Polarization observables in electronuclear two-nucleon knockout

Jan Ryckebusch *, Wim Van Nespen and Dimitri Debruyne
Department of Subatomic and Radiation Physics
University of Gent, Proeftuinstraat 86, B-9000 Gent, Belgium
(May 2, 2017)

Differential (e,e′pp) measurements are presently recognized as a way of studying short-range correlations in finite nuclei. The (e,e′p̅p) and (e,e′p̅n) differential cross section and polarization observables are studied in a microscopic model that accounts for the short-range correlations, outgoing-nucleon distortions, meson-exchange and Δ-isobar currents. It is pointed out that polarization observables represent an attractive alternative for absolute electronuclear two-nucleon knockout measurements. In the polarization transfer P′ for (e,e′p̅p), the effect of central short-range correlations is predicted to be large while at the same time the final-state interaction effects are small.

Keywords : electronuclear nucleon production ; polarization observables

For long, polarization degrees of freedom have been advocated as an attractive way of obtaining nucleon and nuclear structure information from exclusive electron scattering experiments. Often, polarization observables allow for accessing very specific combinations of structure functions with transparent physical interpretations. Recently, explored examples include the precise measurement of the neutron electromagnetic form factors for which extensive programs were set up at the intermediate-energy electron accelerator facilities MAMI, Bates and TJNAF. In these neutron form factor studies, polarized electron beams are used in combination with either a polarized target (3He(e,e′)) or an ejectile polarimeter (d(e,e′n)p).

Although various electronuclear reactions, like the semi-inclusive eA→ e′pX [1] and the inclusive (e,e′) [2,3], have been shown to exhibit some sensitivity to the short-range structure of finite nuclei, the triple-coincidence (e,e′pp) reaction, albeit a rather involving coincidence reaction, is probably one of the most direct ways of probing the two-nucleon correlations [4]. Not only does the electromagnetic interaction avoid complications with respect to the initial-state interaction, the measured properties of the two detected protons makes it possible to reconstruct the characteristics of the correlated diproton in the target nucleus. Recently, it was experimentally verified [4–7] that the inclusive pp) reaction is dominated by photoabsorption on 1S0 diprotons [6]. This observation confirms the potential of the exclusive (e,e′pp) reaction to probe the short-range part of the two-nucleon correlations in the nuclear medium. At the same time, it is now widely recognized that electromagnetic production of a Δ33 resonance with subsequent π0 decay and reabsorption on a proton represents an important competing mechanism that also feeds the (e,e′pp) reaction. Accordingly, it is of the utmost importance to find observables that allow for an unambiguous determination of the short-range correlation effects out of the background of competing processes. As the (e,e′pp) strength generated through intermediate Δ33 creation is predominantly transverse, variables that depend strongly on the longitudinal channel are the obvious candidate to meet this condition. Here, we investigate the potential of polarization observables to gain a better quantitative control on the different reaction mechanisms contributing to direct electronuclear two-nucleon knockout. With the eye on future experimental investigations of proton-neutron correlations at TJNAF and MAMI, we also address the (e,e′pn) channel in our investigations.

The eightfold A(e,e′N1N2) differential cross section for excitation of a narrow discrete state in the residual nucleus reads

\[
\frac{d^8\sigma}{dE_1d\Omega_1d\Omega_2d\vec{e}d\vec{e}'}(\vec{e},e'N_1N_2) = \frac{1}{4(2\pi)^8} p_1 p_2 E_1 E_2 f^{-1}_{rec} \sigma_M \\
\times \left[ v_T W_T + v_L W_L + v_LT W_LT + v_TT W_TT + h \left( v_LT' W_LT' + v_TT' W_TT' \right) \right]
\]

(1)

where h=±1 is the incoming electron helicity, \( f_{rec} \) a recoil factor and \( \sigma_M \) the Mott cross section. The functions \( v_i \) (i=L,T,LT,TT) and \( v_i' \) (i=LT,TT) contain the electron kinematics. They are defined along the conventions of Ref. [6].

