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The ^{3}He spectral function in light-front dynamics

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Abstract. A distorted spin-dependent spectral function for ^{3}He is considered for the extraction of the transverse-momentum dependent parton distributions in the neutron from semi-inclusive deep inelastic electron scattering off polarized ^{3}He at finite momentum transfers, where final state interactions are taken into account. The generalization of the analysis to a Poincaré covariant framework within the light-front dynamics is outlined.

In the next few years, several experiments involving ^{3}He nuclear targets will be performed at JLab, with the aim of extracting information on the parton structure of the neutron. In particular, the three-dimensional neutron structure, described in terms of quark transverse momentum dependent parton distributions (TMDs) [1], will be probed through spin-dependent semi-inclusive deep inelastic scattering (SIDIS) processes off ^{3}He, where a high-energy pion is detected in coincidence with the scattered electron [2]. Hence, to clarify the flavour dependence of the TMDs, high precision experiments, involving both protons and neutrons, are needed. To obtain a reliable information from ^{3}He SIDIS one has to take into account: i) the nuclear structure of ^{3}He, ii) the interaction in the final state (FSI) between the observed pion and the remnant debris, and iii) the relativistic effects. Our efforts about the above issues are summarized here.

An initial study of this kind was reported in Ref. [3], where the plane wave impulse approximation (PWIA) was adopted to describe the reaction mechanism, treating the ^{3}He structure non-relativistically, using the AV18 interaction [4]. In facts, a polarized ^{3}He is an ideal target to study the neutron, since at a 90% level a polarized ^{3}He is equivalent to a free polarized neutron [5]. In Ref. [3] it was found, using a realistic ^{3}He spin-dependent spectral function, $P^{\tau}_{\sigma,\sigma'}(\vec{p}, E)$, with $\vec{p}$ the nucleon momentum in the laboratory frame and E the removal energy [6], that the formula

$$A_n \simeq \left(A_3^{exp} - 2p_p f_p\, A_p^{exp}\right)/(p_n f_n) \tag{1}$$

can be safely adopted to extract the neutron Sivers and Collins asymmetries [7, 8] from ^{3}He and proton data. This formula has been already used by experimental collaborations [9, 10]. Nuclear effects are hidden in the proton and neutron "effective polarizations" (EPs), $p_{p(n)}$, and in the dilution factors, $f_{p(n)}$, properly defined [3]. With the AV18 interaction, one obtains $p_p = -0.023$, $p_n = 0.878$ [3].

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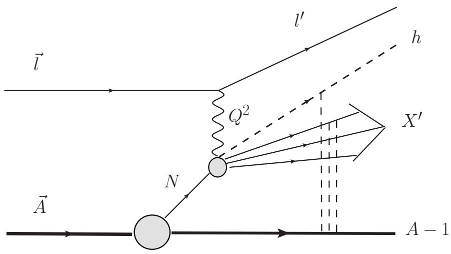

Figure 1. Interaction between the $(A-1)$ spectator system and the debris produced by the absorption of a virtual photon by a nucleon in the nucleus.

We are now taking into account FSI between the observed pion and the remnants. In a recent paper [11], the distorted spin dependent spectral function of ^{3}He has been introduced, and evaluated when the final $A-1$ system is a deuteron state. The evaluation considering the most general final state is in progress [12]. A few preliminary results are reported here. In SIDIS off ^{3}He, the relative energy between the spectator $(A-1)$ system and the system composed by the detected pion and the remnant debris (see Fig. 1) is a few GeV. FSI can be therefore treated through a generalized eikonal approximation (GEA) [11]. The GEA was already successfully applied to unpolarized SIDIS in Ref. [13]. In GEA, FSI effects are due to the propagation of the debris, formed after the γ^* absorption by a target quark, and the subsequent hadronization, both of them influenced by the presence of a fully interacting $(A-1)$ spectator system (see Fig. 1). The key quantity to describe FSI effects is the *distorted* spin-dependent spectral function, whose relevant part in the evaluation of single spin asymmetries (SSAs) is: $P^{PWIA(FSI)} = O^{IA(FSI)}_{\frac{1}{2}\frac{1}{2}} - O^{IA(FSI)}_{-\frac{1}{2}-\frac{1}{2}}$ with:

$$O^{IA}_{\lambda\lambda'}(\vec{p},E) = \sum\!\!\!\!\!\!\int d\epsilon^*_{A-1}\,\rho\,(\epsilon^*_{A-1})\;\langle S_A,\mathbf{P_A}|\Phi_{\epsilon^*_{A-1}},\lambda',\vec{p}\rangle\langle\Phi_{\epsilon^*_{A-1}},\lambda,\vec{p}|S_A,\mathbf{P_A}\rangle\;\delta\,(E-B_A-\epsilon^*_{A-1}) \qquad (2)$$

