Emanuele Pace · Alessio Del Dotto · Leonid Kaptari · Matteo Rinaldi · Giovanni Salmé · Sergio Scopetta

Light-Front Dynamics and the $^3$He Spectral Function

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Abstract. Two topics are presented. The first one is a novel approach for a Poincaré covariant description of nuclear dynamics based on light-front Hamiltonian dynamics. The key quantity is the light-front spectral function, where both normalization and momentum sum rule can be satisfied at the same time. Preliminary results are discussed for an initial analysis of the role of relativity in the EMC effect in $^3$He. A second issue, very challenging, is considered in a non-relativistic framework, namely a distorted spin-dependent spectral function for $^3$He in order to take care of the final state interaction between the observed pion and the remnant in semi-inclusive deep inelastic electron scattering off polarized $^3$He. The generalization of the analysis within the light-front dynamics is outlined.

Keywords Light-front dynamics · Spin-dependent Spectral Function · EMC effect

1 Introduction

The standard model of few-nucleon systems, where nucleon and pion degrees of freedom are taken into account, has achieved a very high degree of sophistication. Nonetheless, one should try to fulfill, as much as possible, the relativistic constraints, dictated by the covariance with respect to the Poincaré group, if processes involving nucleons with large 3-momentum are considered and a high precision is needed. This is the case if one studies, e.g., i) the nucleon structure functions (unpolarized and polarized); ii) semi-inclusive deep inelastic (SIDIS) processes, iii) signatures of short-range correlations. At least, one should carefully deal with the boosts of the nuclear states, $|\Psi_{\text{init}}\rangle$ and $|\Psi_{\text{fin}}\rangle$.

In particular a relativistic treatment is important to accurately describe the JLab program @ 12 GeV for few-body systems (see, e.g., [1], [2], [3]).
Our key tool for a relativistic description of few-body nuclei is a Poincaré covariant spectral function (SF) built up within the light-front Hamiltonian dynamics (LFHD).

Indeed, the Relativistic Hamiltonian Dynamics (RHD) of an interacting system with a fixed number of on-mass-shell constituents (see, e.g., [3]) plus the Bakamjian-Thomas construction of the Poincaré generators [3] allow one to give a fully Poincaré covariant description of DIS, SIDIS and deeply virtual Compton scattering (DVCS) off $^3He$. The light-front (LF) form of RHD is adopted [4], which has a subgroup structure of the LF boosts (with a separation of the intrinsic motion from the global one: very important for us!) and a meaningful Fock expansion (see, e.g., [3]). Furthermore, within the LFHD one can take advantage of the whole successful non-relativistic (NR) phenomenology that has been developed for the nuclear interaction.

In Section 2 the LF spin-dependent (SD) SF obtained from the LF wave functions for the two- and the three-nucleon systems is described. In Section 3 the LF SF is applied to study the role of relativity for the EMC effect in $^3He$ and preliminary results are presented. In Section 4 the actual possibility to get information on the neutron structure from SIDIS experiments on $^3He$ is shown within a non-relativistic approach which include the final state interaction (FSI) through a distorted SF [4]. Preliminary results with the LF SF are reported. In Section 5 conclusions and perspectives are drawn.

2 Light-Front Dynamics and the Light-Front Spectral Function

An explicit construction of the 10 Poincaré generators that fulfills the proper commutation rules in presence of interactions was given by Bakamjian and Thomas [3] through the mass operator, \( M \): i) only \( M \) contains the interaction; ii) it generates the dependence upon the interaction of the three dynamical generators in LFHD, namely \( P^\perp \) and the transverse rotations \( \mathbf{F}_\perp \). \( M \) is obtained adding to the free mass \( M_0 \) of the system an interaction \( V \). There are two possibilities: \( M^2 = M_0^2 + U \) (then for two particles one can easily embed the NR phenomenology) or \( M = M_0 + V \). The interaction, \( U \) or \( V \), must commute with all the kinematical generators, and with the non interacting spin. Then it has to be invariant for translations, as in the NR case, and the angular momentum is a conserved quantity.

