Boffi, C. Ciofi degli Atti, and M. Giannini (World Scientific, Singapore, in press), p. 419; in *Proceedings of the International Conference on the Spectroscopy of Heavy Nuclei, Crete, 1989,* Inst. Phys. Conf. Ser. No. 105 (IOP Publishing, London, in press), p. 223; P. K. A. de Witt Huberts, J. Phys. G **16**, 507 (1990).

[2]G. van der Steenhoven, H. P. Blok, E. Jans, M. de Jong, L. Lapikás, E. N. M. Quint, and P. K. A. de Witt Huberts, Nucl. Phys. **A480**, 547 (1988).

[3]G. van der Steenhoven, H. P. Blok, E. Jans, L. Lapikás, E. N. M. Quint, and P. K. A. de Witt Huberts, Nucl. Phys. **A484**, 445 (1988).

[4]J. W. A. den Herder, H. P. Blok, E. Jans, P. H. M. Keizer, L. Lapikás, E. N. M. Quint, G. van der Steenhoven, and P. K. A. de Witt Huberts, Nucl. Phys. **A490**, 507 (1988).

[5]E. N. M. Quint, Ph.D. thesis, University of Amsterdam, 1988 (unpublished).

[6]R. W. Lourie *et al.,* Phys. Rev. Lett. **56**, 2364 (1986); P. E. Ulmer *et al., ibid.* **59**, 2259 (1987).

[7]L. B. Weinstein and W. Bertozzi, in *Proceedings of the Fourth Workshop on Perspectives in Nuclear Physics at Intermediate Energies, ICTP, Trieste, Italy, 1989,* edited by S. Boffi, C. Ciofi degli Atti, and M. Giannini (World Scientific, Singapore, in press); p. 386.

[8]M. Gari and H. Hebach, Phys. Rep. **72**, 1 (1981).

[9]S. Boffi, C. Giusti, and F. D. Pacati, Nucl. Phys. **A359**, 91 (1981).

[10]B. Schoch, Phys. Rev. Lett. **41**, 80 (1978); B. Schoch, H. Göringer, P. Jennewein, F. Klein, G. Lührs, and F. Zettl, Phys. Rev. C **22**, 2630 (1980); and M. R. Sené, I. Anthony, D. Branford, A. G. Flowers, A. C. Shotter, C. H. Zimmerman, J. C. McGeorge, R. O. Owens, and P. J. Thorley, Nucl. Phys. **A442**, 215 (1985).

[11]M. J. Leitch, J. L. Matthews, W. W. Sapp, C. P. Sargent, S. A. Wood, D. J. S. Findlay, R. O. Owens, and B. L. Roberts, Phys. Rev. C **31**, 1633 (1985); J. L. Matthews, in *Proceedings of the Third Workshop on Perspectives in Nuclear Physics at Intermediate Energies, ICTP, Trieste, Italy, 1987,* edited by S. Boffi, C. Ciofi degli Atti, and M. Giannini (World Scientific, Singapore, in press), p. 611; J. P. McDermott, E. Rost, J. R. Shepard, and C. Y. Cheung, Phys. Rev. Lett. **61**, 814 (1988).

[12]J. Ryckebusch, in Proceedings of the Workshop on Nuclear Physics with Real Photons below Pion Threshold, Gent, Belgium, 1989 (unpublished), p. 19.

[13]H. Ferdinande, D. Ryckbosch, E. Kerkhove, P. Berkvens, R. Van de Vyver, A. De Graeve, and L. Van Hoorebeke, Phys. Rev. C **39**, 253 (1989).

[14]A. C. Schotter, S. V. Springham, D. Branford, J. Yorkston, J. C. McGeorge, B. Schoch, and P. Jennewein, Phys. Rev. C **37**, 1354 (1988).

[15]S. V. Springham, D. Branford, T. Davinson, A. C. Schotter, J. Yorkston, J. C. McGeorge, J. D. Kellie, S. J. Hall, R. Beck, P. Jennewein, and B. Schoch, Nucl. Phys. **A517**, 93 (1990).

[16]D. J. S. Findlay and R. O. Owens, Nucl. Phys. **A292**, 53 (1977); D. J. S. Findlay, R. O. Owens, M. J. Leitch, J. L. Matthews, C. A. Peridier, B. L. Roberts, and C. P. Sargent, Phys. Lett. **74B**, 305 (1978).

[17]S. Boffi, F. Cannata, F. Capuzzi, C. Guisti, and F. D. Pacati, Nucl. Phys. **A379**, 509 (1982).

[18]S. Boffi, R. Cenni, C. Giusti, and F. D. Pacati, Nucl. Phys. **A420**, 38 (1984).

[19]C. Giusti and F. D. Pacati, Nucl. Phys. **A473**, 717 (1987); **A485**, 461 (1988).

[20]M. Cavinato, M. Marangoni, and A. M. Sarius, Nucl. Phys. **A422**, 237 (1984).

[21]J. Ryckebusch, M. Waroquier, K. Heyde, and D. Ryckbosch, Phys. Lett. B **194**, 453 (1987); J. Ryckebusch, M. Waroquier, K. Heyde, J. Moreau, and D. Ryckbosch, Nucl. Phys. **A476**, 237 (1988); J. Ryckebusch, K. Heyde, D. Van Neck, and M. Waroquier, Phys. Lett. B **216**, 252 (1989).

[22]J. R. Comfort and B. C. Karp, Phys. Rev. C **35**, 2347 (1987).

[23]T. de Forest, Jr., Nucl. Phys. **A163**, 237 (1971).

[24]Q. Haider and J. T. Londergan, Phys. Rev. C **23**, 19 (1981).

[25]H. P. Blok and G. van der Steenhoven, Phys. Rev. C **35**, 2347 (1987).

[26]P. D. Kunz, University of Colorado (unpublished).

[27]A. G. M. van Hees, A. A. Wolters, and P. W. M. Glaudemans, Phys. Lett. B **196**, 19 (1987).

[28]It is noted that the listed radius parameters r_0 have to be multiplied by a factor $(A-1)^{1/3}$ in order to get the radius at half maximum of the potential well that binds the $1f$ orbitals with the experimental binding energies.

[29]L. de Vries, private communication (1990).

[30]A. Malecki, P. Picozza, and P. E. Hodgson, Il Nuovo Cimento **101**, 1045 (1989).

[31]A. Malecki and P. Picchi, Riv. Nuovo Cimento **2**, 119 (1969); A. Malecki and P. Picchi, Lett. Nuovo Cimento **8**, 16 (1973).

[32]J. L. Matthews, D. J. S. Findlay, S. N. Gardinet, and R. O. Owens, Nucl. Phys. **A267**, 51 (1976).

[33]H. Goringer, B. Schoch, and G. Luhrs, Nucl. Phys. **A384**, 414 (1982); H. Goringer and B. Schoch, Phys. Lett. **97B**, 41 (1980).

[34]G. van der Steenhoven, H. P. Blok, J. W. A. den Herder, E. Jans, P. H. M. Keizer, L. Lapikás, E. N. M. Quint, and P. K. A. de Witt Huberts, Phys. Rev. C **32**, 1787 (1985).