Meson exchange currents in a relativistic model for electromagnetic one nucleon emission

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We analyze the role of meson exchange currents (MECs) in photon- and electron-induced one nucleon emission reactions in a fully relativistic model. The relativistic mean-field theory is used for the bound state and the Pauli reduction for the scattering state. Direct one-body and exchange two-body terms in the nuclear current are considered. Results for the ^{12}C(γ,p) and ^{16}O(γ,p) differential cross sections and photon asymmetries are displayed in an energy range between 60 and 196 MeV. The two-body seagull current affects the cross section less than in nonrelativistic analyses. In the case of the ^{16}O(γ,n) differential cross section, MEC effects are large but not sufficient to reproduce the data. MECs have a small effect on $(e,e'p)$ calculations.

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I. INTRODUCTION

One nucleon knockout reactions are a primary tool to explore the single-particle aspects of the nucleus. Several measurements at different energies and kinematics have been performed in a wide range of target nuclei, which stimulated the production of a considerable amount of theoretical calculations.

The validity of the direct knockout (DKO) mechanism is clearly established for exclusive $(e,e'p)$ reactions [1]. Theoretical models based on the nonrelativistic and relativistic distorted wave impulse approximation (DWIA) are able to give an excellent description of data in a wide range of nuclei and in different kinematics. In contrast, the reaction mechanism of photonuclear reactions has been the object of a longstanding discussion [1]. On the one hand, the DKO mechanism, with a suitable choice of the theoretical ingredients adopted for bound and scattering states, was able to describe (γ,p) cross sections for photon energies up to $E_\gamma \simeq 100$ MeV [2]. On the other hand, the fact that the transitions with neutron emission are of the same order of magnitude as those with proton emission addressed to a reaction mechanism where the transferred momentum is shared between two nucleons. Indeed, the quasideuteron model [3–5] was applied with some success to photoreactions at low and medium energies. Various corrections were included in the DKO model [6,7], but were unable to give a consistent description of (γ,p) and (γ,n) data.

In recent years, tagged photon facilities were developed and produced data with high-energy resolution and a clear separation between different states of the residual nucleus [8–13]. For the (γ,p) reaction, various analyses in different theoretical approaches suggest that the DKO contribution may be a small fraction of data [14–16], thus indicating that a prominent role is played by more complicated mechanisms, such as meson exchange currents (MECs) and multistep processes due to nuclear correlations.

Nonrelativistic DWIA calculations with ingredients for bound and scattering states consistent with $(e,e'p)$ reactions are unable to describe (γ,p) data [17,18]. A reasonable agreement is obtained when the MEC contribution is added to the DKO. MECs are found to produce an enhancement of the DKO cross sections [17]. The importance of MEC in proton photoemission was also studied in Ref. [19] for the ^{12}C(γ,p) reaction at intermediate energy.

Isobar current (IC) effects in photonuclear reactions were studied in Ref. [20], where a microscopic calculation including both nuclear correlations and Δ excitations showed that ICs are small except at large momentum transfer. The model was then extended to include also MEC and applied to proton capture (p,γ) in Ref. [21] and suggested that the DKO is the most important contribution to this reaction. The role of MEC and Δ excitations in (γ,p) reactions was analyzed in Ref. [22], where also short-range correlations were considered. Large differences between DKO cross sections and those obtained with the inclusion of MECs were found for large proton emission angles.

The relativistic approach was first applied to (γ,p) reactions in Ref. [23], where also MEC were considered, and in Refs. [24,25] within the framework of DKO. The DKO mechanism was able to reproduce the ^{16}O(γ,p) data at $E_\gamma = 60$ MeV [25]. The same approach was then extended in Ref. [26] to a much wider energy range and showed that the DKO is the main contribution to the cross section for missing momentum values up to $p_m \simeq 500$ MeV/c, while MEC and IC are expected to give important effects for larger missing momenta.

The effects of MEC and IC in $(e,e'p)$ reactions at quasielastic peak were first presented within a nonrelativistic framework in Ref. [27], where a small contribution of MEC and a reduction due to IC were obtained. In contrast, in Ref. [28], important effects on the interference response functions were found out. Moreover, the effects were dependent on the shell considered. The sensitivity of polarization observables to MEC and IC in $(\vec{e},e'\vec{p})$ was studied in Ref. [29], where a moderate dependence on MEC was predicted only at $p_m \gtrsim 200$ MeV/c. In Ref. [30], MEC and IC effects on $(e,e'p)$ are generally small.

Different fully relativistic DWIA (RDWIA) models were developed in recent years by different groups and successfully applied to the analysis of $(e,e'p)$ data [31–34]. In a recent paper [35], we have compared nonrelativistic and relativistic calculations for the (γ,N) knockout reactions in order to clarify the relationship between the DWIA and RDWIA approaches for (γ,p) and (γ,n), and to study the relevance of the DKO mechanism in nonrelativistic and relativistic calculations. In this work our interest is focused on the role played by MEC in (γ,N) and in $(e,e'p)$ reactions within the framework of RDWIA.

The RDWIA treatment is the same as in Ref. [35]. The relativistic bound state wave functions are solutions of a Dirac equation containing scalar and vector potentials obtained in the framework of the relativistic mean-field theory. The effective Pauli reduction has been adopted for the outgoing nucleon wave function. This simple scheme is in principle equivalent to the exact solution of the Dirac equation. The resulting Schrödinger-like equation is solved for each partial wave starting from relativistic optical potentials. The same spectroscopic factors obtained in Refs. [34,36] by fitting our RDWIA $(e,e'p)$ results to data have been applied to the calculated (γ,N) cross sections.