The full theory must fulfill the macroscopic locality. This property could be implemented by using interaction-dependent, unitary operators: the packing operators (see, e.g., [4]). Their effects should be small, and therefore they will be neglected in what follows, but in principle should be investigated.

For the three-body case the mass operator is \( M_{BT}(123) = M_0(123) + V^{BT} \), where \( M_0(123) = \sqrt{m^2 + k_1^2} + \sqrt{m^2 + k_2^2} + \sqrt{m^2 + k_3^2} \) is the free mass operator, \( V^{BT} \) a Bakamjian-Thomas (BT) two-body and three-body force, and \( k_i \) (\( i = 1, 2, 3 \)) are intrinsic momenta with \( k_1 + k_2 + k_3 = 0 \) [4].

The NR mass operator is written as \( M^{NR} = 3m + \sum_{i=1,2} k_i^2/2m + V^{NR}_1 + V^{NR}_2 + V^{NR}_3 + V^{NR}_4 \) and must obey the commutation rules proper of the Galilean group, leading to translational and rotational invariance. Those properties are analogous to the ones in the BT construction. This allows us to consider the standard NR mass operator as a sensible BT mass operator, and embed it in a Poincaré covariant approach: \( M_{BT}(123) \sim M^{NR} \).

Coupling angular momenta is accomplished within the Instant Form (IF) of RHD through the Clebsch-Gordan coefficients. To embed this machinery in the LFHD one needs the Melosh rotations that relate LF and IF spin wave functions. For a particle of LF momentum \( \mathbf{k} \equiv (k^+, k_\perp) \) one has

\[
\langle \mathbf{k}; \sigma \sigma' \rangle_{LF} = \sum_{\mu} \mathbf{D}^\mu_{\sigma \sigma'} \left[ R^\dagger_M(\mathbf{k}) \right] \langle \mathbf{k}; \sigma \mu' \rangle_{IF}
\]  

(1)

where \( \mathbf{D}^\mu_{\sigma \sigma'}(R^\dagger_M(\mathbf{k})) \) is the standard Wigner function and \( R_M(\mathbf{k}) \) is the rotation between the rest frames of the particle reached through a LF boost or a canonical, rotationless boost.

Then for quantities, like the spin-dependent SF, taking care of the Melosh rotations, one obtains

\[
O_{\sigma', \sigma}^{LF} = \sum_{\sigma''} D^{1/2}_{\sigma' \sigma''} (R_M) \ O_{\sigma'', \sigma}^{IF} \ D^{1/2}_{\sigma'' \sigma'} (R^\dagger_M)
\]

The NR spin-dependent SF for a nucleus of mass number \( A \) is defined through its matrix elements

\[
P_{\sigma, \sigma', \nu}(\mathbf{p}, E) = \sum_{f(A-1)} \langle \mathbf{p}, \sigma' \tau; \psi_{f(A-1)} | \langle \nu, \mu' \rangle_{IF} | \langle \psi_{f(A-1)}; \mathbf{p}, \sigma' \tau \rangle \delta(E - E_{f(A-1)} + E_A) \rangle
\]  

(2)
where $|\psi_{J,M}\rangle$ is the ground state of the nucleus with energy $E_A$ and polarized along $\mathbf{S}$, $|\psi_{f_{A-1}}\rangle$ an eigenstate of the (A-1)-nucleon system with energy $E_{f_{A-1}}$, interacting with the same interaction of the nucleus, $\langle \mathbf{p} | \sigma \tau \rangle$ the plane wave for the nucleon $\tau = \pm \frac{1}{2}$, with momentum $\mathbf{p}$ in the rest frame and spin along the z-axis equal to $\sigma$ [10–11].