*E-mail : jan.ryckebusch@rug.ac.be
The polar and azimuthal angles are determined relative to the electron scattering plane which is conventionally taken as the $xz$ plane (Figure 3). The above differential cross section is of the familiar form

$$
\frac{d^8\sigma}{dE_1d\Omega_1d\Omega_2d\Omega_{e'}}(\vec{e}, e'N_1N_2) = \sigma_0(1 + hA),
$$

(2)

with $A$ the electron analyzing power and $\sigma_0$ the unpolarized cross section. All of the structure functions $W$ in the cross section of Eq. (4) depend on the variables $(q, \omega, p_1, p_2, \theta_1, \theta_2$ and $\phi_1 - \phi_2$) in a non-trivial manner. Three terms ($W_{LT}$, $W_{TT}$ and $W_{LT}'$) have an additional azimuthal dependency on the variable $\phi_1 + \phi_2$ that can be pulled out of the structure functions [13]. In doing this, each of the structure functions $W_{LT}$, $W_{TT}$ and $W_{LT}'$ falls apart in two terms [11]. In experiments in which none of the polarizations of the produced hadrons are determined, the $W_{LT}'$ vanishes in all kinematical situations and the $W_{LT}$ in coplanar kinematics.

Here, we also consider the situation that the polarization of one ejectile is determined. In that particular case, one obtains a differential cross section in the standard form

$$
\frac{d^8\sigma}{dE_1d\Omega_1d\Omega_2d\Omega_{e'}}(\vec{e}, e'\hat{N}_1N_2) = \sigma_0 \left[ 1 + \vec{P} \cdot \vec{\sigma} + h(A + \vec{P}' \cdot \vec{\sigma}) \right],
$$

(3)

here $\vec{P}$ is the induced polarization and $\vec{P}'$ the polarization transfer. As is commonly done, the polarization of the escaping hadron is expressed in terms of the reference frame determined by the following unit vectors

$$
\hat{\vec{i}} = \frac{\vec{p}_1}{|\vec{p}_1|}, \quad \hat{n} = \frac{\vec{q} \times \vec{p}_1}{|\vec{q} \times \vec{p}_1|}, \quad \hat{\vec{i}} = \hat{n} \times \hat{\vec{i}}
$$

(4)

with $\hat{n}$ pointing in the direction of the momentum $\vec{p}_1$ of the proton for which the recoil polarization is determined. In the coplanar case, $\hat{\vec{i}}$ is in the electron scattering plane and $\hat{n}$ is perpendicular to it. This situation is illustrated in Figure 3. The experimental determination of the induced polarization and polarization transfer along one of these directions ($\vec{P}_i$, $\vec{P}'_i$ with $i=(n,l,t)$) is found by measuring the following ratios

$$
P_i = \frac{\sigma(s_{1i} \uparrow) - \sigma(s_{1i} \downarrow)}{\sigma(s_{1i} \uparrow) + \sigma(s_{1i} \downarrow)},
$$

$$
P'_i = \frac{\sigma(h = +1, s_{1i} \uparrow) - \sigma(h = -1, s_{1i} \downarrow) - [\sigma(h = +1, s_{1i} \downarrow) - \sigma(h = -1, s_{1i} \downarrow)]}{\sigma(h = +1, s_{1i} \uparrow) + \sigma(h = -1, s_{1i} \downarrow) + [\sigma(h = +1, s_{1i} \downarrow) + \sigma(h = -1, s_{1i} \downarrow)]}
$$

(5)

where $s_{1i} \uparrow$ indicates that the proton labelled as “1” is spin-polarized in the positive $\hat{n}$-direction, and $s_{1i} \downarrow$ in the negative.

