At present there exists a great interest in the search for evidence of possible modification of the nucleon form factors inside the nuclear medium. Recent theoretical work predicts changes in the form factors within the experimental limits. Importantly, the longitudinal to sideways transferred polarization ratio has been identified as being ideally suited for such studies, as these polarization observables are believed to be the least sensitive to most standard nuclear structure uncertainties while their ratio shows a high sensitivity to the ratio of the electric to magnetic form factors. The kinematic regime where the measurements have been undertaken is at relatively high energy and it is clear that relativistic effects in wave functions and operators are essential. In the relativistic distorted wave impulse approximation (RDWIA), nucleon wave functions are described by solutions of the Dirac equation with scalar and vector (S-V) potentials, and the relativistic free nucleon current operator is used. So far, RDWIA calculations for cross sections and response functions at low and high missing momenta have clearly improved the comparison with experimental data over the previous non-relativistic approaches. In this work we focus on the analysis of polarized $^{16}O(\vec{e}, e'\vec{p})^{15}N$ observables. Our aim is to explore a selected set of model dependences that could contaminate any attempt to infer medium modifications, mainly related to the description of FSI and to the role played by relativity.

In what follows we briefly review the general formalism needed to describe coincidence $(\vec{e}, e'\vec{p})$ reactions. We consider plane waves for the incoming and outgoing electron (treated in the extreme relativistic limit) and the Born approximation (one virtual photon exchanged). When the incoming electron is polarized and the final nucleon polarization is measured, the differential cross...
section can be written as

$$\frac{d\sigma}{d\varepsilon_e d\Omega_e d\Omega_F} = \frac{\sigma_0}{2} [1 + P \cdot \sigma + h(A + P' \cdot \sigma)],$$

(1)

where the variables \{\varepsilon_e, \Omega_e\} refer to the scattered electron and \Omega_F to the ejected nucleon. The term \sigma_0 is the unpolarized cross section, \(h\) is the incident electron helicity, \(A\) denotes the electron analyzing power, and \(P\) (\(P'\)) represents the induced (transferred) polarization. Here we limit our attention to the longitudinal and sideways transferred polarization asymmetries \(P'_l, P'_s\).

Within RDWIA, the nucleon current matrix elements needed to compute each observable is calculated as

$$J^\mu_N(\omega, q) = \int d\mathbf{p} \Psi_F(\mathbf{p} + q) \hat{J}^\mu_N \Psi_B(\mathbf{p}),$$

(2)

where \(\Psi_B\) and \(\Psi_F\) are relativistic wave functions describing the initial bound and final outgoing nucleons, respectively, and \(\hat{J}^\mu_N\) is the relativistic one-body current operator. The bound wave function \(\Psi_B\) is a four-spinor with well-defined parity and angular momentum quantum numbers \(\kappa_b, \mu_b\), obtained within the framework of the relativistic independent particle shell model. The wave function for the ejected proton \(\Psi_F\) is a scattering solution of a Dirac-like equation, which includes S-V global optical potentials obtained by fitting elastic proton scattering data. Finally, for the nucleon current operator we consider the two usual choices denoted as CC1 and CC2.

As is well known, the presence of the S-V potentials leads to a significant dynamical enhancement of the lower components of the Dirac solution at the nuclear interior. This effect has been also referred to as spinor distortion. The analysis of these dynamical effects can be done by constructing properly normalized four-spinor wave functions where the negative-energy components have been projected out. Thus, instead of the fully relativistic expression given in Eq. (2), the nucleon current is evaluated as

$$J^{\mu(++, +)}_N(\omega, q) = \int d\mathbf{p} \Psi_F^{(+)}(\mathbf{p} + q) \hat{J}^\mu_N \Psi_B^{(+)}(\mathbf{p}),$$

(3)

where \(\Psi_B^{(+)}(\mathbf{p})\), \(\Psi_F^{(+)}(\mathbf{p})\) is the positive-energy projection of \(\Psi_B(\mathbf{p})\), \(\Psi_F(\mathbf{p})\). Notice that the relationship between lower and upper components in the projected wave functions is similar to that corresponding to free nucleon wave functions, but with the positive-energy projectors depending explicitly on the integration variable \(\mathbf{p}\). An additional approach, referred to as asymptotic projection, consists of introducing the asymptotic values of the momenta into the positive-energy projectors. This asymptotic projection is very similar to the effective momentum approximation (EMA-noSV) introduced originally by Kelly, where the four spinors used have the same upper components as those of the Dirac equation solutions, but the lower components are obtained by enforcing the “free” relationship between upper and lower components and using the asymptotic momenta at the nucleon vertex.
We analyze the recoil nucleon transferred polarization asymmetries for proton knockout from $^{16}O$. Coulomb gauge has been assumed and the bound nucleon wave function is obtained using the parameters of the set NLSH$^7$. Results computed with other parameterizations are found to be similar. For the outgoing nucleon wave function, we show and compare results using different relativistic optical potentials parametrizations$^8$, which provide the best phenomenological global optical potentials available in the literature. Finally, the nucleon form factor parameterization of Gari and Krumpelmann$^9$ is considered.

