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Meson exchange currents and high-resolution (γ,p) reactions

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The role of one-pion-exchange currents in intermediate-energy photonuclear reactions of the type $A(\gamma,p)B$ is studied within a mean-field approach. Calculations are presented for the $^{12}\mathrm{C}(\gamma,p)$ reaction leading to the low-lying states of $^{11}\mathrm{B}$ including states with a predominant hole character and states with a more complicated two-hole–one-particle (2h-1p) structure. The level of agreement with the data for decay to the 2h-1p states suggests the important role of meson exchange currents in (γ,p) reactions at intermediate energies.

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The prevailing reaction mechanism in (γ,p) reactions at intermediate energies has been the subject of many discussions. Mainly, the relative importance of a direct knockout reaction mechanism and the role of meson exchange currents (MEC) is under debate [1]. Experimental limitations restricted the early (γ,p) investigations to the measurement of the cross sections for the reaction to the ground state and a few isolated states in the residual $(A-1)$ nucleus. As a consequence the data were somehow restricted to reactions in which the residual nucleus is created in a state with a predominant single-hole character relative to the ground state of the target nucleus.

More recently, the advent of tagged photon facilities with a high duty cycle made high resolution (γ,p) measurements feasible. The first data were taken for $^{12}\mathrm{C}$ and some of the results came as a real surprise [2]. Some states in $^{11}\mathrm{B}$ which are weakly excited in quasielastic $(e,e'p)$ reactions were observed to be very strongly populated in the (γ,p) process. The high-resolution $^{12}\mathrm{C}(\gamma,p)$ measurements of Springham *et al.* [3] and Van Hoorebeke *et al.* [4] reported an unexpected strong feeding of an (unresolved) triplet of states ($\frac{7}{2}^-$, $\frac{1}{2}^+$, and $\frac{5}{2}^+$) around 7 MeV excitation energy in $^{11}\mathrm{B}$. Early publications quoted the 7 MeV state as a ($\frac{7}{2}^-$, $\frac{1}{2}^+$) doublet [2,3]. In the meantime the doublet has been recognized as a triplet [4]. The achieved experimental resolution does not allow a separation between the $\frac{7}{2}^-$ (6.74 MeV), $\frac{1}{2}^+$ (6.79 MeV) and the $\frac{5}{2}^+$ (7.29 MeV) state. High-resolution quasielastic $(e,e'p)$ measurements found very little hole strength concentrated in all of these states [5]. The measurements of Ref. [3] further indicated that the proton angular distributions for the triplet of states shows different features from the ones for the ground state. The $\frac{3}{2}^-$ ground state is known to carry a substantial part of the 1p hole strength. It is well known that the (γ,p) angular distribution for the ground state strongly decreases with increasing photon energy and proton angle [6]. The excitation of the 7 MeV triplet was found to exhibit slower variations with photon energy and proton emission angle.

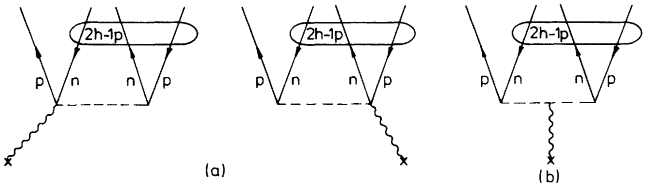

FIG. 1. Diagrams representing the exchange current contributions. (a) Pair current; (b) pion-in-flight current. Hole (particle) states are denoted with an arrow down (up).

This observation together with the knowledge that very little hole strength is concentrated in the 7 MeV triplet [5] lends support to the picture that its strong excitation in real photon reactions is definitely not the result of direct proton knockout in the sense of quasielastic $(e,e'p)$ processes. Attempts to explain the 7 MeV cross sections in terms of multistep processes and short-range correlations by van der Steenhoven and Blok [7] were only moderately successful. It turned out that these effects can account for only a fraction of the observed strength. A satisfactory quantitative analysis of the high-resolution (γ,p) data has as yet not been presented.

