

# POLARIZATION DEGREES OF FREEDOM IN TWO-NUCLEON KNOCKOUT FROM FINITE NUCLEI

Jan Ryckebusch \* and Wim Van Nespen  
*Department of Subatomic and Radiation Physics*  
*University of Gent*  
*Proeftuinstraat 86, B-9000 Gent, Belgium*

Polarization observables for the  $A(e, e'NN)$  and  $A(\gamma, NN)$  reactions are a powerful tool to study nucleon-nucleon correlations in the nuclear medium. In this paper, model calculations for the  ${}^4\text{He}(e, e'pp)$ ,  ${}^{16}\text{O}(\vec{e}, e'\vec{pp})$ ,  ${}^{16}\text{O}(\vec{e}, e'\vec{pn})$  and  ${}^{12}\text{C}(\vec{\gamma}, \vec{p}N)$  reactions are presented. The sensitivity of the differential cross sections and polarization observables to central and spin-dependent nucleon-nucleon correlations is discussed.

## I. INTRODUCTION

The holy grail in the study of electromagnetically induced two-nucleon knockout processes is the detection of signals and study of the short-range correlations in the nuclear medium. Eventhough the latter are generally accepted to be indispensable for the binding of nuclei, a direct experimental confirmation of their existence is still lacking. Our goal here is to show that polarization degrees of freedom in  $A(e, e'NN)$  and  $A(\gamma, NN)$  studies offer good opportunities to probe and study nucleon-nucleon correlations. To do this we present results of model calculations in a non-relativistic framework. We start from a shell-model formulation for the two-nucleon knockout reaction process, implement corrections for central and spin-dependent correlations and then show how important these correlations are for  $A(\gamma, NN)$  and  $A(e, e'NN)$  differential cross sections and polarization observables. These studies are conducted in a model which also accounts for the “background” of meson-exchange and  $\Delta$ -isobar currents. These conventional two-nucleon currents are unmistakably a strong source of two-nucleon knockout strength and complicate the interpretation of the data in terms of nucleon-nucleon correlations.

The paper is organized as follows. In Section 2 we briefly review the two-nucleon knockout observables in terms of structure functions and discuss their dependence on the different observables. In Section 3 we present a framework that aims at extracting from the two-nucleon knockout observables the information on the nucleon-nucleon correlations. Section 4 discusses the model which was employed to calculate the cross sections and polarization observables. In Section 5 we apply this machinery to the calculation of  ${}^{16}\text{O}(\vec{e}, e'\vec{pp})$ ,  ${}^{16}\text{O}(\vec{e}, e'\vec{pn})$  and  ${}^{12}\text{C}(\vec{\gamma}, \vec{N}N)$  observables.

## II. STRUCTURE FUNCTIONS AND POLARIZATION OBSERVABLES IN $(E, E'NN)$ AND $(\gamma, NN)$

The  $(e, e'NN)$  differential cross section for excitation of specific states in the residual nucleus can be cast in the form

$$\frac{d^8\sigma}{dE_1 d\Omega_1 d\Omega_2 d\epsilon' d\Omega_{e'}}(\vec{e}, e'N_1N_2) = \frac{1}{4(2\pi)^8} p_1 p_2 E_1 E_2 f_{rec}^{-1} \sigma_M$$

$$\times \left[ v_T W_T + v_L W_L + v_{LT} W_{LT} + v_{TT} W_{TT} + h \left[ v'_{LT} W'_{LT} + v'_{TT} W'_{TT} \right] \right].$$

Here, all structure functions  $W$ 's depend on the variables  $(q, \omega, p_1, p_2, \theta_1, \theta_2)$  and  $\phi_1 - \phi_2$  in a non-trivial manner. In addition, the structure functions  $W_{LT}$ ,  $W_{TT}$  and  $W'_{LT}$  depend on the azimuthal angle of the center-of-mass (c.o.m.) of the active nucleon pair  $\Phi \equiv \frac{\phi_1 + \phi_2}{2}$ . This dependence reflects itself in factors of the form  $\sin(2\Phi)$  and  $\cos(2\Phi)$  that can be formally pulled out of the structure functions. The question arises whether the availability of polarized electrons is a great asset in two-nucleon knockout studies. For symmetry reasons, the structure function  $W'_{LT}$  is identical zero in coplanar kinematics and  $W'_{TT}=0$ . Additional observables come into reach of investigation when considering

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the possibility of performing recoil polarization measurements on one of the ejected nucleons. We express the recoil polarization in the reference frame determined by the unit vectors (Figure 1)

$$\hat{l} = \frac{\vec{p}_1}{|\vec{p}_1|} \quad \hat{n} = \frac{\vec{q} \times \vec{p}_1}{|\vec{q} \times \vec{p}_1|} \quad \hat{t} = \hat{n} \times \hat{l}.$$

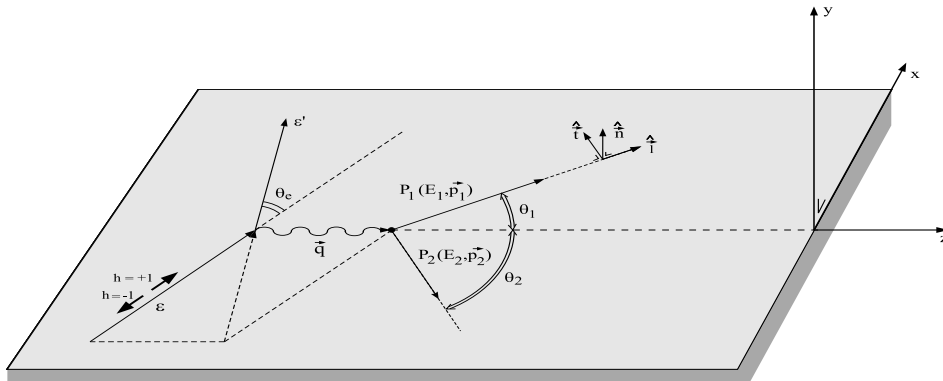


FIG. 1. Kinematic definitions for the  $A(\vec{e}, e'\vec{N}N)$  reaction in coplanar kinematics.