Results for ^{12}C and ^{16}O target nuclei at different photon energies have been considered. The one-body part of the relativistic current is written following the most commonly used current conserving (cc) prescriptions for the $(e,e'p)$ reaction introduced in Ref. [37]. The ambiguities connected with different choices of the electromagnetic current cannot be dismissed. In the $(e,e'p)$ reaction the predictions of different prescriptions are generally in close agreement [38]. Large differences can however be found at high missing momenta [39,40]. These differences are increased in (γ,N) reactions, where the kinematics is deeply off shell, and higher values of the missing momentum are probed.

The two-body part of the current is constructed starting from the pseudovector πN Lagrangian as in Refs. [41,42]. As a first step, in this paper we include in the two-body current only the term corresponding to the seagull (contact) diagram with one-pion exchange. Thus, we consider only a part of the contribution of MEC. This contribution, however, should be able to understand the relevance of the two-body currents in a relativistic approach also in comparison with previous nonrelativistic calculations.

The formalism is outlined in Sec. II. Relativistic calculations of the ^{12}C(γ,p) and ^{16}O(γ,p) cross sections are presented in Sec. III, where also MEC effects on the (γ,n) and $(e,e'p)$ reactions are discussed. Some conclusions are drawn in Sec. IV.

II. FORMALISM

The matrix elements of the nuclear current operator, i.e.,

$$J^\mu = \langle \Psi_{\rm f} | j^\mu | \Psi_{\rm i} \rangle, \tag{1}$$

represent the main ingredient of the cross section and contain all the physical information that can be extracted from the reaction.

The nuclear current operator can be expanded into one-body, two-body, and higher-order components. In this paper one-body, $j^\mu(1b)$, and two-body, $j^\mu(2b)$, terms are included. The nuclear initial state $|\Psi_{\rm i}\rangle$ is the many-body independent-particle model wave function, i.e., a Slater determinant, where only correlations due to the Pauli principle are included. For exclusive processes where only one nucleon is emitted, and under the assumption that only the observed channel contributes to the scattering wave function, we can assume that only one nucleon undergoes a transition and that the residual nucleus is a pure one-hole state in the target. Then, the matrix elements in Eq. (1) are given by the sum of two terms, for the one-body and the two-body current operators, as

$$\begin{aligned}\langle \Psi_{\rm f} | j^\mu | \Psi_{\rm i} \rangle \simeq & \langle \chi^{(-)}(1) | j^\mu(1b) | \Psi_\beta(1) \rangle \\ & + \sum_{\alpha=1}^{\rm A} \langle \chi^{(-)}(1)\Psi_\alpha(2) | j^\mu(2b) | \Psi_\beta(1)\Psi_\alpha(2) \\ & - \Psi_\alpha(1)\Psi_\beta(2) \rangle,\end{aligned} \tag{2}$$

where $\chi^{(-)}$ is the distorted wave function of the emitted nucleon, and $\Psi_{\alpha(\beta)}$ are single-particle bound state wave functions.

In the first term the interaction occurs, through a one-body current, only with the nucleon that is ejected; and the other nucleons behave as spectators. This term corresponds to the DKO mechanism and gives the RDWIA. In the second term the interaction occurs, through a two-body current, with a pair of nucleons. Only one nucleon is emitted and the other nucleon of the pair is reabsorbed in the residual nucleus. For the nucleon that has not been emitted a sum over all the single-particle states is performed in the calculations.

At present, there is no unambiguous approach for dealing with off-shell nucleons. Here, we discuss the three cc expressions for the one-body current [37,43,44]

$$j^\mu_{\rm cc1} = G_M(Q^2)\gamma^\mu - \frac{\kappa}{2M} F_2(Q^2)\overline{P}^\mu,$$

$$j^\mu_{\rm cc2} = F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M} F_2(Q^2)\sigma^{\mu\nu}q_\nu,$$

$$j^\mu_{\rm cc3} = F_1(Q^2)\frac{\overline{P}^\mu}{2M} + \frac{i}{2M} G_M(Q^2)\sigma^{\mu\nu}q_\nu, \tag{3}$$

where $q^\mu = (\omega, \boldsymbol{q})$ is the four-momentum transfer, $Q^2 = |\boldsymbol{q}|^2 - \omega^2$, $\overline{P}^\mu = (E+E', \boldsymbol{p}_{\rm m} + \boldsymbol{p}')$, E' and $\boldsymbol{p}'$ are the energy and momentum of the emitted nucleon, κ is the anomalous part of the magnetic moment, F_1 and F_2 are the Dirac and Pauli nucleon form factors, $G_M = F_1 + \kappa F_2$ is the Sachs nucleon magnetic form factor, and $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$. These expressions are equivalent for on-shell particles due to Gordon identity, but they give different results when applied to off-shell nucleons.

The two-body current is due to meson exchanges between nucleons. We have considered in this paper only the seagull diagram. The corresponding current is written in momentum space as [41,42]

$$J_{\mathrm{S}}^{\mu}=-F_{\mathrm{S}}\frac{f^2}{m_\pi^2}\overline{\Psi}(1)\gamma^\mu\gamma^5\Psi(1)\overline{\Psi}(2)\not{k}_2\gamma^5\Psi(2),$$

$$\frac{1}{k_2^2-m_\pi^2}\xi_1^\dagger\xi_2^\dagger i(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\xi_1\xi_2+(1\leftrightarrow 2), \tag{4}$$

where $F_{\mathrm{S}}=G_E^p-G_E^n$, $f^2/(4\pi)\simeq 0.079$, $m_\pi\simeq 140$ MeV is the pion mass, and ξ is the isospin wave function. We have performed calculations with the cutoff $\Lambda=1250$ MeV in the pion propagator.

Current conservation is restored by replacing the longitudinal current and the bound nucleon energy by [37]

$$J^L=J^z=\frac{\omega}{|\boldsymbol{q}|}J^0, \tag{5}$$

$$E=\sqrt{|\boldsymbol{p}_{\mathbf{m}}|^2+M^2}=\sqrt{|\boldsymbol{p}'-\boldsymbol{q}|^2+M^2}. \tag{6}$$

The bound state wave functions,

$$\Psi_{\alpha(\beta)}=\begin{pmatrix} u_{\alpha(\beta)} \\ v_{\alpha(\beta)} \end{pmatrix}, \tag{7}$$

are given by the Dirac-Hartree solution of a relativistic Lagrangian containing scalar and vector potentials.