In this paper we report on a model which aims at a quantitative description of all aspects of high-resolution (γ,p) reactions. In order to facilitate the comparison with the data we concentrate on the ^{12}C(γ,p) reaction, which is by far the experimentally best studied process in this type of reactions. High-resolution data sets for other target nuclei will become available in the near future. First we address the unresolved puzzle of the unexpected strong population of the 7 MeV triplet in ^{11}B. We show that this effect can be explained by assuming that the photoabsorption takes place on a two-body current. This absorption process is assumed to be followed by the prompt emission of a proton leaving the residual nucleus in a two-hole–one-particle (2h-1p) state. In a further step we will point out that this mechanism has also implications for decay to states which were recognized to contain most of the 1p hole strength.

We have systematically neglected all contributions involving the exchange of two or more mesons and have restricted ourselves to the two-body current associated with one-pion exchange. The corresponding diagrams are shown in Fig. 1. We adopt pseudovector πNN coupling. The conventional monopole parametrization (cutoff parameter $\Lambda_\pi = 1.25$ GeV/c) of the hadronic form factor was used [8]. The bound-state single-particle wave functions in the target nucleus are taken from a Hartree-Fock calculation with an extended Skyrme force [9]. The proton continuum wave functions are obtained by solving the Schrödinger equation with the mean-field potential determined by the Hartree-Fock procedure.

To start with we make some simplifying assumptions with respect to the structure of the excited states in ^{11}B. A spherical description for the target and residual nucleus is adopted. State-of-the-art ^{12}C(γ,p) measurements can resolve the ground state $(J^\pi = \frac{3}{2}^-)$, 2.13 MeV $(J^\pi = \frac{1}{2}^-)$, 5.02 MeV $(J^\pi = \frac{3}{2}^-)$ and the 7 MeV triplet of ^{11}B. The cross section for the 4.45 MeV $(J^\pi = \frac{5}{2}^-)$ state was found to be very small [3,4]. For the odd parity states we consider the following structure:

$$|\tfrac{1}{2}^-,\tfrac{3}{2}^-\rangle = \alpha|0^+(\text{g.s.})\otimes(1p)_\pi^{-1}\rangle + \beta|2_1^+(4.44\ \text{MeV})\otimes(1p)_\pi^{-1}\rangle\ , \tag{1}$$

$$|\tfrac{5}{2}^-,\tfrac{7}{2}^-\rangle = |2_1^+(4.44\ \text{MeV})\otimes(1p)_\pi^{-1}\rangle\ . \tag{2}$$

The proton (neutron) states are denoted by $\pi(\nu)$. The hole excitation built on the 2_1^+ state will generally result in nh-$(n-1)$p$(n \geq 2)$ configurations. These configurations are closed for direct proton knockout following photoabsorption on one single nucleon. The 2h-1p admixtures can be excited in a direct (γ,p) process through photoabsorption on a two-body current. It is important to remark that the charge-exchange nature of the pionic currents brings about that exclusively $|(ph^{-1})_\nu(h^{-1})_\pi\rangle$ configurations can be excited (Fig. 1). The $|(ph^{-1})_\pi(h^{-1})_\pi\rangle$ admixtures cannot be fed. Consequently, if we assume good isospin only 50% of the total 2h-1p strength in the final state is open for the (γ,p) process. Large-scale shell-model calculations with the program OXBASH [10] revealed a 2_1^+ state consisting of 52% 1p-1h excitations. The main 1p-1h component (amplitude 0.72) was found to be the $(1p\frac{3}{2})^{-1}(1p\frac{1}{2})$ configuration. Therefore, the excitation of the $|((1p\frac{3}{2})^{-1}1p\frac{1}{2})_\nu(1p\frac{3}{2})_\pi^{-1}\rangle$ will dominate the pionic-induced (γ,p) process to the negative-parity states in ^{11}B. For the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels, the squared amplitude for this component has to be estimated around 0.26 $[=(0.72)^2/2]$. For the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states the factor 0.26 has to be multiplied with $\beta\times|\beta|$.