To obtain within the LFHD a Poincaré-covariant spin-dependent SF for a three-particle system in the bound state $|\Psi_0; S, T_z\rangle$, let us replace the NR overlaps $\langle \mathbf{p}, \sigma \tau; \psi_{f_{A-1}}| \psi_{J,M}\rangle$ with their LF counterparts $L_F\langle \tau_S; T_S; \alpha, \epsilon; J_z; \tau \sigma; \tilde{k}| \Psi_0; S, T_z\rangle$, that depend upon the energy $\epsilon$ of the system of two fully interacting particles (say, particles 2 and 3) and upon the intrinsic momentum, $\kappa$, of the third particle (say, particle 1) in the intrinsic reference frame of the cluster (1,23). Then, the LF spin-dependent SF for the three-nucleon system $(3H^e$ or $3H^i$) is [12]

$$P^T_{\sigma,\alpha}(\xi, \kappa_\perp, \kappa^-, S) = \left| \frac{\partial \kappa^+}{\partial \xi} \right| T \int d\tau \rho(\epsilon) \delta(\kappa^- - M_3 + \frac{M_3^2 + |\kappa_\perp|^2}{(1 - \xi)M_3}) \times \sum_{J_z, \alpha} L_F\langle \tau_S; T_S; \alpha, \epsilon; J_z; \tau \sigma; \tilde{k}| \Psi_0; S, T_z\rangle \langle S, T_z; \Psi_0| \kappa, \sigma \tau; J_z; \epsilon, \alpha, T_S, \tau_S \rangle_{LF}$$ (3)

where $\tau = \pm \frac{1}{2}$, $M_3$ is the nucleon mass, $\epsilon$ the intrinsic energy of the two-nucleon eigenstate, $\rho(\epsilon)$ the corresponding density of states ($\rho(\epsilon) = \sqrt{\epsilon/m}$ for the two-body continuum states and $\rho(\epsilon) = 1$ for the deuteron bound state), $J$ the spin, $T_S$ the isospin of the two-body state, $\alpha$ the set of quantum numbers needed to completely specify this eigenstate, and $M_S = 2\sqrt{m^2 + m\epsilon}$ its mass. From $\xi, M_S, \kappa_\perp$ one can define $\kappa^+ = \xi M_0(1,23)$, where $M_0(1,23)$ is the free mass of the cluster (1,23)

$$M_0^2(1,23) = \frac{m^2 + |\kappa_\perp|^2}{\xi} + \frac{M_3^2 + |\kappa_\perp|^2}{(1 - \xi)}$$ (4)

The overlap $L_F\langle \tau_S; T_S; \alpha, \epsilon; J_z; \tau \sigma; \tilde{k}| \Psi_0; S, T_z\rangle$ is defined as follows [12]

$$L_F\langle \tau_S; T_S; \alpha, \epsilon; J_z; \tau \sigma; \tilde{k}| \Psi_0; S, T_z\rangle = \sum_{\sigma'} D_{\sigma \sigma'}^2[R_M^+(\tilde{k})]_{\sigma \sigma'}\sum_{\tau_2, \tau_3} \int dk_{23} \sum_{\sigma_2, \sigma_3} \sqrt{\frac{\kappa^+ E_{23}}{k^+ E_S}} \times \sqrt{(2\pi)^3 k^+ \frac{\partial k_\perp}{\partial k^+}} L_F\langle \tau_S; T_S; \alpha, \epsilon; J_z; k_{23}; \sigma_2, \sigma_3; \tau_2, \tau_3| \langle \tau_2, \tau_3; \tau, \sigma_2, \sigma_3' | k, k_{23}| \Psi_0; S, T_z \rangle_{LF}$$ (5)

where $k_{23}$ is the intrinsic momentum of the (23) pair, $k$ is the intrinsic nucleon momentum in the (123) system ($k_\perp = \kappa_\perp$, since we choose the $3H^e$ transverse momentum $P_\perp = 0$), $\kappa^+ = \xi M_0(123) = \kappa^+ M_0(123)/M_0(1,23)$, with $M_0(123)$ the free mass of the three-particle system

$$M_0^2(123) = \frac{m^2 + |\kappa_\perp|^2}{\xi} + \frac{M_{23}^2 + |\kappa_{23}|^2}{(1 - \xi)}$$ (6)

and and $M_{23}^2 = 4(m^2 + |k_{23}|^2)$ the mass of the spectator pair without interaction! In Eq. (5) one has $k_{23} = \frac{1}{2} \left[ k^+ - (m^2 + |\kappa_\perp|^2)/k^+ \right]$, $E_{23} = \sqrt{M_{23}^2 + |k|^2}$ and $E_S = \sqrt{M_S^2 + |\kappa|^2}$.