Recoil polarization observables can be determined through measuring **ratios**

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

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

where  $s_{1i} \uparrow$  denotes that nucleon “1” is spin-polarized in the positive  $i$  direction  $i=(n,l,t)$ . For the sake of completeness we mention that for real photons the differential cross section and photon asymmetry can be written as

$$\frac{d^4\sigma}{d\Omega_1 d\Omega_2 dE_1 dE_2} = \frac{1}{(2\pi)^5 2E_\gamma} p_1 p_2 E_1 E_2 \delta(E_{A-2} + E_1 + E_2 - E_A - E_\gamma) \frac{1}{2} W_T$$

$$\Sigma = \frac{d\sigma_{\parallel}(\vec{\gamma}, NN) - d\sigma_{\perp}(\vec{\gamma}, NN)}{d\sigma_{\parallel}(\vec{\gamma}, NN) + d\sigma_{\perp}(\vec{\gamma}, NN)} = -\frac{W_{TT}}{W_T},$$

### III. CENTRAL AND SPIN-DEPENDENT CORRELATIONS IN $(E, E'NN)$ AND $(\gamma, NN)$

Two-nucleon knockout observables have the potential of providing information on the following transition matrix elements

$$m_F^{fi}(\lambda = \pm 1, 0) = \langle \widetilde{\Psi}_f(E_f) | J_{\pm 1, 0}^{[1]} + J_{\pm 1}^{[2]} | \widetilde{\Psi}_i(E_i) \rangle, \quad (1)$$

where the exclusive character of the reaction imposes the final state to be of the form

$$|\Psi_f\rangle = \left| \Psi_f^{A-2}(E_x, J_R M_R); \vec{p}_1 m_{s_1} \vec{p}_2 m_{s_2} \right\rangle, \quad (2)$$

and  $|\Psi_i\rangle$  is the ground-state of the target nucleus. A convenient and widely used way of writing correlated wave functions is

$$|\widetilde{\Psi}\rangle = \mathcal{S} \left[ \prod_{i < j=1}^A \left( 1 - g_c(r_{ij}) + f_{t\tau}(r_{ij}) \widehat{S}_{ij} \vec{\tau}_i \cdot \vec{\tau}_j + f_{\sigma\tau}(r_{ij}) \vec{\sigma}_i \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \right) \right] |\Psi\rangle,$$

where  $\mathcal{S}$  is a symmetrization operator and  $|\Psi\rangle$  is the Slater determinant wave function as it can be determined in an independent particle model (IPM) for the nucleus. The functions  $g_c$ ,  $f_{t\tau}$  and  $f_{\sigma\tau}$  are the central, tensor and spin-spin correlation functions. They are expected to be nearly mass independent and therefore represent an universal feature of nuclei [1]. In our calculations, the one-body current operator  $J_{\pm 1,0}^{[1]}$  in Eq. 1 is considered in the non-relativistic impulse approximation. For the two-body contributions  $J_{\pm 1}^{[2]}$  we consider the conventional pion-exchange (MEC) and include also  $\Delta$ -isobar current terms.

We restrict ourselves to exclusive two-nucleon knockout reactions. The cross sections are computed in the so-called spectator approximation which in some sense is equivalent with a lowest-order cluster expansion retaining all operators up to the two-body level. For inclusive reactions this approach was shown to be a reasonable approximation (see e.g. Refs. [2] and [3]). For exclusive reactions, it is expected to be an even better approximation as the exclusive character of the process is heavily selective with respect to the number of nucleons that get involved in the reaction process and three- and more-body operators are likely to play only a marginal role. In the spectator approximation, one ends up with the following two contributions to the transition matrix elements. First, there is the contribution from the two-body currents that produces two-nucleon strength even in the strict IPM limit

### UNCORRELATED PART

$$\langle \Psi_f(E_f) | J_{\mu}^{[2]}(q) | \Psi_i(E_i) \rangle$$

Second, the information with regard to the nucleon-nucleon correlations comes from

### CORRELATED PART

$$\langle \Psi_f | \sum_{i < j=1}^A \left[ \left( J_{\mu}^{[1]}(i; q) + J_{\mu}^{[1]}(j; q) + J_{\mu}^{[2]}(i, j; q) \right) \left( -g_c(r_{ij}) + f_{t\tau}(r_{ij}) \widehat{S}_{ij} \vec{\tau}_i \cdot \vec{\tau}_j + f_{\sigma\tau}(r_{ij}) \vec{\sigma}_i \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \right) + h.c. \right] | \Psi_i \rangle$$

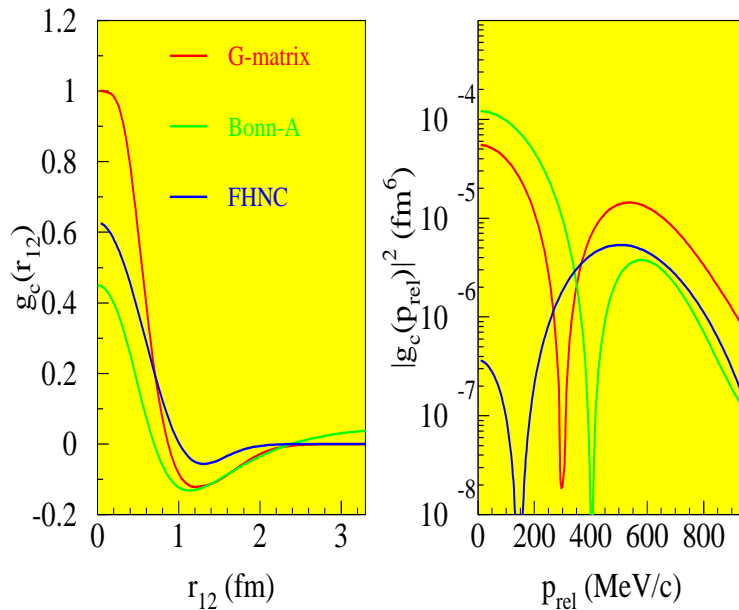


FIG. 2. The central correlation function in coordinate and momentum space as calculated in various many-body theories.