In a recent publication [12], it was pointed out that the structure of the finite nucleus can act as a filter for the different mechanisms contributing to the $(e,e'pp)$ reaction. Elaborating on the suggestion that the structure of the final state may be selective as far as the dominating reaction mechanisms is concerned, we have considered the $^{16}$O$(e,e'pp)$ reaction for excitation of specific states in the discrete part of the energy spectrum in the residual nucleus. This reaction is currently under investigation at NIKHEF [7] and MAMI [6]. The numerical calculations of which the results are presented here are performed within the model outlined in Ref. [13]. It involves a non-relativistic distorted wave calculation in a shell-model framework. The discrete final state of the residual nucleus is conceived as a linear combination of two-hole states relative to the ground-state of the target nucleus. The distorted outgoing nucleon waves are generated through a partial wave expansion in terms of the continuum eigenfunctions of the mean-field potential. As the latter is also used to calculate the bound-state wave functions the orthogonality between initial and final states is obeyed thus avoiding that spurious effects contribute to the calculated cross sections. This procedure neglects the final-state interaction between the escaping nucleons. The $\Delta p \rightarrow pp$ decay is assumed to be regulated by $\pi^0$ decay. In constructing the two-body isobaric current that corresponds with this process, the standard $\pi N\Delta$ and $\gamma N\Delta$ couplings are introduced [13]. The $\Delta$ propagators that are used in the present work are described in Ref. [13]. Apart from the standard $\pi N$ decay width, an extra 40 MeV complex width is introduced. The latter accounts for the medium modifications and was found necessary in order to reach a fair agreement between the model predictions and the $^{12}$C($\gamma, pp$) and $^{12}$C($\gamma, pn$) data in the $\Delta$-resonance region [14]. The ground- and final-state correlations are implemented through the introduction of a central Jastrow correlation function $g(r_{12})$. In calculating the transition between the (correlated) initial and (correlated) final state we adopt a cluster expansion in terms of the correlation function retaining these terms with a single correlation line that is directly connected to the two ejectiles. This procedure is equivalent with a lowest-order cluster expansion in which all three-point diagrams
have been neglected \[13,15\]. Recent calculations addressed the amount of two-nucleon knockout strength induced by the ground-state correlations to the inclusive longitudinal \(^{12}\text{C}(e,e')\) structure function starting from a correlated groundstate and evaluating both the two-point and three-point diagrams. The latter were stressed to be essential in order to guarantee the wave-function normalization in an inclusive \((e,e')\) calculation. Nevertheless, the two-point diagrams were found to represent the major source of 2N knockout strength. The 2N knockout strength from the three-point diagrams was found to be considerably smaller and to simply sum up to the strength from the two-point diagrams. Here, we restrict ourselves to exclusive \((e,e'\text{NN})\) reactions in kinematics that favour two-nucleon processes. The normalization of the final \(A\)-body wave functions is fixed through its asymptotic behaviour. All this justifies the neglect of the three-point diagrams that would rather play a role in kinematic regions where three-nucleon kinematics is favoured. Unless otherwise specified the results of this paper are obtained with the central correlation function from Ref. \[16\] that is obtained from a G-matrix calculation.

The specific kinematic situation in which the two hadrons are detected along the direction of the three-momentum transfer \(\vec{q}\) is referred to as “super-parallel” kinematics. As the resonant terms in the elementary pion photoproduction operator are transverse in nature \[17,13\] one expects that contributions from \(\gamma^*pp \rightarrow \Delta^+p \rightarrow ppn^0 \rightarrow pp\) to \((e,e'pp)\) will be suppressed in “super-parallel” kinematics. In this particular case, only two structure functions \((W_L\) and \(W_T)\) will contribute to the differential cross section and the polarization observables \(P_n, P'_L, P'_T\) are uniquely determined by the \(W_{LT}, W'_{LT}\) and \(W''_{LT}\) terms respectively. In that sense, super-parallel kinematics in \((e,e'pp)\) resembles the selectivity of the \((\vec{e},e')\) situation in parallel kinematics \[14,13\]. The results of Figure 2 are obtained in super-parallel kinematics for electron energies and angles that coincide with the central values adopted in the MAMI measurements \[13\]. The cross sections and polarization observables of Fig. 2 are shown as a function of the missing momentum. In super-parallel kinematics, this variable is determined by \(|\vec{P}| = -|\vec{p}_1| + |\vec{p}_2| + |\vec{q}|\), where we have adopted the convention that \(\vec{p}_1\) is parallel and \(\vec{p}_2\) anti-parallel to \(\vec{q}\). The variation in missing momentum is reached by varying the kinetic energy of the nucleon escaping in the direction of the three-momentum transfer \(\vec{q}\). Negative missing momenta correspond with a fast forward and a slow backward proton. As the missing momentum gets larger the backward going nucleon (anti-parallel to \(\vec{q}\)) gains in kinetic energy. For the nuclear structure inputs in our calculations we rely on the results of a recent calculation \[20\] that predicted the following two-hole structure for the \(^{14}\text{C}\) wave functions \(|0^+; \text{g.s.}\rangle = 0.77 \left(\left|1(p_{1/2})^{-2}, 0^+\right\rangle + 0.18 \left(\left|1(p_{3/2})^{-2}, 0^+\right\rangle \right)\right) + |1^+; E_x = 11.3\ \text{MeV}\rangle = 0.77 \left(\left|1(p_{1/2})^{-1}(1(p_{3/2})^{-1}, 1^+\right\rangle\right)\). A recent analysis of the \(^{16}\text{O}(e,e'pp)\) data \[1\] provided some evidence for the realistic character of these wave functions. More detailed information about the different wave function amplitudes will become available from high-resolution experiments that are presently under analysis \[3\]. The curves of Figure 2 confirm that the structure of the final state is very selective with respect to the reaction mechanism. Whereas short-range correlations dominate the ground-state transition their effect is hardly visible for the \(1^+\) transition that is completely dominated by intermediate \(\Delta^+\) creation and subsequent two-proton knockout. The dominant reaction mechanism reflects itself very clearly in the polarization observable \(P_n\) that is driven by longitudinal-transverse interference effects. The predicted longitudinal excitation of the \(1^+\) state is so marginal over the whole missing momentum range covered that the \(P_n\) is almost vanishing. For the \(0^+\) state, on the other hand, the longitudinal strength produces a large normal component of the induced polarization through interference of the central correlation effects with the transverse background. Clearly, the \(P_n\) is a measure for the strength induced by the central short-range correlations. Also shown in Fig. 2 is the result of a plane-wave (PW) calculation. This limiting case was reached by using spherical Bessel functions in the partial wave expansions for the two ejectiles without affecting the other ingredients of the calculations. The PW groundstate and 11.3 MeV missing momentum distribution look respectively like an \(F_{1S}\) and \(F_{1P}\) center-of-mass distribution for the initial pair. Note that this is not such a trivial result as one might conceive it, as the PW approximation is not a sufficient condition to reach a formal factorization of the \((e,e'pp)\) cross section in terms of \(F_{NL}(P)\) (\(NL\) denoting the quantum numbers corresponding with the c.o.m. motion of the nucleon pair) \[21,22\]. The apparent scaling in terms of the \(F_{NL}(P)\) in unfactorized calculations lends support for the factorized approaches to electromuclear diproton knockout. The major effect of the distortion effects is a reduction of the cross section and a shift in missing momentum. This shift can be understood by considering that there is substantial asymmetry in the kinetic energies of the two ejectiles in super-parallel kinematics.

