1 Introduction

Our main aim in this work is to study the effects of meson-exchange currents (MEC) over asymmetries and recoil polarization observables in \( A(e, e'p)B \) reactions. The present DWIA+MEC model\(^1\),\(^2\) takes care of relativistic degrees of freedom by using semi-relativistic (SR) operators for the one-body current as well as for the two-body MEC. These SR currents are obtained by a direct Pauli reduction of the corresponding relativistic operators by an expansion in terms of missing momentum over the nucleon mass, \( O(p/m_N) \), while the current dependence on the transferred energy and momentum is treated exactly\(^3\). Relativistic kinematics for the ejected nucleon is assumed throughout this work. The final-state interactions (FSI) are incorporated through a phenomenological optical potential which, for high momentum transfer, is taken as the Schrödinger-equivalent form of a S-V Dirac optical potential. The use of the SR model becomes, as a starting point, a convenient way of implementing relativistic effects in existing non-relativistic descriptions of the reaction mechanism in order to explore the high momentum region.

2 DWIA Model of \( (\bar{e}, e'\bar{p}) \)

We consider the process in which an incident electron with four-momentum \( K^\mu_e = (\epsilon_e, k_e) \) and helicity \( h_e \) interacts with a nucleus \( A \), scatters through an angle \( \theta_e \) to four-momentum \( K'^\mu_e = (\epsilon'_e, k'_e) \) and is detected in coincidence with a nucleon with momentum \( p' = (p', \theta', \phi') \) and energy \( E' \). The four-momentum transferred to the nucleus is \( Q^\mu = K'^\mu_e - K^\mu_e = (\omega, q) \). We work in the Lab system with the \( z \)-axis in the \( q \) direction and the \( x \)-axis in the direction defined by the \( k_e \)-component perpendicular to \( q \). The polarization of the final nucleon is measured along an arbitrary direction defined by the unitary vector \( \vec{s} \). Results will be shown as functions of the missing momentum \( p = p' - q = (p, \theta, \phi) \) for a
fixed value of the excitation energy of the (discrete) final state of the daughter nucleus. Assuming plane waves for the electrons and neglecting the nuclear recoil, the cross section can be written in the extreme relativistic limit

\[
\frac{d\sigma}{d\epsilon' d\Omega'} = \Sigma + h\Delta, \tag{1}
\]

where a separation has been made into terms involving polarized and unpolarized incident electrons. Using the general properties of the leptonic tensor it can be shown that both terms, \(\Sigma\) and \(\Delta\), have the following decompositions:

\[
\Sigma = K\sigma_M \left( v_L R^L + v_T R^T + v_{TL} R^{TL} + v_{TT} R^{TT} \right), \tag{2}
\]

\[
\Delta = K\sigma_M \left( v_{TL} R^{TL'} + v_{T'} R^{T'} \right), \tag{3}
\]

where \(\sigma_M\) is the Mott cross section, \(K \equiv m_N p'/(2\pi\hbar)^3\), and the \(v_\alpha\)-coefficients are the usual electron kinematical factors.

The hadronic dynamics of the process is contained in the exclusive response functions \(R^K\), in which \(K = L, T, TL, TT, T', TL'\). Isolating the explicit dependences on the azimuthal angle of the ejected nucleon \(\phi' = \phi\), the hadronic responses can be expressed in the form

\[
R^L = W^L, \quad R^{TT} = \cos 2\phi W^{TT} + \sin 2\phi \tilde{W}^{TT}, \tag{5}
\]

\[
R^T = W^T, \quad R^{TT'} = \cos 2\phi W^{TT'} + \sin 2\phi \tilde{W}^{TT'}, \tag{6}
\]

where the 9 \(W\)-response functions \(W^K\) and \(\tilde{W}^K\) are totally specified by four kinematical variables \(\{E, \omega, q, \theta'\}\), and the polarization direction \(\{\theta_s, \Delta\phi = \phi - \phi_s\}\).

In the case of \((e, e'N)\) processes, the hadronic response functions are usually given by referring the recoil nucleon polarization vector \(\vec{s} = (s_l, s_n, s_t)\) to the barycentric system defined by the axes \(\vec{t} = p'/p', \vec{n} = q \times \vec{t}/q, \) and \(\vec{n} = \vec{n} \times \vec{t}\). It can be shown\(^4\) that the W-response functions (4–6) can be written as a sum of unpolarized and spin-vector dependent terms \(W^K = \frac{1}{2} W^K_{unpol} + W^K_{n}\), \(K = L, T, TL, TT, T', TL'\) and \(\tilde{W}^K = W^K_{l} + W^K_{l'}\), \(K = TL, TT, T', TL'\). Therefore a total of eighteen reduced response functions (i.e., independent of the polarization angles) enter in the analysis of these reactions.