A transparent way of connecting the  $A(e, e'NN)$  observables to the information on the nucleon-nucleon correlations is provided by the *FACTORIZED APPROACH* as it was e.g. formulated in Ref. [4]. In this semi-analytical scheme, that admittedly involves rather severe approximations, a strict separation between the relative and c.o.m. momentum of the active pair in the expression for the  $A(e, e'pp)$  differential cross sections can be attained

$$\frac{d^5\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_1 d\Omega_2 dE_1} = E_1 p_1 E_2 p_2 f_{rec}^{-1} \sigma_{epp}(k_+, k_-, q) F_{h_1, h_2}(P), \quad (3)$$

where the relative ( $k_{\pm}$ ) and c.o.m. momentum ( $P$ ) of the active pair in the initial state are determined from the measured momenta by

$$\begin{aligned}\vec{p}_{rel} &= \vec{k}_{\pm} = \frac{\vec{p}_1 - \vec{p}_2}{2} \pm \frac{\vec{q}}{2} \\ \vec{P} &= \vec{p}_1 + \vec{p}_2 - \vec{q}\end{aligned}\quad (4)$$

and the information on the relative motion of the ejected proton pair is contained in

$$\sigma_{epp} = \sigma_M \left[ \frac{q_{\mu}^4}{q^4} w_L + \left( \frac{-q_{\mu}^2}{2q^2} + \tan^2 \frac{\theta_e}{2} \right) w_T + \frac{q_{\mu}^2}{2q^2} w_{TT} + \frac{1}{\sqrt{2}} \frac{q_{\mu}^2}{q^3} (\epsilon + \epsilon') \tan \frac{\theta_e}{2} w_{LT} \right]. \quad (5)$$

For example, in the spectator approximation the longitudinal contribution  $w_L$  can be cast in the form

$$\begin{aligned}w_L &= 4e^2 (g_c(k_+) + g_c(k_-))^2 (G_E(q_{\mu}q^{\mu}))^2 \\ &+ 40e^2 (f_{\sigma\tau}(k_+) + f_{\sigma\tau}(k_-))^2 (G_E(q_{\mu}q^{\mu}))^2 \\ &+ 24e^2 (g(k_+) + g(k_-)) (f_{\sigma\tau}(k_+) + f_{\sigma\tau}(k_-)) (G_E(q_{\mu}q^{\mu}))^2 \\ &+ \frac{16}{3} \sqrt{\frac{\pi}{5}} e^2 (g(k_+) + g(k_-)) \left( f_{t\tau}^0(-\vec{k}_+) + f_{t\tau}^0(-\vec{k}_-) \right) (G_E(q_{\mu}q^{\mu}))^2.\end{aligned}$$

This expression nicely illustrates that the correlation functions  $g_c$ ,  $f_{t\tau}$  and  $f_{\sigma\tau}$  establish the link between two-nucleon knockout observables and the physics beyond mean-field behaviour of nuclei.

As illustrated in Figure 2 the various many-body theories produce vastly different predictions for the central correlation function  $g_c$ . The G-matrix calculation in nuclear matter with the Reid potential by W.H. Dickhoff and C. Gearhart [12] is the only calculation contained in Figure 2 that produced a correlation function with a hard core at short distances. This correlation function produced a favorable agreement with the  $^{12}\text{C}(e, e'pp)$  data from MAMI [5].

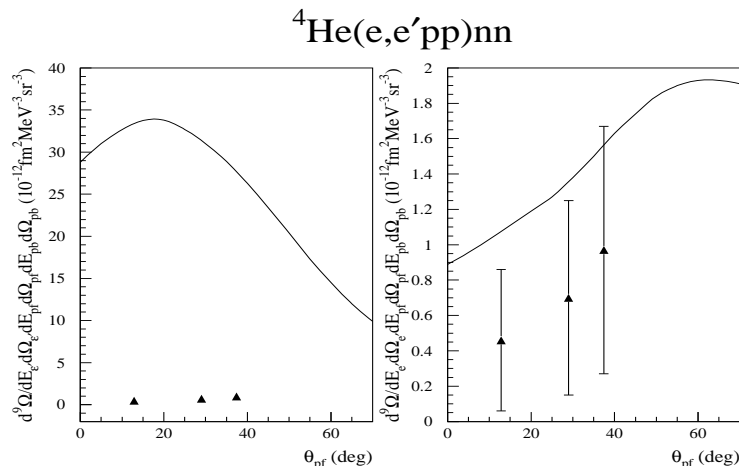


FIG. 3. Dependence of the  $^4\text{He}(e, e'pp)$  differential cross section on the polar angle of the forward emitted proton ( $\equiv \theta_{pf}$ ). The solid curve in the left (right) panel is obtained by using the OMY (G-matrix) correlation function in the factorized model of Ref. [4]. With increasing  $\theta_{pf}$  the relative momentum of the ejected diproton grows. The data are from Ref. [6].

Figure 3 illustrates for the  $^4\text{He}(e, e'pp)$  case the sensitivity of the measured differential cross sections to the choice of the correlation function. The curves were obtained with the factorized formulae of Eq. (3) and represent a weighted average over the experimental phase space. The  $^4\text{He}$  data from Ref. [6] seem to prefer the G-matrix correlation function and clearly exclude a hard-core correlation function like the OMY one. Other correlation functions included in Figure 2 are the ones obtained by FHNC calculations for  $^{16}\text{O}$  by F.Arias de Saavedra et al. [7] and the dressed RPA calculation by W. Geurts *et al.* [8] with the Bonn-A potential. The latter correlation function is extremely soft at short distances and predicts strong central correlations at intermediate distances (1-2 fm). In momentum space this behaviour reflects itself in little high relative momenta components. It is foreseen that continued two-nucleon knockout investigations will eventually be able to fully map the correlation functions, thereby establishing the origin of the high-momentum components in the nuclear wave functions.