and

$$O^{FSI}_{\lambda\lambda'}(\vec{p},E) = \sum\!\!\!\!\!\!\int d\epsilon^*_{A-1}\,\rho\,(\epsilon^*_{A-1})\;\langle S_A,\mathbf{P_A}|(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}},\lambda',\vec{p}\}\rangle\langle(\hat{S}_{Gl})\{\Phi_{\epsilon^*_{A-1}},\lambda,\vec{p}\}|S_A,\mathbf{P_A}\rangle \times \delta\,(E-B_A-\epsilon^*_{A-1})\;, \qquad (3)$$

where $\rho\left(\epsilon^*_{A-1}\right)$ is the density of the $(A-1)$-system states with intrinsic energy ϵ^*_{A-1}, and $|S_A,\mathbf{P_A}\rangle$ is the ground state of the A-nucleons nucleus with polarization S_A. $\hat{S}_{Gl}$ is the Glauber operator:

$$\hat{S}_{Gl}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \prod_{i=2,3}[1-\theta(z_i-z_1)\Gamma(\mathbf{b}_1-\mathbf{b}_i,z_1-z_i)] \qquad (4)$$

and $\Gamma(\mathbf{b}_{1i},z_{1i})$ the generalized profile function:

$$\Gamma(\mathbf{b}_{1i},z_{1i}) = \frac{(1-i\,\alpha)\;\sigma_{eff}(z_{1i})}{4\,\pi\,b_0^2}\;\exp\left[-\frac{\mathbf{b}_{1i}^2}{2\,b_0^2}\right], \qquad (5)$$

where $\mathbf{r}_{1i} = \{\mathbf{b}_{1i},\mathbf{z}_{1i}\}$ with $\mathbf{z}_{1i} = \mathbf{z}_1-\mathbf{z}_i$ and $\mathbf{b}_{1i} = \mathbf{b}_1-\mathbf{b}_i$. The models for the profile function, $\Gamma(\mathbf{b}_{1i},z_{1i})$, and for the effective cross section, $\sigma_{eff}(z_{1i})$, as well as the values of the parameters α and b_0, are the ones used in Ref. [13] to successfully describe deuteron JLab data [14]. $\sigma_{eff}(z_{1i})$ is the cross section for the interaction of the formed hadrons, α is the ratio of the real to the imaginary part of the forward scattering amplitude, b_0 is the slope parameter (cf Ref. [15] for details). It occurs that P^{PWIA} and P^{FSI} can be very different, but the relevant observables for the SSAs involve integrals, dominated by the low momentum region, where the FSI effects are minimized and the spectral function is large [13]. As a consequence, the EPs change from the $PWIA$ values, i.e. $p_p = -0.023$ and $p_n = 0.878$, to $p_p^{FSI} = -0.026$, $p_n^{FSI} = 0.76$, where

$$p^{FSI}_{p(n)} = \int d\epsilon_S \int d\vec{p}\;Tr[\mathbf{S}_{He} * \sigma\;P^{p(n)}_{FSI}(\vec{p},\epsilon_S,S_{He})]\;. \qquad (6)$$

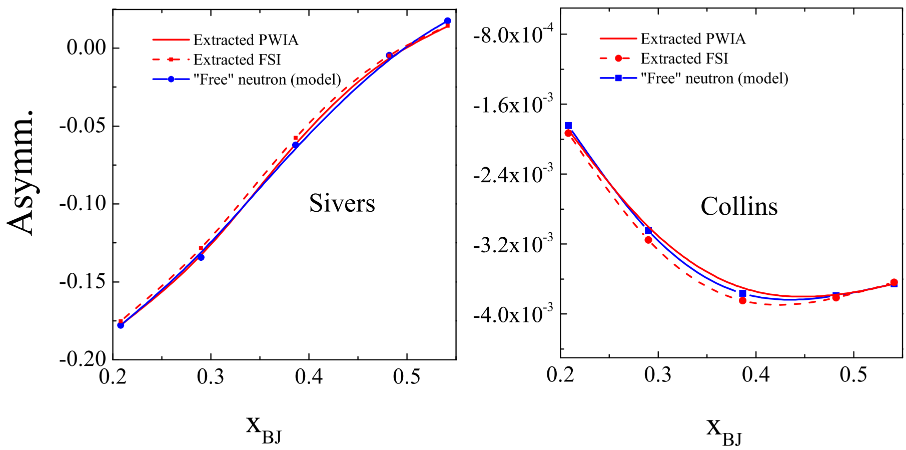

Figure 2. Effectiveness of the extraction procedure, Eq. (7), for the Sivers (left panel) and Collins (right panel) asymmetries, with and without FSI, in the actual kinematics of JLab [2]. Preliminary results to appear in [12].