In Fig. 2 we compare the calculated angular distribu-

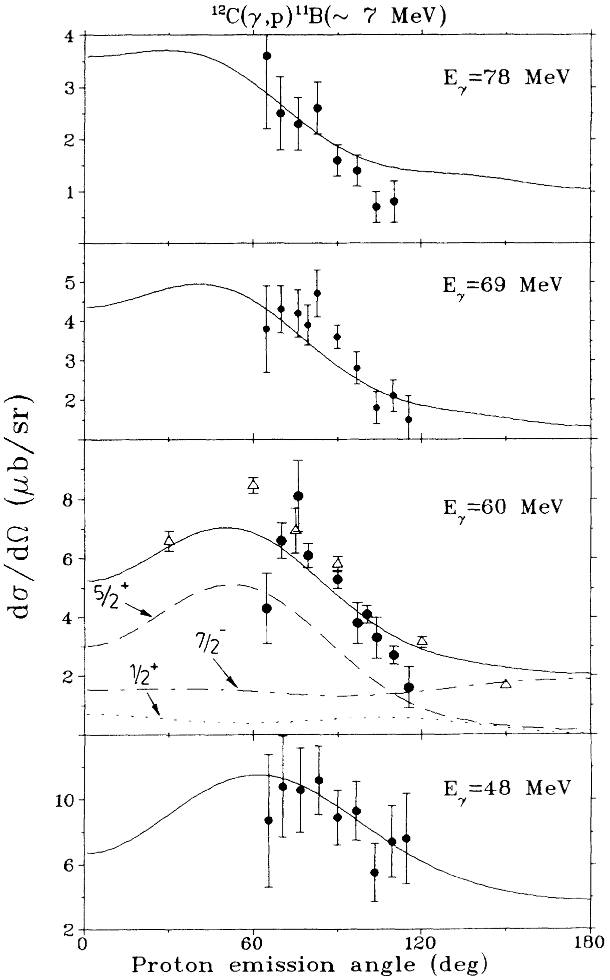

FIG. 2. Angular distribution for the ^{12}C$(\gamma,p)^{11}$B* (~7 MeV). Circles are from Springham *et al.* [3]. Triangles are unpublished data from the Gent-Lund collaboration [15].

tion for decay to the 7 MeV triplet with the data at four different values of the photon energy. The theoretical curves were obtained by an incoherent sum of the cross sections for each of the three states. The comparison is on an absolute scale. We remark that within the present model assumptions the triplet states can only be reached through two-body photoabsorption. In a first approximation the structure of the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states can be interpreted as a $1p\frac{3}{2}$ proton hole coupled to the lowest negative-parity states in ^{12}C: 3^- (9.64 MeV) and 1^- (10.84 MeV). The shell-model calculations of Ref. [10] and $^{12}C(p,p')$ experiments [11] confirm a predominant $(1p)^{-1}(1d\frac{5}{2})$ character for these states. The corresponding configuration in ^{11}B which can be reached through the pionic current is then $|((1p\frac{3}{2})^{-1}1d\frac{5}{2})_\nu(1p\frac{3}{2})_\pi^{-1};\frac{1}{2}^+,\frac{5}{2}^+\rangle$. The theoretical results of Fig. 2 were obtained for this configuration with a squared amplitude of 0.4 In line with the experimental observations a relatively smooth variation of the 7 MeV cross section with photon energy and proton emission angle is predicted. In Fig. 2 the 60 MeV cross section was decomposed in its three contributions. To a large extent the forward-angle behavior of the cross section is determined by the $\frac{5}{2}^+$ state. The forwardly peaked shape has to be totally ascribed to the characteristic behavior of the $\frac{5}{2}^+$ state (Fig. 2). At backward angles the cross section reflects contributions from all of the three states. The curves of Fig. 2 provide a good reproduction of *both the shape and the magnitude* of the angular distributions in the considered photon-energy range. The calculations lend strong support to the idea that the (γ,p) process leading to 2h-1p states is dominated by pionic effects.

In Fig. 3 we plotted the angular distributions for the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states at $E_\gamma = 60$ MeV. In the light of previous explanations and Eq. (1), the angular distributions for these states will be the result of a coherent sum of a single hole and a 2h-1p contribution. The single-hole matrix elements were calculated in the random phase approximation (RPA) according to the method outlined in Ref. [9]. In this way we do involve collective states as doorway states for proton emission. This effect was frequently shown to be important at photon energies below the pion threshold [9,12]. The calculation of the single-hole transition matrix elements is consistent with the one for the 2h-1p exchange current contribution in the sense that we use the same effective Skyrme nucleon-nucleon interactions in all of our calculations. The RPA calculations are performed with the one-body current of the impulse approximation (IA), except for a radial-dependent effective mass in the convection current. The effective mass stems from the nonlocality of the used effective nucleon-nucleon interaction and ensures the gauge invariance of the RPA calculations [9,13].