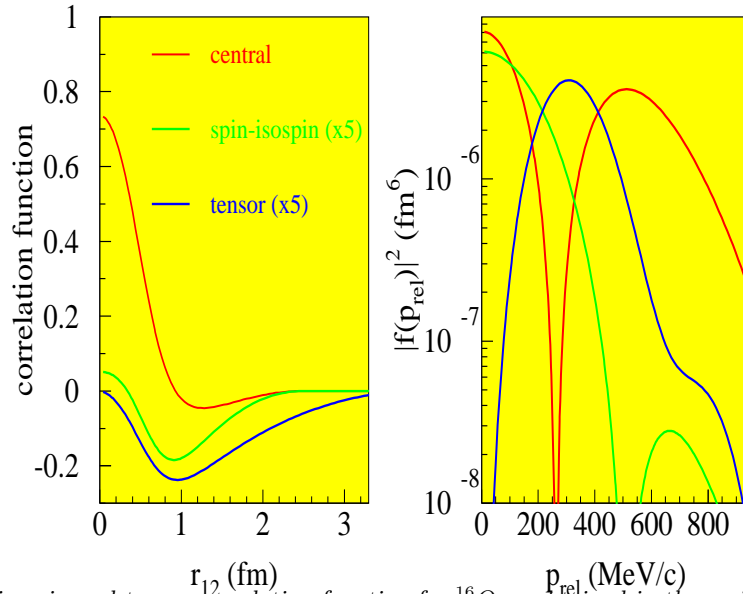


FIG. 4. The central, spin-isospin and tensor correlation function for  $^{16}\text{O}$  as obtained in the variational calculation of Ref. [9].

Figure 4 shows the central and spin-dependent correlation functions as they were obtained in the variational calculations for the ground-state of  $^{16}\text{O}$  with the Argonne  $v_{14}$  NN potential [9]. In coordinate space the spin-isospin and tensor correlation function appear considerably weaker than the central one (note that they were multiplied with a factor of five in the left panel of Figure 4). In momentum space a very different picture emerges. For relative momenta in the region 200-400 MeV/c the spin-dependent correlation functions overshoot the central correlation function. For  $p_{rel} > 500$  MeV/c the central correlations dominate. Using the factorized approach of Eq. (3) in combination with the central and state-dependent correlation functions of Fig. 4 no favorable agreement with the  $^{12}\text{C}(e, e'pp)$  data from Ref. [5] could be reached. This might be due to the fact that the central correlation function obtained in the variational calculations is too soft.

#### IV. THEORY

In order to extract from the two-nucleon knockout data information on the nucleon-nucleon correlations, a framework is required in which besides the NN correlations also the final-state interaction and the conventional (meson-exchange and  $\Delta$ -isobar) two-body currents are accounted for. We have developed such a formalism [10]. It is based on a consistent shell-model description for the initial and final state. This approach has the advantage of respecting the orthogonality and antisymmetry of all the nuclear wave functions involved in the calculation. A distorted wave description of the two ejected nucleons is adopted and the differential cross section and polarization observables can be calculated for excitation of each discrete state in the spectrum of the final nucleus. In constructing the nuclear Slater determinants a realistic set of single-particle wave functions is used. This makes a formal separation of the relative and c.o.m. motion impractical as this would require an additional expansion of the wave functions in terms of a harmonic oscillators. One of greatest difficulties in performing exclusive two-nucleon knockout calculations is the dimensionality of the problem. In contrast to calculations of cross sections for inclusive processes like  $A(e, e')$ , no closure relations can be used to reduce the dimensionality of the problem. We have exploited partial wave expansion and Racah algebra techniques to analytically reduce the dimension of the matrix elements which occur when considering three particles (two ejectiles and the residual nucleus) in the final state.

## V. RESULTS AND DISCUSSION

$^{16}\text{O}(e,e'pp)^{14}\text{C}$  ;  $\omega=210$  MeV ;  $q=300$  MeV/c

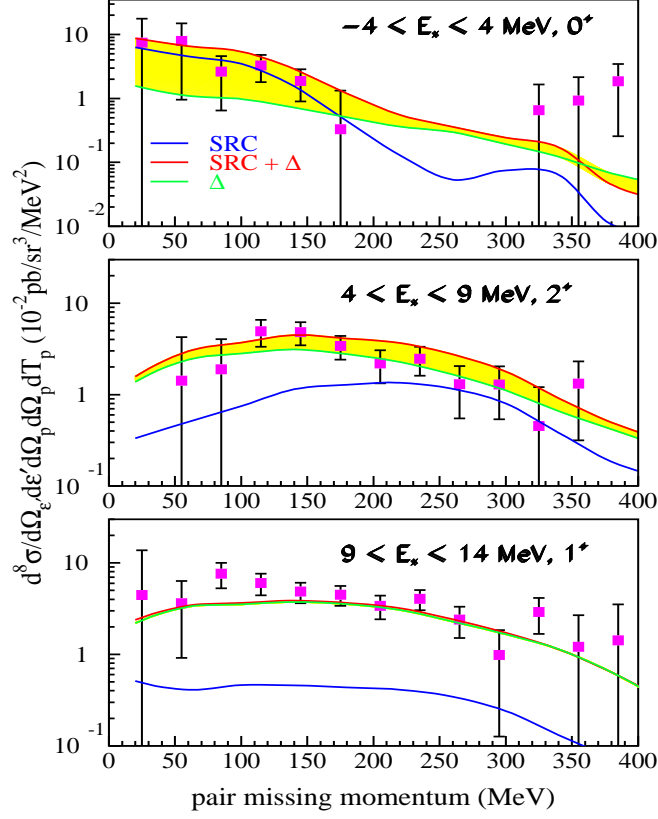


FIG. 5. Calculated  $^{16}\text{O}(e,e'pp)$  differential cross sections for the kinematics of the NIKHEF experiment from Ref. [11]. The green curve is the calculated contribution from intermediate  $\Delta$  creation, ignoring all effects from SRC. The blue curve the contribution from the central correlations and the red curve the coherent sum of the  $\Delta$  and SRC contribution.