Alternatively, the cross section (1–3) can be written in terms of the unpolarized one and of the induced and transferred polarizations and electron analyzing power

\[
\frac{d\sigma}{d\epsilon' d\Omega' d\hat{p}'} = \frac{1}{2} \sum_{unpol} \left[ 1 + \mathbf{P} \cdot \vec{s} + h(A + \mathbf{P}' \cdot \vec{s}) \right]. \tag{7}
\]

In our model the response functions are obtained by a multipole expansion following a general procedure developed for \((e, e'p)\) reactions from polarized nuclei\(^6\). We refer to our recent works\(^1,2\) for more details.
3 Electromagnetic Operators

In the present calculation we consider a semi-relativistic (SR) model for describing the electromagnetic one-body (OB) and two-body MEC current operators. The dependence on the transfer and final momenta, which can be large, is treated exactly. The SR-OB current, given by

\[ J_0(p', p) = \rho_c + i\rho_{so}(\cos \phi \, \sigma_x - \sin \phi \, \sigma_y)\chi, \quad (8) \]
\[ J_x(p', p) = iJ_m\sigma_y + J_c \chi \cos \phi, \quad (9) \]
\[ J_y(p', p) = -iJ_m\sigma_x + J_c \chi \sin \phi, \quad (10) \]

where \( \chi = (p/m_N)\sin \theta \), includes charge and spin-orbit parts, in the case of the time-component, and magnetization and convection parts, in the case of the transverse component.

\[ \rho_c = \frac{\kappa}{\sqrt{\tau}} G_E \quad \rho_{so} = \frac{\kappa}{2\sqrt{1 + \tau}} \frac{2G_M - G_E}{2G_M - G_E}, \quad (11) \]
\[ J_m = \sqrt{\tau}G_M \quad J_c = \frac{\sqrt{\tau}}{\kappa} G_E. \quad (12) \]

Here \( G_E \) and \( G_M \) are the electric and magnetic nucleon form factors. Note that this current differs from traditional non relativistic expansions by relativistic correction factors dependent on \( \kappa = q/2m_N \) and \( \tau = |Q^2|/4m_N^2 \).

![Feynman diagrams](image)

Figure 1: Feynman diagrams contributing to the two-body current with one pion-exchange. Contact (C) (a,b), pionic (P) (c), and isobar (∆) (d)–(g).

The two-body MEC operators of pionic (P), seagull or contact (S) and ∆-isobar kinds, displayed in the Feynman diagrams of Fig.1, have also been obtained by making use of a SR approach leading to simple prescriptions that
include relativistic corrections through multiplicative factors:

\[ J_{SR}^{MEC} = \frac{1}{\sqrt{1 + \tau}} J_{NR}^{MEC} \]  

(13)

where \( J_{NR}^{MEC} \) is the traditional non-relativistic MEC operator.

4 Results.

As an example we show results for a selection of observables in proton knock-out from the \( p_{1/2} \) and \( p_{3/2} \) shells of \(^{16}\text{O}\). In Fig.2 we show results for the \( A_{TL} \) asymmetry for \( q = 995 \) MeV/c and \( \omega = 439 \) MeV. \( A_{TL} \) is obtained from the difference of unpolarized cross sections measured at \( \phi' = 0 \) and \( \phi' = 180^\circ \) divided by the sum, hence this observable is particularly interesting because it does not depend on the spectroscopic factors. The effect of MEC is very small for low missing momentum values and it starts to be important for \( p \geq 300 \) MeV/c, a region where other relativistic effects are also playing a role. We show two sets of calculations: including the spin-orbit part of the optical potential \( V_{ls} \) (left panels) and without it (right panels). Note the discrepancy between the calculation and the data for low \( p \) in the case of \( p_{1/2} \) with the full potential. Our results show that the MEC effects for high missing momenta strongly depend on the FSI.

Coming back to the case of polarization observables, in Fig.3 we compare the computed transferred polarization with the recent experimental data from TJlab. Although being aware of the possible modifications that the “dynamical” relativistic ingredients may introduce in the present calculations, the results
Figure 3: Transferred polarization asymmetries and their quotient $P_t'/P_l'$ for proton knock-out from $^{16}\text{O}$ for $q = 1000$ MeV/c and $\omega = 450$ MeV. The electron energy is $\epsilon_e = 2450$ MeV and $\phi = 180^\circ$. Dotted lines: DWIA with OB current only; Solid: total OB+MEC result; Dot-dashed: The OB+MEC result but without the spin-orbit term of the optical potential. All of them have been obtained using the electromagnetic nucleon form factors of Galster. Dashed: The total OB+MEC result using instead the form factors of Gari-Krumplemann.

in this figure give us a clear indication of how much the DWIA calculation is expected to be modified after including the two-body (MEC) contributions (compare dotted with solid lines). We see that the effects of MEC lead to a global reduction of all of these polarization observables, hence the OB calculation using the Gari-Krumplemann form factors would be clearly located above the corresponding results including MEC (dashed lines). This makes our present results to come closer to the relativistic ones. Note also that the uncertainty introduced by the nucleon form factor parameterization shows up in $P_l'$, being negligible for $P_t'$.

Finally in Fig.4 we show an example of what typically we find regarding the effects of MEC on the 13 polarized response functions and the “fifth” response function for the $1p_{1/2}$ shell of $^{16}\text{O}$ for intermediate momentum transfer. In general, MEC effects over the transferred $T', TL'$ responses are small and tend to increase as $q$ goes higher, due mainly to the $\Delta$ current. The role of MEC gets clearly more important for the induced $T, TL$ and $TT$ polarized responses. Emphasis should be placed on $W_{TT'}$ and $W_{TT}$ (Fig.4) which are reduced at the maximum by $\sim 20\%$ and $\sim 30\%$, respectively. However these effects are negligible in the case of $p_{3/2}$. For $q = 1$ GeV/c the role of MEC diminishes. 5
In conclusion, our results are showing that MEC effects are in general small over the \((e,e')p\) observables for low missing momentum, although they are appreciable over some of the separate polarized response functions. Non negligible MEC effects are found for higher missing momentum \((p > 300\,\text{MeV/c})\) over the asymmetries and polarizations. Note however that in this region dynamical relativistic effects are also essential for describing the process, so it would be desirable to have a completely relativistic model including MEC in order to describe properly the high missing momentum dependence.

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