The ejectile wave function is written in terms of its positive energy component following the direct Pauli reduction scheme [45], i.e.,

$$\chi=\begin{pmatrix} \chi_+ \\ \dfrac{\boldsymbol{\sigma}\cdot\boldsymbol{p}'}{M+E'+S-V}\chi_+ \end{pmatrix}, \tag{8}$$

where $S=S(r)$ and $V=V(r)$ are the scalar and vector potentials for the nucleon with energy E'. The upper component χ_+ is related to a Schrödinger equivalent wave function Φ_f by the Darwin factor $D(r)$, i.e.,

$$\chi_+=\sqrt{D(r)}\Phi_f, \tag{9}$$

$$D(r)=1+\frac{S-V}{M+E'}. \tag{10}$$

Φ_f is a two-component wave function that is the solution of a Schrödinger equation containing equivalent central and spin-orbit potentials obtained from the scalar and vector potentials.

The coincidence cross section of the $(e,e'p)$ reaction can be written in terms of four response functions $f_{\lambda\lambda'}$, as

$$\sigma=\sigma_{\mathrm{M}}f_{\mathrm{rec}}E'|\boldsymbol{p}'|\ \{\rho_{00}f_{00}+\rho_{11}f_{11}+\rho_{01}f_{01}\cos(\vartheta)$$
$$+\rho_{1-1}f_{1-1}\cos(2\vartheta)\}, \tag{11}$$

where σ_{M} is the Mott cross section, f_{rec} is the recoil factor [1,46], and ϑ is the out-of-plane angle between the electron scattering plane and the $(\boldsymbol{q},\boldsymbol{p}')$ plane. The coefficients $\rho_{\lambda\lambda'}$ are obtained from the lepton tensor components and depend only upon the electron kinematics [1,46].

In case of an incident photon with energy E_γ, the (γ,N) cross section can be written in terms of the pure transverse response, i.e.,

$$\sigma_\gamma=\frac{2\pi^2\alpha}{E_\gamma}f_{\mathrm{rec}}E'|\boldsymbol{p}'|f_{11}, \tag{12}$$

where $\alpha\simeq 1/137$. If the photon beam is linearly polarized, the interference transverse-transverse response is also nonzero and appears in the definition of the photon asymmetry

$$A=-\frac{f_{1-1}}{f_{11}}. \tag{13}$$

The response functions are given by bilinear combinations of the nuclear current components, i.e.,

$$f_{00}=\langle J^0(J^0)^\dagger\rangle,$$
$$f_{11}=\langle J^x(J^x)^\dagger\rangle+\langle J^y(J^y)^\dagger\rangle,$$
$$f_{01}=-2\sqrt{2}\mathrm{Re}[\langle J^x(J^0)^\dagger\rangle],$$
$$f_{1-1}=\langle J^y(J^y)^\dagger\rangle-\langle J^x(J^x)^\dagger\rangle, \tag{14}$$

where $\langle\cdots\rangle$ means that average over the initial and sum over the final states is performed fulfilling energy conservation.

III. RESULTS AND DISCUSSION

The results of this section have been obtained with the same bound state wave functions and optical potentials as in Refs. [34,35], where the RDWIA one-body analysis was successfully applied to reproduce $(e,e'p)$ and (γ,p) data.

The relativistic bound state wave functions have been obtained from the code of Ref. [47], where relativistic Hartree-Bogoliubov equations are solved in the context of a relativistic mean-field theory that satisfactorily reproduces single-particle properties of several spherical and deformed nuclei [48]. The direct Pauli reduction is applied for the scattering state which is calculated by means of the energy-dependent and mass-number-dependent complex phenomenological optical potential (EDAD1) of Ref. [49]. The EDAD1 potential is obtained from fits to proton elastic scattering data on several nuclei in an energy range up to 1040 MeV. Since there is no unambiguous prescription for handling off-shell nucleons, we have performed calculations with different cc expressions for the one-body current. The Dirac and Pauli form factors are taken from Ref. [50].

A. The (γ,p) and (γ,n) reactions

The analysis of (γ,p) reactions has been the object of a longstanding discussion about the reaction mechanism. Many nonrelativistic calculations in different theoretical approaches suggested that MEC and Δ excitations should play a prominent role. On the contrary, the RDWIA approach

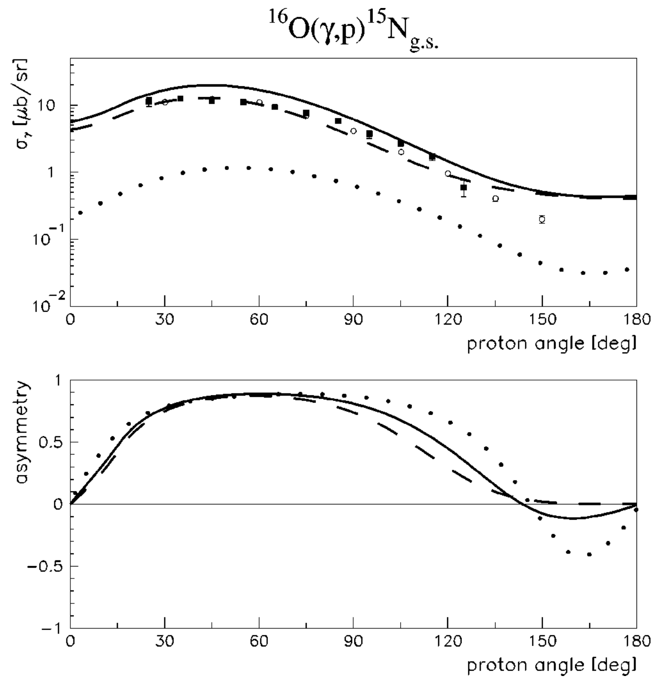

FIG. 1. The cross section and photon asymmetry for the $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}_{\mathrm{g.s.}}$ reaction as functions of the proton scattering angle at $E_\gamma = 60$ MeV. The data are from Ref. [9] (black squares) and from Ref. [51] (open circles). Solid lines represent the DKO +SEAG results, dashed lines the DKO results, and dotted lines the SEAG results.