Figure 5 shows the measured and calculated differential cross sections versus missing momentum for the kinematics of the  $^{16}\text{O}(e,e'pp)$  NIKHEF experiment reported in Ref. [11]. In this experiment the average energy and momentum transfer was  $\omega=206$  MeV and  $q \approx 300$  MeV/c. A satisfactory agreement between the calculations and the data is obtained using the correlation function from Ref. [12]. Remark that this correlation function, denoted as “G-matrix” in Figure 2, could satisfactorily describe the  $^{12}\text{C}(e,e'pp)$  data from Ref. [5] and the  $^4\text{He}(e,e'pp)$  results contained in Fig. 3. The central correlations are manifesting themselves in the  $(e,e'pp)$  differential cross sections at low pair c.o.m. momenta. Accordingly, the central correlations are selecting diprotons for which the c.o.m. angular momentum is determined by  $\Lambda = 0$  and the relative motion by  $^1S_0$  quantum numbers. This selectivity makes the central correlations to be an almost vanishingly small contribution for the transition to the  $1^+$  state that is dominated by relative  $P$ -wave amplitudes and, consequently, intermediate  $\Delta$  creation.

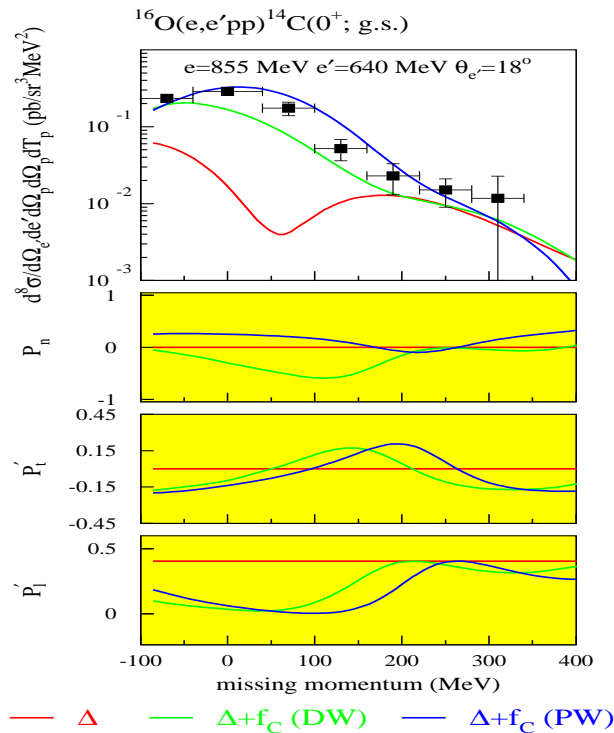


FIG. 6. The missing momentum dependence of the  $^{16}\text{O}(\vec{e}, e'\vec{p}p)^{14}\text{C}(0^+, \text{g.s.})$  differential cross section and recoil polarization observables in superparallel kinematics. The preliminary data are from Ref. [13]. Both plane (PW) and distorted wave (DW) calculations are shown. The red curves include only  $\Delta$  currents. The green and blue curves include  $\Delta$  currents and central correlations. The latter are implemented using the  $G$ -matrix correlation function from Ref. [12].

We now consider the reaction  $^{16}\text{O}(\vec{e}, e'\vec{p}p)$  in the kinematics of a MAMI experiment that is presently in the process of being analyzed [13,14]. These measurements have resolved transitions to discrete states in the  $^{14}\text{C}$  residual nucleus. For this particular case we address the sensitivity of the different observables to both the central and spin-dependent correlations. Furthermore, we want to demonstrate the power of using recoil polarization measurements with and without polarized electrons. The sensitivity to the final-state interactions is investigated in Figure 6. In the asymmetric situation of super-parallel kinematics, the distortions which the ejectiles undergo induce both a shift and reduction of the plane-wave result for the differential cross section. The double polarization observables  $P'_t$  and  $P'_l$ , on the other hand, are only marginally affected by the FSI effects. The results of Figure 6 include solely central correlations. The central correlations were implemented with the GD correlation function that was also used in Figure 5. Just as for the latter case, the effect of the central correlations is restricted to the low pair missing (or c.o.m.) momenta. The large missing momentum tail is dominated by the  $\Delta$  currents. Figure 7 shows the results of a distorted wave calculation including both central, spin-isospin and tensor correlations using the correlation functions from the variational calculations shown in Figure III. The variational calculations produce a very soft central correlation function and this results in a severe underestimation of the  $^{16}\text{O}(e, e'pp)^{14}\text{C}(0^+, \text{g.s.})$  data at low pair missing momenta. The inclusion of the state-dependent correlations (spin-isospin and tensor) makes the calculated results to move further away from the preliminary data as a destructive interference between the state-dependent and the central correlations is observed. It appears that the variational calculations of Ref [9] predict a central correlation functions that is presumably too soft. Inclusion of the state-dependent correlations, which were consistently derived in the variational calculations, does not seem to cure the observed deviation between the model predictions and the preliminary data. A similar qualitative deviation between the predictions with the correlation functions from Ref. [9] was observed in the  $^{12}\text{C}(e, e'pp)$  case (Ref. [5]). The power of the recoil polarization measurements in super-parallel kinematics is illustrated in Figures 6 and 7. The  $P_n$  and  $P'_t$  recoil polarization observable are respectively determined by the  $W_{LT}$  and  $W'_{LT}$  structure functions. Accordingly, they vanish in the situation that only (transverse) two-body currents contribute to the reaction process. After inclusion of the correlations the recoil polarization observables become relatively large.