The corresponding \((e,e'pn)\) results for the two-proton knockout results of Figure 2 are shown in Figure 3. We have considered a \((1(p_{1/2})^{-2}\) shell-model structure for the lowest two states in \(^{14}\text{N}\). In the proton-neutron knockout calculations also the pion-exchange currents are included. This additional source of proton-neutron knockout strength, which is transverse in nature, makes the relative contribution of the central short-range correlations to the differential cross section to be smaller. The minor role of the central correlations relative to the meson-exchange and isobaric contributions makes the \(P_n\) to be relatively small for proton-neutron knockout in super-parallel kinematics. The predicted missing momentum dependence for the \(0^+\) state bears a strong resemblance with the corresponding \((e,e'pp)\) results of Fig. 2 and has a clear S-wave shape, pointing towards photoabsorption on proton-neutron pairs.
in a relative $^1S_0(T=1)$ state. Strong absorption on proton-neutron pairs in a relative $^{2S+1}P_J$ state would imply a missing momentum dependence for the $1^+$ state that has a considerable $F_{1p}$ component. This situation was encountered for the $1^+$ state in the proton-proton knockout results of Fig. 2. The calculated $(e,e'pn)$ missing momentum dependence, however, reflects a $F_{NS}(N=1,2)$ shape which for the considered shell-model configuration points towards photoabsorption on $^3S_1(T = 0)$ and $^3D_1(T = 0)$ proton-neutron pairs \cite{23}. This result confirms the strong likelihood of the electromagnetic probe to couple to “quasi-deuteron” like proton-neutron pairs in the target nucleus and lends support for exploiting the $(e,e'pn)$ to study tensor correlations in the medium. Globally, in super-parallel kinematics, the induced polarization component $P_n^\perp$ is a measure for the amount of two-nucleon knockout strength that can be attributed to the central short-range correlations.