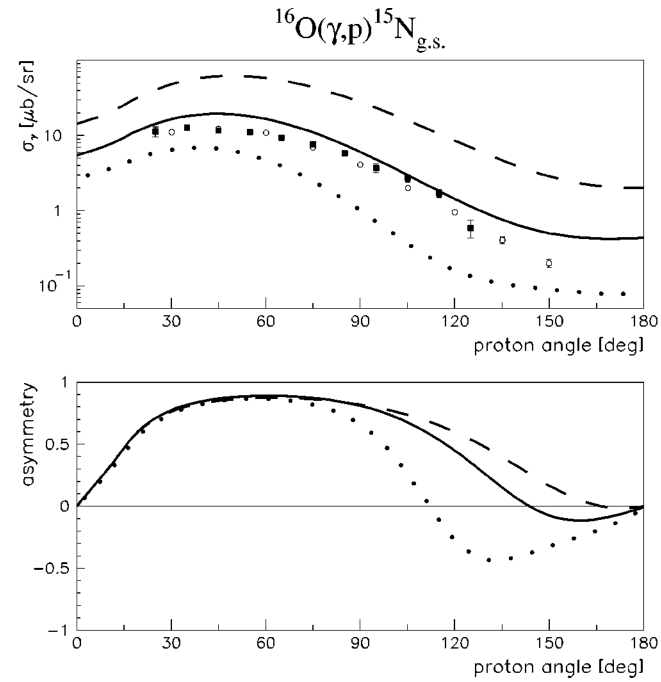

FIG. 2. The cross section and photon asymmetry for the $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}_{\mathrm{g.s.}}$ reaction as functions of the proton scattering angle at $E_\gamma = 60$ MeV. The data are from Ref. [9] (black squares) and from Ref. [51] (open circles). Dashed, solid, and dotted lines represent the DKO+SEAG results, with cc1, cc2, and cc3 prescriptions for the one-body current, respectively.

seems to indicate that the DKO mechanism is the leading process, at least for low photon energies and missing momenta up to $\simeq 500$ MeV/c. Our aim is to study whether this conclusion is correct investigating the effects of the seagull (SEAG) current on the cross section. The comparison between the DKO+SEAG, DKO, and SEAG results is shown in Fig. 1 for the cross section and photon asymmetry of the $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}_{\mathrm{g.s.}}$ reaction at $E_\gamma = 60$ MeV. The cc2 current has been used and the spectroscopic factor $Z(p\frac{1}{2}) = 0.71$ has been applied [34–36]. As it was already known from previous analyses [26,35], the one-body term provides the main contribution to the cross section and can satisfactorily reproduce the data, at least for small angles. The pure contribution of the two-body term is one order of magnitude lower than the one-body one, but their interference is large. The total result is enhanced above the data and the shape is slightly affected. The SEAG contribution is sizable but is less than in previous nonrelativistic calculations [17]. It has been pointed out in a nonrelativistic approach [22] that the SEAG term overestimates MEC. A substantial reduction is obtained when the pion-in-flight diagram is added, while the Δ current is important only with increasing photon energies. If these results were confirmed in relativistic calculations, the pion-in-flight term would reduce the contribution of seagull and bring the calculated cross section in Fig. 1 closer to the DKO results and also to the data.

The photon asymmetry at $E_\gamma = 60$ MeV is shown in the lower panel of Fig. 1. The differences between the DKO+SEAG and the DKO results are generally small, but at large angles, where the SEAG contribution becomes negative.

The sensitivity of the (γ,p) calculations at $E_\gamma = 60$ MeV to different cc prescriptions for the one-body current is presented in Fig. 2, where results for the DKO+SEAG contribution are displayed. As we already pointed out in Ref. [35], large differences are given by the three expressions of the one-body current at the considered photon energy. These differences are somewhat reduced when the seagull current is added, but remain anyhow large. The calculated cross sections are strongly enhanced if we use cc1; this is probably due to an overestimation of the convective current contribution for an off-shell nucleon. Results with cc3 are lower than those with cc2, but the difference decreases with increasing photon energy. Large differences are obtained also for the photon asymmetry at large scattering angles. In Figs. 3 and 4 the comparison between the DKO+SEAG and DKO results is shown for the cross section and the photon asymmetry for energy ranging from 80 to 196 MeV. The seagull contribution enhances the cross section at all the considered photon energies. Thus, the experimental cross sections at $E_\gamma = 80$ and 100 MeV, which are already reproduced by the DKO result, are overestimated, while a better agreement with data is found at $E_\gamma = 150$ and 196 MeV. In order to draw definite conclusions in comparison with data, however, it would be useful to check the relevance of the pion-in-flight contribution, and also of the IC, which should play a significant role above 150 MeV. For the photon asymmetry in Fig. 4, the differences between the DKO+SEAG and DKO results increase with the scattering angle and with the photon energy.