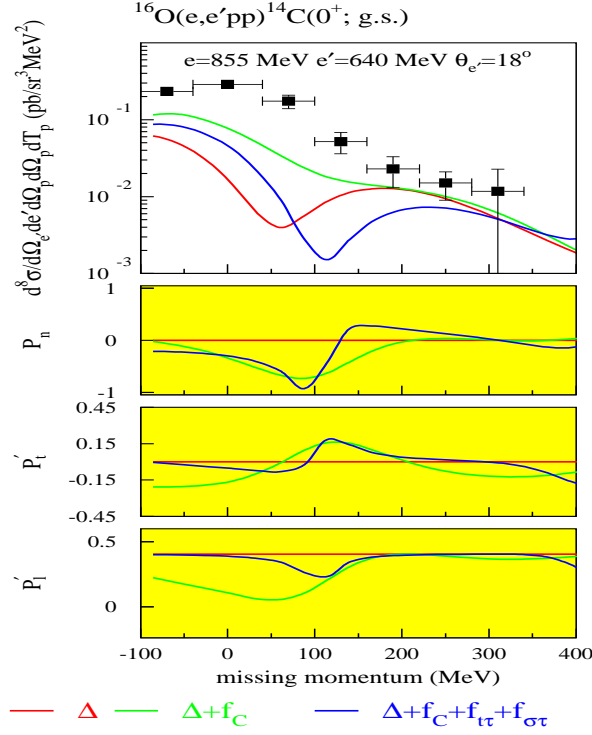


FIG. 7. The sensitivity of the  $^{16}\text{O}(\bar{e}, e'\bar{p}p)^{14}\text{C}(0^+, g.s.)$  differential cross section and recoil polarization observables to the spin dependent correlation functions.

Triple coincidence reactions of the type  $A(e, e'pn)$  are expected to exhibit a major sensitivity to tensor correlations in nuclei, provided that one can separate the strength arising from one-body photon coupling to a tensor correlated proton-neutron pair from two-body current contributions, like meson-exchange contributions. In  $(e, e'pp)$  studies at lower four-momentum transfer, a powerful tool in the search for nucleon-nucleon correlations is the selectivity of the final state with respect to the quantum numbers of the correlated nucleon pair that actively participates in the reaction process [15,16]. To study whether a similar sort of sensitivity exists for the tensor correlations,  $^{16}\text{O}(e, e'pn)$  results for excitation of specific states in  $^{14}\text{N}$  are presented. Experiments of this type are scheduled at the Mainz electron accelerator [17]. Restricting ourselves to the (dominant)  $p$ -shell components, the following selectivity for the quantum numbers of the active proton-neutron pair emerges when considering  $^{16}\text{O}(e, e'pn)$  decay to the states with angular momentum  $J_R$  in  $^{14}\text{N}$

$$\begin{aligned}
 J_R = 0^+ & \quad {}^1S_0(\Lambda = 0), {}^3P_1(\Lambda = 1) \\
 J_R = 1^+ & \quad {}^3S_1(\Lambda = 0, 2), {}^3P_{0,1,2}(\Lambda = 1), \\
 & \quad {}^1P_1(\Lambda = 1), {}^3D_1(\Lambda = 0) \\
 J_R = 2^+ & \quad {}^1S_0(\Lambda = 2), {}^3S_1(\Lambda = 0, 2), {}^3P_{1,2}(\Lambda = 1), \\
 & \quad {}^1D_2(\Lambda = 0), {}^3D_2(\Lambda = 0)
 \end{aligned} \tag{6}$$

where the standard convention  $({}^{2S+1}l_J)$  for the relative two-nucleon wave function is adopted and  $\Lambda$  is the orbital quantum number corresponding with the c.o.m. motion of the pair. Predictions for the exclusive  $^{16}\text{O}(e, e'pn)$  cross sections are shown in Figure 8 for the two low-lying  $1^+$  states (respectively at 0. and 3.95 MeV excitation energy) and the  $0^+$  state at  $E_x = 2.31$  MeV. These states in the low-energy spectrum of  $^{14}\text{N}$  are established to have a two-hole character relative to the ground state of  $^{16}\text{O}$  [18] and are therefore expected to be substantially populated in a direct  $^{16}\text{O}(e, e'pn)$  reaction. The two-hole overlap amplitudes employed in these calculations are taken from Ref. [19]. The correlation functions are those from [9]. We have selected so-called “superparallel” kinematics which makes the two nucleons to move along the momentum transfer. As is clearly reflected in the calculated cross sections of Figure 8, the ground state has a mixed  $\Lambda=0,2$  character, whereas the  $J_R = 1^+$  state at  $E_x = 3.95$  MeV has a clear  $\Lambda=0$  structure. As evidenced by the results of Figure 8 the effect of the tensor correlations in exclusive proton-neutron knockout is sizeable. The strongest sensitivity to the tensor correlations is noticed in the peak of the cross sections for the transition to the  $1^+$  states. In this missing momentum domain the reaction is dominated by absorption on a proton-neutron pair in a  ${}^3S_1$  configuration. The effect of the central correlations is small in comparison with the



tensor contributions. For the transition to the  $0^+(T=1)$  state, for which no  ${}^3S_1$  pair combination contributes, the effect of the central and tensor correlations is modest and about equal. In this particular case the proton-neutron knockout cross section is dominated by the two-body currents.