The curves of Fig. 3 are dependent on the relative sign and the magnitude of the wave-function amplitudes in Eq. (1). All calculations agree on the relative sign of α and β [14]. The amplitude α refers to the hole strength, which in turn is related to the spectroscopic factor. In our calculations we have used the spectroscopic factors extracted from an $(e,e'p)$ experiment by van der Steenhoven *et al.* [5] leading to $\alpha = 0.69$ (g.s.), $\alpha = 0.34$ (2.13 MeV) and $\alpha = 0.22$ (5.02 MeV). In order to estimate the amplitude for the relative contribution of the 2h-1p part we used the method explained earlier in the paper. Also for the low-lying states in ^{11}B a fair agreement with the data is obtained. We remark how the angular distribution for the 5.02 MeV ($\frac{3}{2}^-$) state is the result of single-nucleon (exciting the hole part) and multinucleon (exciting the 2h-1p part) processes. Combination of both gives a fair account of the data. At backward emission angles the 5.02 MeV cross section gets dominated by the 2h-1p contribution. The ground-state cross section gets only slightly affected by the (small) 2h-1p admixture. Despite its relatively small spectroscopic amplitude ($\alpha = 0.34$) the $\frac{1}{2}^-$ cross section is dominated by the hole part. This is because the calculations predict a small 2h-1p $\frac{1}{2}^-$ cross section. In general, with increasing photon energies the 2h-1p part will gain in importance relative to the 1h part.

In conclusion, for the first time a parameter-free quantitative interpretation of the high-resolution $^{12}C(\gamma,p)$ data could be obtained by combining elements of single-nucleon and pionic photoabsorption. The calculations lend strong support to the idea that the photoproton decay to some selective 2h-1p states is dominated by the pionic degrees of freedom in the target nucleus. A pro-

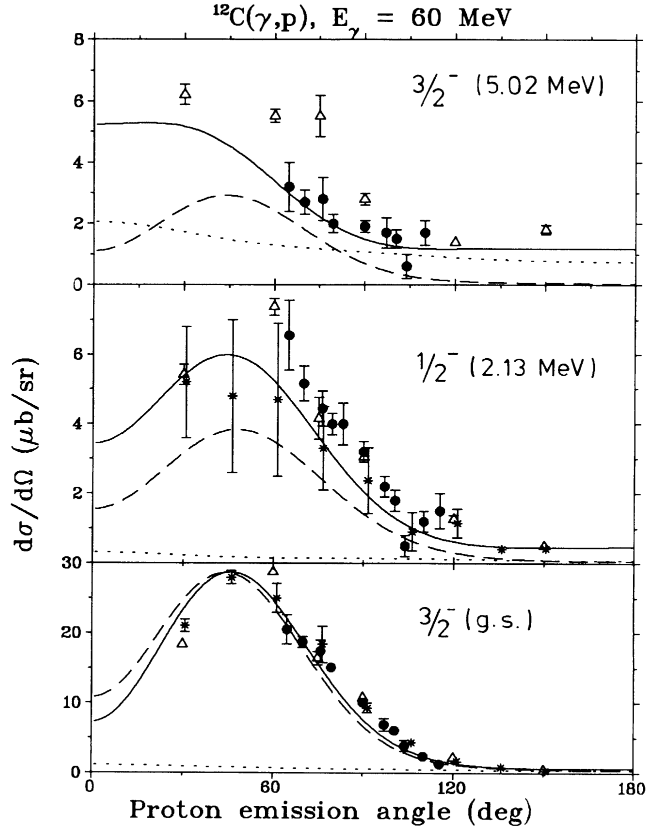

FIG. 3. $^{12}C(\gamma,p)$ angular distributions for low-lying negative-parity states in ^{11}B. The dotted line gives the 2h-1p contribution, the dashed line the hole contribution, and the solid line is their coherent sum. Data as in Fig. 2. The crosses are from Matthews *et al.* [6].

found study of these specific photoproton cross sections might even open some perspective to study pionic currents in finite nuclei.

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