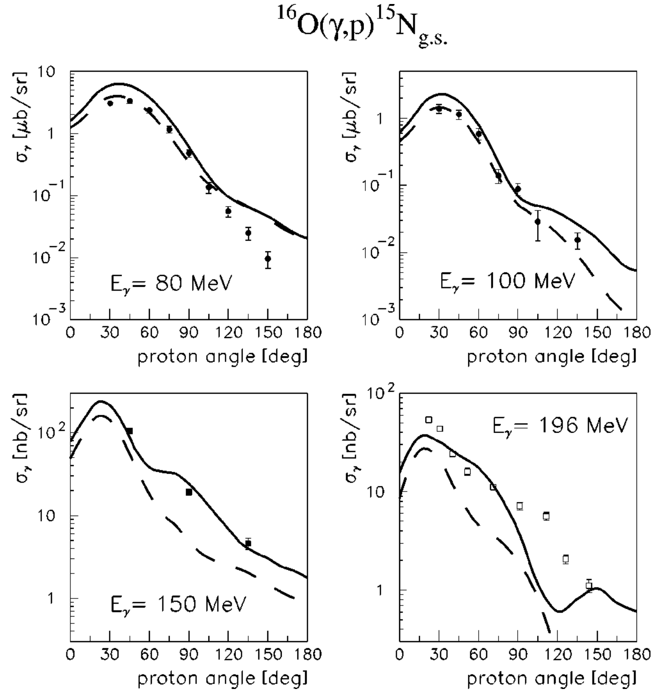

FIG. 3. The cross section for the ^{16}O$(\gamma,p)^{15}$N$_{\text{g.s.}}$ reaction as a function of the proton scattering angle at a photon energy ranging from 80 to 196 MeV. The data at 80 and 100 MeV are from Ref. [51]. The data at 150 MeV are from Ref. [52]. The data at 196 MeV are from Ref. [53]. Solid lines represent the DKO+SEAG results and dashed lines the DKO results.

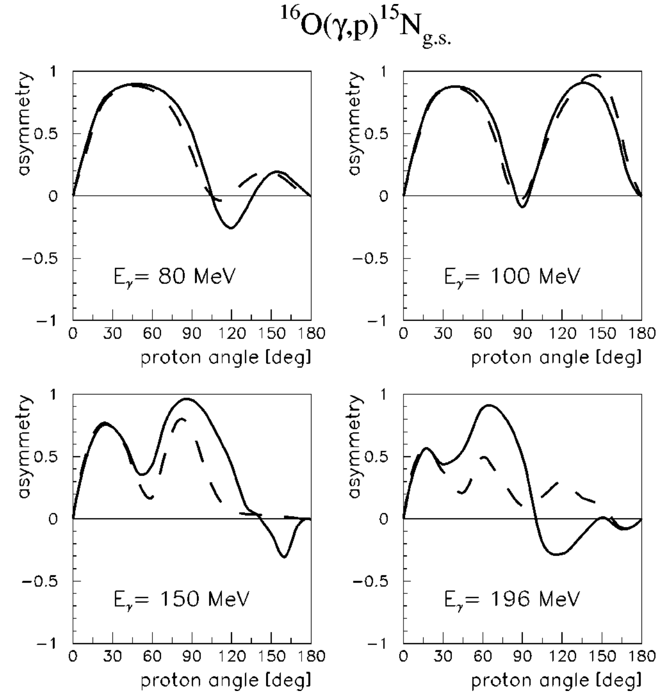

FIG. 4. The same as in Fig. 3, but for the photon asymmetry.

In Fig. 5 the cross section and the photon asymmetry for the ^{12}C$(\gamma,p)^{11}$B$_{\text{g.s.}}$ reaction at $E_\gamma=58.4$ MeV are presented. The spectroscopic factor $Z(p\frac{3}{2})=0.56$ has been applied. Also in this case, the DKO+SEAG results are greater than the DKO ones. However, the most apparent feature is that none of them can reproduce the data. This fact was already found out in Refs. [26,35], where it was suggested that a better agreement might be obtained with a more clear determination of the ^{12}C ground state, which should take into account its intrinsic deformation. Results for neutron photoemission at $E_\gamma=60$ MeV are displayed in Fig. 6. The same spectroscopic factor as in the (γ,p) reaction has been applied. The fact that the ratio between experimental (γ,p) and (γ,n) cross sections is comparable to unity has been traditionally interpreted as a signal of the dominance of a two-body mechanism in the (γ,n) reaction. We see that results with DKO+SEAG are greatly increased with respect to the DKO ones, but this enhancement is still insufficient to reproduce the magnitude of the data. These results seem to indicate that more complicated effects are needed to reproduce the data, such as, e.g., a rescattering process [11,20,22,56].

B. The $(e,e'p)$ reaction

The study of the exclusive $(e,e'p)$ knockout reaction for $Q^2 \leqslant 0.4$ (GeV/c)^2 was successfully performed in the theoretical framework of nonrelativistic DWIA. In more recent years different models based on a fully relativistic approach were developed. These models were able to successfully describe the data at $Q^2 \simeq 0.8$ (GeV/c)^2 from Jefferson Laboratory (JLab) [57,58]. Both nonrelativistic and relativistic $(e,e'p)$ analyses were performed including the one-body current only. In fact, the two-body diagrams were not expected to give an important contribution, at least over the explored kinematics conditions.

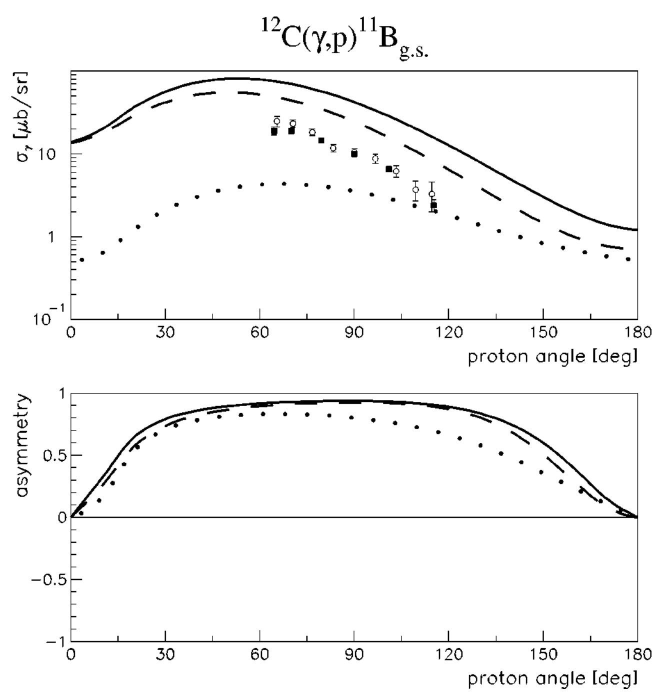

FIG. 5. The cross section and photon asymmetry for the ^{12}C$(\gamma,p)^{11}$B$_{\text{g.s.}}$ reaction as functions of the proton scattering angle at $E_\gamma=58.4$ MeV. The data are from Ref. [54] (black squares) and from Ref. [8] (open circles). Line convention as in Fig. 1.