Two-nucleon knockout studies that discriminate between the different final states impose hefty requirements as far as experimental energy resolution is concerned. In Fig. 4 predictions for proton-proton and proton-neutron knockout from $^{12}$C are shown. For these results we have integrated the strength in the full (p-shell)$^2$ region (which would correspond with a missing-energy range of roughly $28 \leq E_{2\text{m}} \leq 40$ MeV) creating conditions that would be accessible in a moderate energy resolution experiment. We considered so-called quasi-deuteron (QD) kinematics that is defined by imposing the condition $F = 0$. For a given missing energy, polar angle $\theta_p$ and electron kinematics this constraint determines the variables $T_p,T_n$ and $\theta_n$ in $(e,e'pn)$ and likewise for the $(e,e'pp)$ case. Note that the $\theta_p=0^\circ$ point in QD kinematics corresponds with the $P=0$ situation in super-parallel kinematics. Thus, for the $\theta_p=0^\circ$ case in QD kinematics, the $P_p$ and $P'_p$ are vanishing when solely transverse strength is contributing to the cross section. Comparing the $(e,e'pn)$ to the $(e,e'pp)$ predictions, the latter are globally characterized by larger polarization observables. In line with the conclusions drawn in super-parallel kinematics, the effect of the central correlations is substantial in the $(e,e'pp)$ channel and rather small in the $(e,e'pn)$ case. Also shown in Figure 4 is the result of a plane wave calculation. As is usually the case, the $P'_p$ and $P'_n$ that involve polarized electrons are less affected by the distortion effects related to the final-state interaction of the ejectiles with the residual nucleus, than the unpolarized differential cross section and the induced polarization.

We realize that polarization measurements in triple-coincidence reactions are a challenging task. On the other hand, we deem it to be a valid alternative for absolute cross section measurements as the polarization observables are predicted to be rather large. From an experimental point of view the induced polarization and polarization transfer can be determined through ratios which allows one to divide out some systematic uncertainties and bypass some tedious calibration tasks. Also in polarized one-nucleon knockout there are good chances of observing indirect indications for two-nucleon knockout. Recent measurements at MIT-Bates \cite{24} revealed a non-zero induced polarization ($0 \leq P_n \leq 0.5$) for the deep continuum (missing energies larger than 50 MeV) in $^{12}$C$(e,e'p)$. This missing-energy range is open for two (and more) nucleon knockout. The above results suggest that the normal component of the induced polarization $P_n$ in electronuclear two-nucleon knockout is quite sizeable and therefore the measurements of Ref. \cite{23} are not incompatible with a picture in which 2N knockout mechanisms are feeding the $(e,e'p)$ reaction at high missing energies.

Concluding, we have studied the polarization observables in electronuclear two-nucleon knockout from finite nuclei. Particularly in the $(e,e'pp)$ case the polarization observables turned out to be large and sensitive to the presence of scalar short-range correlations in the ground-state of the target nucleus. The double polarization observable $P'_p$ has the additional advantage of being almost insensitive to final-state interaction effects.

**Acknowledgement**

This work was supported by the Fund for Scientific Research of Flanders. Stimulating discussions with G. Rosner are gratefully acknowledged.

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FIG. 1. The coordinate system for the coplanar $\Lambda(\vec{e}e'\vec{p}N)$ reaction in the laboratory frame. The recoil polarimetry is performed on the nucleon characterized by the four-vector $P_1$. 

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FIG. 2. The missing momentum dependence of the $^{16}\text{O}(e,e'pp)^{14}\text{C}(0^+;\text{g.s.})$ differential cross section and polarization observables in superparallel kinematics. The solid curve is calculated in the distorted-wave approximation including the $\Delta$-current and ground-state correlations. The latter are implemented through the Jastrow function from Ref. [16]. The dot-dashed curve is the equivalent of the solid line but is calculated with plane wave outgoing nucleons waves. The dashed line is the result of a distorted-wave calculation including only the $\Delta$ current.
$^{16}$O(e,e'pn)$^{14}$N(0$^+$; $E_x$=2.31 MeV)

**FIG. 3.** As in figure 2 but now for the $^{16}$O(e,e'pn) reaction.
FIG. 4. The polar angle dependence of the $^{12}$C(e,e′pp) and (e,e′pn) differential cross section and polarization observables in quasi-deuteron kinematics (P=0). The strength is integrated over the missing-energy range where strength from the (1p)$_2^+$ shells is expected. The solid curves and dotted curves are calculated in the distorted-wave approximation including the Δ-current and ground-state correlations. The solid (dotted) curve is obtained with the correlation function from Ref. [16] ([24]). The dot-dashed curve is the equivalent of the solid line but is calculated with plane wave outgoing nucleons waves. The dashed line is the result of a distorted-wave calculation including only the Δ current.