Then $p_{p(n)}$ with and without the FSI differ by 10-15% . Actually, one has also to consider the effect of the FSI on dilution factors. We have found, in a wide range of kinematics typical for the experiments at JLAB [2], that the product of polarizations and dilution factors changes very little [16]. Indeed the effects of FSI on the dilution factors and on the EPs are found to compensate each other to a large extent and the usual extraction seems to be safe, viz. :

$$A_n \simeq \left(A_3^{exp} - 2p_p^{FSI} f_p^{FSI} A_p^{exp}\right)/(p_n^{FSI} f_n^{FSI}) \simeq \left(A_3^{exp} - 2p_p f_p \, A_p^{exp}\right)/(p_n f_n)\,, \quad (7)$$

as one can clearly see in Fig. 2.

We now address the relativistic description of the parton structure of ^{3}He, within a novel approach which, due to the high energies involved in the forthcoming experiments [2], is very timely [17, 18]. To study relativistic effects, we adopt the Light-Front (LF) form of the Relativistic Hamiltonian Dynamics (RHD) for an interacting system with a fixed number of on-mass-shell constituents. The Bakamijan-Thomas construction of the Poincaré generators leads to a fully Poincaré covariant RHD [17, 18]. The Light-Front form of RHD has a subgroup structure of the LF boosts, which allows a separation of the intrinsic motion from the global one, very important for the description of DIS, SIDIS and deeply virtual Compton scattering processes. We have not taken into account a possible violation of cluster separability in our approach [19]. The key quantity to consider in SIDIS processes is the LF relativistic spectral function, $\mathcal{P}^{\tau}_{\sigma'\sigma}(\tilde{\kappa}, \epsilon_S, S_{He})$, with $\tilde{\kappa}$ an intrinsic nucleon momentum and ϵ_S the energy of the two-nucleon spectator system. The LF spectral function is useful also for other studies (e.g., for nuclear generalized parton distributions, where final states have to be properly boosted). With respect to previous attempts to describe DIS processes off ^{3}He in a LF framework (see, e.g., the one in Ref. [20]), here a special care is devoted to the definition of the intrinsic light-cone variables as well as to the spin degrees of freedom in $\mathcal{P}^{\tau}_{\sigma'\sigma}(\tilde{\kappa}, \epsilon_S, S_{He})$. This PWIA LF spectral function is defined in terms of LF overlaps [18] between the ground state of a polarized ^{3}He and the cartesian product of an interacting state of two nucleons with energy ϵ_S and a plane wave for the third nucleon. Within a reliable approximation [18], it can be given in terms of the Melosh Rotations, $D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\kappa})]$, and the usual instant-form spectral function $P^{\tau}_{\sigma'_1\sigma_1}$:

Table 1. Proton and neutron EPs in PWIA, within the non relativistic appproach (NR) and within the LF RHD. First line: longitudinal EP; second line: transverse EP. Preliminary results.

	proton NR	*proton LF*	*neutron NR*	*neutron LF*
$\int d\epsilon_S d\tilde{\kappa}\ Tr(\mathcal{P}\sigma_z)_{\vec{S}_A=\widehat{z}}$	-0.02263	-0.02231	0.87805	0.87248
$\int d\epsilon_S d\tilde{\kappa}\ Tr(\mathcal{P}\sigma_y)_{\vec{S}_A=\widehat{y}}$	-0.02263	-0.02268	0.87805	0.87494

$$\mathcal{P}^{\tau}_{\sigma'\sigma}(\tilde{\kappa}, \epsilon_S, S_{He}) \propto \sum_{\sigma_1\sigma'_1} D^{\frac{1}{2}}[\mathcal{R}^{\dagger}_M(\tilde{\kappa})]_{\sigma'\sigma'_1}\ P^{\tau}_{\sigma'_1\sigma_1}(\mathbf{p}, \epsilon_S, S_{He})\ D^{\frac{1}{2}}[\mathcal{R}_M(\tilde{\kappa})]_{\sigma_1\sigma} \tag{8}$$

Preliminary results are quite encouraging, since, as shown in Tab. 1, LF longitudinal and transverse EPs change little from the ones obtained within the NR spectral function and weakly differ from each other. Then the usual extraction procedure should work well also within the LF approach. Concerning FSI, we plan to include in our LF description the FSI between the jet produced from the hadronizing quark and the two-nucleon spectator system through the GEA introduced in Ref. [13].

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