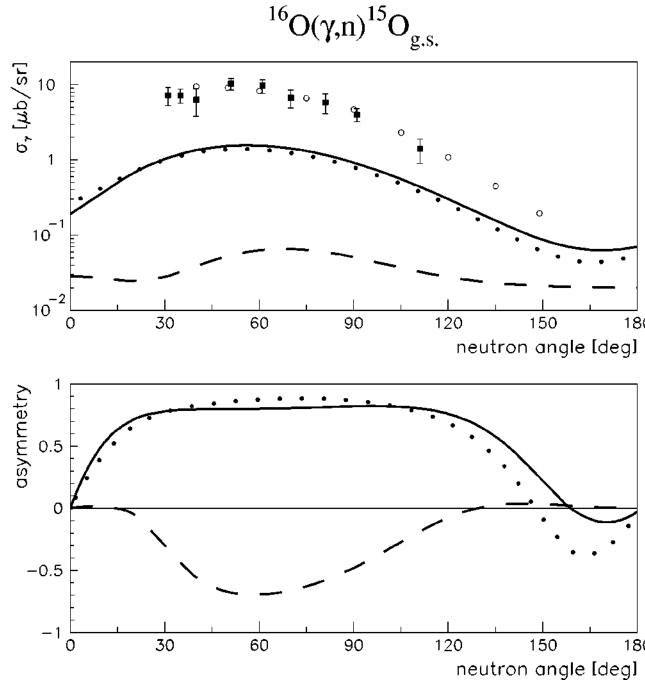

FIG. 6. The cross section and photon asymmetry for the $^{16}\mathrm{O}(\gamma,n)^{15}\mathrm{O}_{\mathrm{g.s.}}$ reaction as functions of the neutron scattering angle at $E_\gamma = 60$ MeV. The data are from Ref. [11] (black squares) and from Ref. [55] (open circles). Line convention as in Fig. 1.

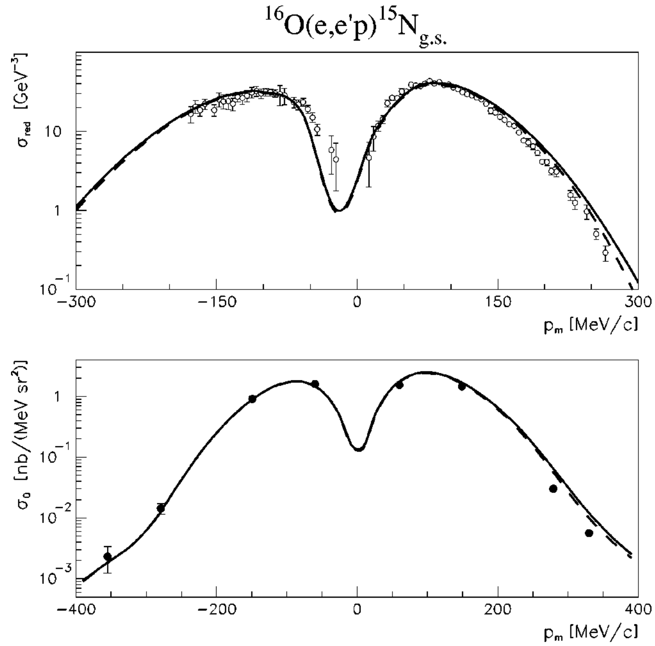

FIG. 7. Upper panel shows the reduced cross section for the $^{16}\mathrm{O}(e,e'p)^{15}\mathrm{N}_{\mathrm{g.s.}}$ reaction at $E_p = 90$ MeV constant proton energy in the center-of-mass system in parallel kinematics [59]. Lower panel shows the cross section for the same reaction, but at $Q^2 = 0.8$ $(\mathrm{GeV}/c)^2$ in constant $(\boldsymbol{q},\omega)$ kinematics [57]. Solid lines represent the DKO+SEAG results and dashed lines the DKO results.

In Fig. 7 the $^{16}\mathrm{O}(e,e'p)^{15}\mathrm{N}_{\mathrm{g.s.}}$ reaction is considered. In the upper panel the reduced cross section data measured at NIKHEF [59] in parallel kinematics with a proton energy of 90 MeV in the center-of-mass system are compared with our DKO+SEAG and DKO calculations. The cc2 prescription for the one-body current has been used and the spectroscopic factor is $Z(p\frac{1}{2}) = 0.71$. In the lower panel the same reaction is studied at the JLab constant $(\boldsymbol{q},\omega)$ kinematics [57]. As it was already found in Ref. [34], the DKO calculation gives good descriptions of the data in both kinematics. A slight enhancement is due to the seagull current and is visible only at higher values of p_m. This result is consistent with usual expectations for which quasifree electron scattering is almost unaffected by MEC.