In the actual calculations, we identified the IF overlaps of Eq. (5) with the NR wave functions for the two-nucleon and the three-nucleon [12] systems, corresponding to the NN interaction AV18 [14].

### 3 Light-front momentum distribution and preliminary results for the EMC effect

From the LF SF one can obtain the light-cone momentum distribution $f^A_{p(n)}(z)$

$$f^A_{\tau}(z) = \int_0^1 d\xi \int d\kappa_\perp \int d\kappa^+ \frac{1}{(2\pi)^3 k^+} Tr \left[ P^T(\xi, \kappa_\perp, \kappa^-, S) \right] \delta \left( z - \frac{\xi M_A}{m} \right)$$ (7)

that fulfills the following relations, given the SF normalization

$$\int_0^{M_A/m} dz f^A_{\tau}(z) = 1 \quad N_A = \frac{1}{A} \int_0^{M_A/m} dz \left[ Z f^A_{\tau}(z) + (A - Z) f^A_{n}(z) \right] = 1$$ (8)
The symmetry of the three-body bound state naturally entails the momentum sum rule (see [12])

\[ MSR = \frac{1}{A} \int_0^{M/A} dz \int_0^{\infty} d\kappa_+ \int_0^{\infty} d\kappa_- \left[ Z f_p^A(\kappa_+) + (A-Z) \right] = 1 \]  

(9)

We evaluated the nuclear structure function \( F_2^A(x) \) \((x = Q^2/2m_\nu)\) as a convolution of the nuclear spectral function and of the structure function of the nucleon

\[ F_2^A(x) = \int_0^1 d\xi \int d\kappa_+ \int \frac{d\kappa_-}{2(2\pi)^3} \left[ ZTr P^p(\xi, \kappa_+, \kappa_-)F_p^A \left( \frac{x}{\xi} \right) + NTr P^n(\xi, \kappa_+, \kappa_-)F_n^A \left( \frac{x}{\xi} \right) \right] \]  

(10)

Then, to investigate whether the LF SF can affect the EMC effect, the ratios

\[ R_2^A(x) = \frac{F_2^A(x)}{Z F_2^p(x) + (A-Z) F_2^n(x)} \]  

and \( R_{He}^A(x)/R_{D}^A(x) \) were evaluated. The Pisa group wave function [13], corresponding to the NN interaction AV18 [14], was used. For the two-body channel an exact calculation was performed. In the three-body channel average values for \( k_{23} \) were inserted in Eq. (5), different for the proton and the neutron (113.53 MeV and 91.27 MeV, respectively), corresponding to the average kinetic energy of the intrinsic motion of the spectator pair in the continuum part of the spectrum. We checked in the two-body channel that using the average value \( k_{23} = 136.37 \) MeV, proper for this channel, a result similar to the exact calculation is obtained. Our preliminary results are shown in Fig. 1 and encourage us in performing the full LF calculation.

With the same approximation used for the three-body channel, we checked that \( MSR_{calc} = 0.3331 \).