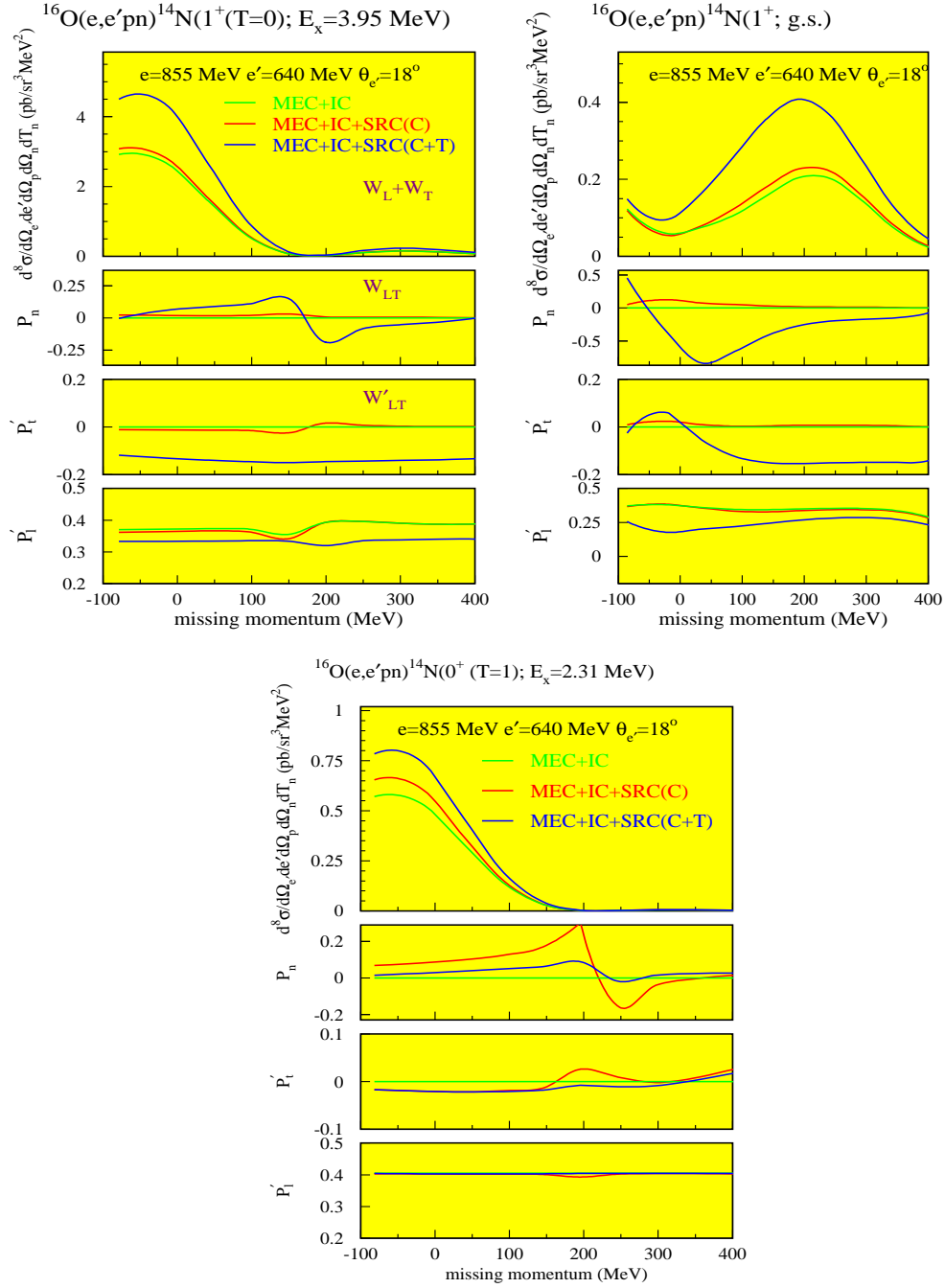


FIG. 8. The missing momentum dependence of the  ${}^{16}\text{O}(e, e'pn)$  differential cross section and recoil polarization observables  $P_n$ ,  $P'_t$  and  $P'_l$  for excitation of the low lying states with two-hole structure in  ${}^{14}\text{N}$ . The calculations refer to the situation in which the proton (neutron) is detected parallel (anti-parallel) to the direction of the momentum transfer. The blue curve is calculated in the distorted-wave approximation including the two-body currents, central (“C”) and tensor (“T”) correlations. The green curve shows the contribution from the two-body currents (“MEC+IC”). The red curves omit tensor correlations from the full calculation.

Also shown in Fig. 8 are the predictions for the double recoil polarization observables ( $P'_l$  and  $P'_t$ ) that can be determined in  $(\vec{e}, e'\vec{p}n)$  measurements. In superparallel kinematics,  $P'_l$  is uniquely determined by the  $W'_{LT}$  structure

function. The background of two-body current contributions to proton-neutron knockout is exclusively transverse. With no ground-state correlations contributing,  $P'_t$  would be extremely small. The calculations learn that as soon as sizeable tensor correlation effects come into play, the  $P'_t$  becomes large. In that respect, the recoil polarization observable is a measure for the tensor correlations which is relatively free of ambiguities with respect to the final-state interaction.

Next, we investigate the role of tensor correlations in real photon studies. Figure 9 shows the the photon asymmetry for p-shell knockout in  $^{12}\text{C}(\vec{\gamma}, pn)$  from 100 up to 440 MeV photon energy. For these results coplanar and symmetrical kinematics was selected. A sizeable sensitivity to the tensor correlations is observed. We find the strongest effects in the photon energy range 200-300 MeV where the  $\Delta$ -isobar currents are heavily contributing. This behaviour points towards a strong interference between tensor correlations and  $\Delta$  currents. A similar sort of qualitative mechanism was observed by A. Fabrocini when studying the role of the nucleon-nucleon correlations and two-body currents in inclusive  $(e, e')$  [20].