We have also performed calculations for the transition to the $p\frac{3}{2}$ first excited state of ^{15}N at the same kinematics as in Fig. 7, but we have not found any appreciable difference with respect to the $p\frac{1}{2}$ state. We have also calculated the response functions measured in $^{16}\mathrm{O}(e,e'p)^{15}\mathrm{N}$ at JLab [57] and the polarization observables from MIT-Bates [60] on $^{12}\mathrm{C}(e,e'\vec{p})^{11}\mathrm{B}$ and JLab [58] on $^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N}$. MEC might be expected to give a more significant effect in the induced polarization, but we have not found any significant difference with respect to our RDWIA results of Refs. [34,36].

IV. SUMMARY AND CONCLUSIONS

In this paper a first step has been made to study the role of MEC in (γ,N) and $(e,e'p)$ reactions in a fully relativistic framework. In previous relativistic and nonrelativistic DWIA calculations the DKO mechanism was clearly established for quasifree $(e,e'p)$ reactions in comparison with data, and only a small contribution is expected from two-body currents. Various nonrelativistic calculations give different results, but confirm that the contribution of MEC in $(e,e'p)$ is not very important. Nonrelativistic analyses of (γ,p) reactions generally indicate a prominent role of MEC. Their contribution is important to reproduce the data and affects the shape and size of the calculated cross sections at all the photon energies. In contrast, RDWIA calculations suggest that the DKO mechanism is already able to give a reasonable agreement with data and MEC seem to be required only at $p_m \gtrsim 500$ MeV/c. Thus, our aim was to study the relevance of two-body currents in comparison with DKO within a fully relativistic framework.

The nuclear current operator is expanded into one-body and two-body components. The one-body term gives the DKO contribution. For the two-body term we assume that only a pair of nucleons are involved in the reaction: one is emitted from a specific state and the other one is reabsorbed in the nucleus, i.e., the residual nucleus is a one-hole state in the target.

In the transition matrix elements of the nuclear current operator the bound state wave function is obtained in the framework of the relativistic mean-field theory, and the direct Pauli reduction method with scalar and vector potentials is used for the ejectile wave functions. In order to study the ambiguities in the one-body electromagnetic vertex due to the off shellness of the initial nucleon, we have performed calculations using three current conserving expressions.

As a first step, we have considered in this paper only the contribution to the MEC due to the seagull diagram. We have discussed the effect of this term on the (γ,p) reactions for photon energies up to 196 MeV. As in previous RDWIA analyses, the DKO term provides the main contribution to the cross section and is in satisfactory agreement with the data, at least for small energies and angles. The pure SEAG term is smaller than the DKO one. The total effect enhances the cross section, but less than in nonrelativistic calculations. On the other hand, in nonrelativistic calculations the pion-in-flight diagram reduces the effect of the seagull current, while the Δ excitation is important only with increasing photon energies. In the case of our RDWIA calculation, we expect a similar result. The inclusion of all MEC contributions should have a more limited but still visible effect on the cross section, while IC should become important at increasing photon energies.

Large ambiguities to the different prescriptions for the one-body current are generally found in the (γ,p) cross section also when the seagull current is included.

For the (γ,n) reaction, the dominant contribution of a two-body mechanism has been traditionally claimed to explain the magnitude of the experimental cross section. Our RDWIA results are greatly increased when the SEAG contribution is included, but the enhancement is still insufficient to reproduce the data. This seems to indicate that more complicated effects are needed to reproduce the data. A careful and consistent analysis of these mechanisms in a relativistic framework would be important and helpful to clarify this question.

We have also performed calculations for the $(e,e'p)$ reaction at different kinematics. Also in this case, the seagull diagram enhances the RDWIA results, but, in contrast to (γ,p), the effects are generally small and visible only at high missing momenta. Thus, the comparison with data that were already well reproduced by the DKO model, is practically unaffected.

[1] S. Boffi, C. Giusti, F. D. Pacati, and M. Radici, *Electromagnetic Response of Atomic Nuclei*, Oxford Studies in Nuclear Physics Vol. 20 (Clarendon, Oxford, 1996).

[2] S. Boffi, C. Giusti, and F.D. Pacati, Nucl. Phys. **A358**, 91 (1981).

[3] J.S. Levinger, Phys. Rev. **84**, 43 (1951); Phys. Lett. **82B**, 181 (1979).

[4] B. Schoch, Phys. Rev. Lett. **41**, 80 (1970).

[5] J.A. Eden *et al.*, Phys. Rev. C **44**, 753 (1991).

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

[7] S. Boffi, F. Capuzzi, C. Giusti, and F.D. Pacati, Nucl. Phys. **A436**, 438 (1985).

[8] S.V. Springham *et al.*, Nucl. Phys. **A517**, 93 (1990).

[9] G.J. Miller *et al.*, Nucl. Phys. **A586**, 125 (1995).

[10] C. Van den Abeele, D. Ryckbosch, J. Dias, L. Van Hoorebeke, R. Van de Vyver, J.O. Adler, K. Hansen, L. Isaksson, H. Ruijter, and B. Schröder, Nucl. Phys. **A586**, 281 (1995).

[11] B.E. Andersson *et al.*, Phys. Rev. C **51**, 2553 (1995).

[12] L.J. de Bever *et al.*, Phys. Rev. C **58**, 981 (1998).

[13] D. Branford *et al.*, Phys. Rev. C **63**, 014310 (2001).

[14] I. Bobeldijk *et al.*, Phys. Lett. B **356**, 13 (1995).

[15] K. Mori *et al.*, Phys. Rev. C **51**, 2611 (1995).

[16] D.G. Ireland and G. van der Steenhoven, Phys. Rev. C **49**, 2182 (1994).

[17] G. Benenti, C. Giusti, and F.D. Pacati, Nucl. Phys. **A574**, 716 (1994).

[18] M.K. Gaidarov, K.A. Pavlova, A.N. Antonov, M.V. Stoitsov, S.S. Dimitrova, M.V. Ivanov, and C. Giusti, Phys. Rev. C **61**, 014306 (2000); M.V. Ivanov, M.K. Gaidarov, A.N. Antonov, and C. Giusti, *ibid.* **64**, 014605 (2001).