The kinematics is chosen with $(q, \omega)$ constant, $q = 1 \text{ GeV/c}$ and $\omega = 439 \text{ MeV}$, yielding $|Q|^2 = 0.8 \text{ (GeV/c)}^2$. This roughly corresponds to the experimental conditions of experiments E89-003 and E89-033 performed at JLab$^{10}$. In Fig. 1 we compare the results within the relativistic plane wave impulse approximation (RPWIA), that includes the dynamical enhancement of the lower components of the bound nucleon wave function but neglects the distortion effects in the scattered wave function, with plane wave calculations after projecting out these negative-energy components, denoted as PWIA. As explained in$^{11}$, the RPWIA and their respective positive-energy projection results mainly differ for $p \geq 250 - 300 \text{ MeV/c}$, although there are sizeable differences even for low/medium $p$ values, in particular for $P'_s$. More importantly, RPWIA results present oscillations that are completely absent in PWIA. This is connected with the factorization property which is exactly recovered when projecting out the negative energy components. RDWIA results evaluated using the energy-dependent, $A$-independent optical potential derived for $^{16}O$ (EDAIO), are also presented in Fig. 1. For low missing momentum values $p \leq 200 \text{ MeV/c}$, the effects of FSI do not modify substantially the behaviour of the polarization asymmetries, particularly when compared with PWIA. Similar comments also apply to the $p_{3/2}$ and $s_{1/2}$ shells, although in these cases a smaller effect is observed for $P'_s$. It is important to point out that FSI lead to a significant reduction of the individual response functions. Hence, the results in Fig. 1 clearly indicate
that for low $p$-values, FSI effects are partially cancelled when constructing the transferred polarization asymmetries. For high missing momentum, $p \geq 200$ MeV/c, FSI strongly modify the behaviour of the polarizations. The oscillations appearing in RPWIA results are also present in RDWIA, although the maxima and minima are located at different $p$-values.

Next we focus on the uncertainties introduced by different relativistic optical potentials. In Fig. 2 we present $P'_{l}$ and $P'_{s}$ for the $p_{1/2}$ shell evaluated using three different relativistic optical potential parameterizations: EDAIO, EDAD1 and EDAD2. Transferred polarization asymmetries are expected to be relatively insensitive to the choice of optical potential at low missing momenta. This can be seen in Fig. 1, at least up to $p = 150$ MeV/c. For larger $p$-values, $P'_{l}$ exhibits a strong dependence on the optical potential. Note also that the current operator choice gives rise to very significant differences in $P'_{l}$ within this $p$-region, being of the same order as those introduced by the optical potentials. In the case of $P'_{s}$, in general less dependence on the interaction model as well as on the current is observed. We conclude that both transferred polarization asymmetries at moderate $p$ values ($p \approx 100$ MeV/c) are independent of the optical potential choice. Increasing $p$ from here, each optical potential corresponds to a different curve especially for $P'_{l}$. However, caution should be placed on this kinematical region because other ingredients beyond the impulse approximation, such as meson exchange currents (MEC), $\Delta$-isobar, short-range correlations, etc., may also play a crucial role.

In Fig. 3 we focus on dynamical relativistic effects. All of the results have been obtained using EDAIO. To make explicit the effects introduced by spinor distortion, in each graph we compare the fully relativistic calculations (blue lines) with the results after projecting out the negative-energy components (pink lines). Finally we also present for reference the results corresponding to the EMA-noSV approach (green line). In contrast to the plane wave limit, results in Fig. 3 make it clear that, within the relativistic distorted wave approximation, the oscillatory behaviour persists even after projecting the bound and scattered proton wave
functions over positive-energy states. The same comment applies to the EMA-noSV approach. On the contrary, this last fact does not apply to the left-right asymmetry $A_{TL}$, as we can see in the right panel of Fig. 3. Note also that model dependences at low $p$ are substantially larger for $A_{TL}$.

Finally, we compare our calculations with the experimental data measured at JLab. Fig. 4 shows $P'_l$ (top panels), $P'_s$ (middle panels) and the ratio $P'_s/P'_l$ (bottom panels) for proton knockout in $^{16}O$ from the $1p_{1/2}$ (left panels), $1p_{3/2}$ (middle panels) and $1s_{1/2}$ (right panels) shells. Note the change of notation for the transverse polarization ratio. Curves corresponding to RDWIA, positive-energy projected and EMA-noSV calculations are presented. All of the results have been obtained using the EDAIO potential. As shown, all theoretical calculations satisfactorily reproduce the data, improving somehow the general agreement compared with previous semi-relativistic (SR) analyses.

Summarizing, an analysis of recoil nucleon polarized $(e', e\bar{p})$ asymmetries within RDWIA has been performed in the case of proton knockout from $^{16}O$ and quasi-perpendicular kinematics. Effects linked to the description of FSI and dynamical relativity have been studied. FSI constitutes a basic ingredient in order to get reliable results, and our model presents a great stability for low missing momenta. Also effects linked to relativity are shown to be quite modest in this $p$-region. We conclude that this region may allow to look for other more exotic effects such as medium modifications of the nucleon form factors. On the other hand, although being aware of the experimental difficulties, measurements at higher $p$ could provide a good test of the different model ingredients. Other effects that go beyond the impulse approximation, such as meson exchange currents and the $\Delta$-isobar contribution, may also play a very important role. These remain to be investigated in a relativistic context. In the final analysis, any interpretation in terms of medium modified nucleon form factors requires having excellent control of all of these model dependences.

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Figure 3: $P'_l$ and $P'_s$ (left and middle panels, respectively) and $A_{TL}$ (right panel) for the $1p_{1/2}$ shell in $^{16}O$ (see text for details). All results correspond to CC2 current choice.
Figure 4: $P'_l$, $P'_t$ and the ratio $P'_t/P'_l$ compared with experimental data (see text).

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