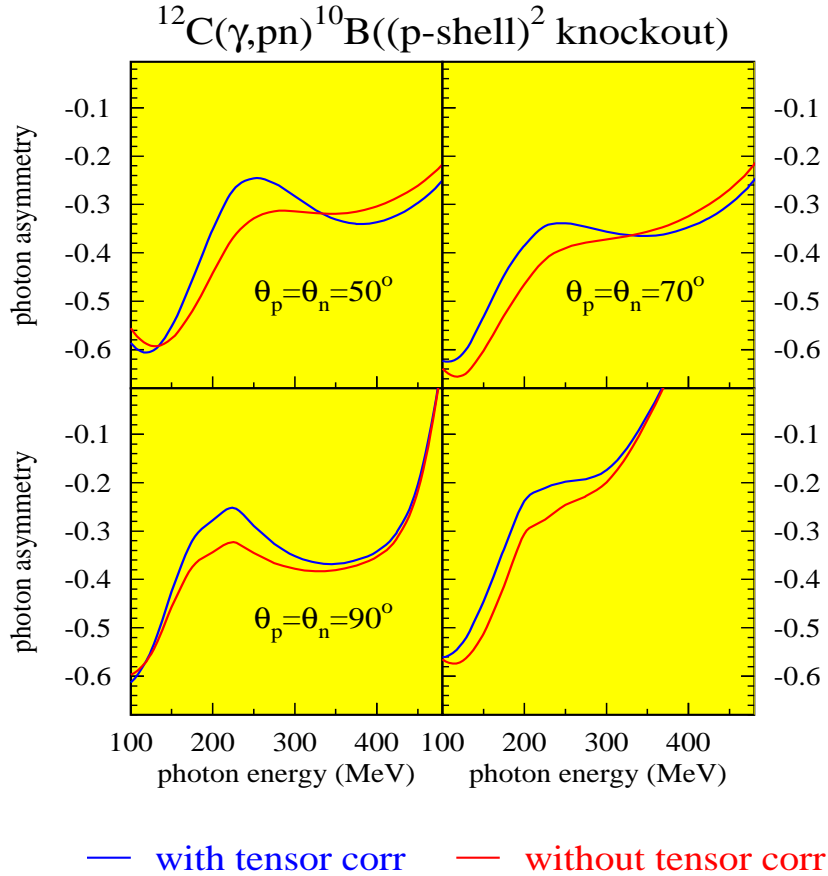


FIG. 9. The photon asymmetry as a function of the photon-energy for  $(p - shell)^2$  knockout in  $^{12}\text{C}(\vec{\gamma}, pn)$  at various polar angles in coplanar and symmetrical kinematics. The red curve omits tensor correlations from the full calculations that include the meson-exchange currents,  $\Delta$ -isobar currents, central and spin-dependent correlations.

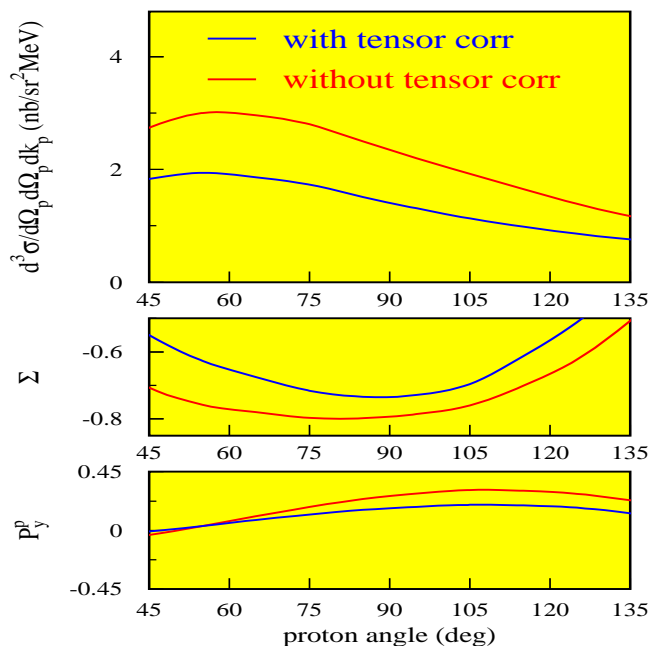
$^{12}\text{C}(\gamma, pp) ; P=0 ; E_\gamma=200 \text{ MeV}$ 


FIG. 10. The differential cross section, photon asymmetry and analyzing power for the reaction  $^{12}\text{C}(\gamma, pp)$  as a function of the polar angle for  $E_\gamma=200 \text{ MeV}$ . Quasi-deuteron kinematics is selected. The red curve omits tensor correlations from the full calculation that includes  $\Delta$ -currents, central and spin-dependent correlations.

One could wonder whether this strong interference effect could be further exploited to study tensor correlations in the medium. The  $(\gamma, pp)$  channel was recently shown to be dominated by the  $\Delta$ -isobar currents. Therefore, we address the question whether tensor correlations could be probed in proton-proton knockout. This could be a way of probing triplet  $S$  diprotons, which is a unique medium effect, and of learning more about the medium dependence of the tensor correlations. As displayed in Figure 10 the effects of the tensor correlations in the  $(\gamma, pp)$  channel are significant. In the differential cross section the tensor correlations induce a substantial global reduction which exhibits a weak proton angle dependence. Also for the photon asymmetry the tensor correlations are important. As the photon asymmetry is far less subject to uncertainties with respect to the FSI than the cross sections, it represents a promising method for studying tensor correlations in the medium.

## VI. SUMMARY

A framework in which the effect of central, tensor and spin-isospin NN-correlations on  $A(e, e' NN)$  and  $A(\gamma, NN)$  cross sections and polarization observables can be calculated is available. In this formalism, also the “background” two-nucleon knockout strength attributed to meson-exchange and  $\Delta_{33}$  currents is incorporated. The results indicate that short-range central correlations produce sizeable contributions to  $A(e, e' pp)$ . The major effects are observed at low missing “diproton” momenta. This observation supports the picture that the central short-range correlations result in hard back-to-back collisions producing relatively high relative momenta  $p_{rel} \gg$  and small c.o.m. momenta  $P \approx 0$  in the correlated part of the spectral function  $P(\vec{k}, E)$ . The tensor correlations, on the other hand, appear in a wider range of pair c.o.m. momenta, which reflects the fact that they are of intermediate range. The results of the calculations indicate that  $A(\vec{e}, e' \vec{p}N)$  polarization observables offer the possibility of effectively isolating the longitudinal channel, creating favorable conditions to study the central and spin-dependent correlations with “minimized” FSI effects. For these studies, superparallel kinematics (both nucleons are ejected along the momentum transfer) reduces the systematic uncertainties as it is very selective with respect to the structure functions that are contributing to each of the observables. The results indicate that tensor correlations are *STRONGLY* contributing to the proton-neutron knockout channel  $A(e, e' pn)$ . Here, the sensitivity to central short-range correlations is rather weak. The  $A(e, e' pn)$  channel carries stronger signals from the nucleon-nucleon correlations than  $A(e, e' pp)$  in comparable kinematics.

A strong interference between the  $\Delta$  current and tensor correlations is found. This feature makes the  $A(\vec{\gamma}, NN)$  asymmetries a promising variable to study tensor correlations in the medium.

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