[19] J. Ryckebusch, K. Heyde, L. Machenil, D. Ryckbosch, M. Vanderhaeghen, and M. Waroquier, Phys. Rev. C **46**, R829 (1992).

[20] T.B. Bright and S.R. Cotanch, Phys. Rev. Lett. **71**, 2563 (1993).

[21] T.B. Bright, B. Hölstad, R. Johansson, E. Traneus, and S.R. Cotanch, Nucl. Phys. **A603**, 1 (1996).

[22] M. Anguiano, G. Co', A.M. Lallena, and S.R. Mokhtar, Ann. Phys. (N.Y.) **296**, 235 (2002).

[23] J.P. McDermott, E. Rost, J.R. Shepard, and C.Y. Cheung, Phys. Rev. Lett. **61**, 814 (1988).

[24] G.M. Lotz and H.S. Sherif, Nucl. Phys. **A537**, 285 (1992).

[25] J.I. Johansson, H.S. Sherif, and G.M. Lotz, Nucl. Phys. **A605**, 517 (1996).

[26] J.I. Johansson and H.S. Sherif, Phys. Rev. C **56**, 328 (1997).

[27] S. Boffi and M. Radici, Nucl. Phys. **A526**, 602 (1991).

[28] V. Van der Sluys, J. Ryckebusch, and M. Waroquier, Phys. Rev. C **49**, 2695 (1994).

[29] J. Ryckebusch, D. Debruyne, W. Van Nespen, and S. Janssen, Phys. Rev. C **60**, 034604 (1999).

[30] J.E. Amaro, A.M. Lallena, and J.A. Caballero, Phys. Rev. C **60**, 014602 (1999).

[31] A. Picklesimer, J.W. Van Orden, and S.J. Wallace, Phys. Rev. C **32**, 1312 (1985); A. Picklesimer and J.W. Van Orden, *ibid.* **40**, 290 (1989).

[32] Y. Jin, D.S. Onley, and L.E. Wright, Phys. Rev. C **45**, 1311 (1992); Y. Jin and D.S. Onley, *ibid.* **50**, 377 (1994).

[33] J.M. Udías, P. Sarriguren, E. Moya de Guerra, E. Garrido, and J.A. Caballero, Phys. Rev. C **48**, 2731 (1993); **51**, 3246 (1995); J.D. Udías, P. Sarriguren, E. Moya de Guerra, and J.A. Caballero, *ibid.* **53**, R1488 (1996); J.M. Udías and J.R. Vignote, *ibid.* **62**, 034302 (2000).

[34] A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **64**, 014604 (2001).

[35] A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **64**, 064615 (2001).

[36] M. Radici, A. Meucci, and W.H. Dickhoff, nucl-th/0205013.

[37] T. de Forest, Jr., Nucl. Phys. **A392**, 232 (1983).

[38] S. Pollock, H.W.L. Naus, and J.H. Koch, Phys. Rev. C **53**, 2304 (1996).

[39] J.A. Caballero, T.W. Donnelly, E. Moya de Guerra, and J.M. Udías, Nucl. Phys. **A632**, 323 (1998).

[40] S. Jeschonnek and J.W. Van Orden, Phys. Rev. C **62**, 044613 (2000).
[41] J.W. Van Orden and T.W. Donnelly, Ann. Phys. (N.Y.) **131**, 451 (1981).
[42] M.J. Dekker, P.J. Brussaard, and J.A. Tjon, Phys. Rev. C **49**, 2650 (1994); G.H. Martinus, O. Scholten, and J.A. Tjon, *ibid.* **58**, 686 (1998).
[43] J.J. Kelly, Phys. Rev. C **56**, 2672 (1997); **59**, 3256 (1999); **60**, 044609 (1999).
[44] A. Meucci, Phys. Rev. C **65**, 044601 (2002).
[45] M. Hedayati-Poor, J.I. Johansson, and H.S. Sherif, Nucl. Phys. **A593**, 377 (1995); Phys. Rev. C **51**, 2044 (1995).
[46] J.J. Kelly, Adv. Nucl. Phys. **23**, 75 (1996).
[47] W. Pöschl, D. Vretenar, and P. Ring, Comput. Phys. Commun. **103**, 217 (1997).
[48] G.A. Lalazissis, J. König, and P. Ring, Phys. Rev. C **55**, 540 (1997).
[49] E.D. Cooper, S. Hama, B.C. Clark, and R.L. Mercer, Phys. Rev. C **47**, 297 (1993).
[50] P. Mergell, Ulf-G. Meissner, and D. Drechsel, Nucl. Phys. **A596**, 367 (1996).
[51] D.J.S. Findlay and R.O. Owens, Nucl. Phys. **A279**, 385 (1977).
[52] 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).
[53] G.S. Adams, E.R. Kinney, J.L. Matthews, W.W. Sapp, T. Soos, R.O. Owens, R.S. Turley, and G. Pignault, Phys. Rev. C **38**, 2771 (1988).
[54] A.C. Shotter, S. Springham, D. Branford, J. Yorkston, J.C. McGeorge, B. Schoch, and P. Jennewein, Phys. Rev. C **37**, 1354 (1988).
[55] H. Goringer, B. Schoch, and G. Lührs, Nucl. Phys. **A384**, 414 (1982).
[56] J. Ryckebusch, L. Machenil, M. Vanderhaeghen, V. Van der Sluys, and M. Waroquier, Phys. Rev. C **49**, 2704 (1994).
[57] J. Gao *et al.*, Phys. Rev. Lett. **84**, 3265 (2000).
[58] S. Malov *et al.*, Phys. Rev. C **62**, 057302 (2000).
[59] M. Leuschner *et al.*, Phys. Rev. C **49**, 955 (1994).
[60] R.J. Woo *et al.*, Phys. Rev. Lett. **80**, 456 (1998).