4 Extraction of neutron asymmetries from SIDIS experiments off \( ^3H_e \)

In Ref. [17] it was shown, within the plane wave impulse approximation (no interaction, after the electron scattering off one of the \( ^3H_e \) nucleons, between the measured fast \( \pi \), the remnant debris and the interacting two-nucleons recoiling system) and using the NR SF of Ref. [10], that the formula [18]

\[ A_n \simeq \frac{1}{p_{n}f_{n}} \left( A^{exp}_{n} - 2p_{p}f_{p}A^{exp}_{p} \right) \]  

(12)
already widely used to extract neutron asymmetries in DIS from experiments on $^3$He, works also in SIDIS, both for the Collins and Sivers single spin asymmetries. Nuclear effects are hidden in the effective polarizations (EP) $p_p = -0.023$ and $p_n = 0.878$ and in the dilution factors, $f_{p(n)}$.

To investigate whether the formula (12) can be safely applied even in presence of the FSI, in Ref. [2] a generalized eikonal approximation (GEA) is used to take care of the FSI through a distorted spin-dependent SF in a NR approach. The relevant part of the (GEA-distorted) spin-dependent SF is

$$\mathcal{P}_\lambda^\text{FSI} = \mathcal{O}_\lambda^\text{FSI} - \mathcal{O}_\lambda^\text{FSI} / \mathcal{O}_\lambda^\text{FSI}$$

$$= \sum_{\mathcal{N}} \rho \left( \epsilon_{\lambda_{A-1}} \right) \langle S_A, \mathcal{P}_A \mid \hat{S}_{\mathcal{G}I} \rangle \langle \Phi_{\lambda_{A-1}}, \lambda' \rangle \langle \Phi_{\lambda_{A-1}}, \lambda \rangle \langle S_A, \mathcal{P}_A \rangle \delta \left( E - B_A - \epsilon_{\lambda_{A-1}} \right)$$

where $\hat{S}_{\mathcal{G}I}(r_1, r_2, r_3) = \prod_{i=2,3} \left[ 1 - \theta(z_i - z_1) \Gamma(b_i - b_1, z_1 - z_i) \right]$ is a Glauber operator [19] which takes care of hadronization and FSI. The model of Ref. [20] for the (generalized) profile function $I'(b, z)$, already successfully applied to $^2H(e, e'p)X$ [21], is adopted.

![Fig. 2](image)

Fig. 2 Neutron asymmetries extracted through Eq. (12), from 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 [2].

It occurs that effects of GEA-FSI in the dilution factors and in the EP compensate each other to a large extent: $p_{p,F}^\text{FSI}/p_{p,F}^\text{FSI} \approx p_{p,F}^\text{FSI}/p_{n,F}^\text{FSI} \approx p_{n,F}$. Then the usual extraction of Eq. (12) is safe, as shown at $E_1 = 8.8$ GeV in Fig. 2.

Relativity effects seem weak, since LF longitudinal and transverse EPs change little from the ones obtained with the NR SF [22]. 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 of [21].

5 Conclusions and Perspectives

A Poincaré covariant description of $A=3$ nuclei, based on the LF Hamiltonian dynamics, has been proposed. The Bakamjian-Thomas construction of the Poincaré generators allows one to embed the successful NR phenomenology for few-nucleon systems in a Poincaré covariant framework. A LF SF can be defined that exactly fulfills both the normalization and the momentum sum rule. The nucleon SF for $^3$He, has been evaluated by approximating the IF overlaps in Eq. (5) with their NR counterparts, calculated with the AV18 NN interaction, since fulfills rotational and translational symmetries.

A first test of our approach is the EMC effect for $^3$He. The 2-body contribution to the nucleon SF has been calculated with the full expression, while for the 3-body contribution an average value for
<k_f^2> has been used. In the comparison with experimental data encouraging improvements clearly
appear with respect to the non-relativistic result. The next step will be the full calculation of the EMC
effect for \(^3\text{He}\), including the exact 3-body contribution.

An investigation of SIDIS processes off \(^3\text{He}\) beyond the NR, impulse approximation (IA) approach
is presently being carried out. A Generalized Eikonal Approximation has been used to deal with the
FSI effects and a distorted spin-dependent spectral function, still non relativistic, has been defined. It
has been shown that the formula (12) can be safely used to obtain both the Collins and Sivers neutron asymmetries from the measured Collins and Sivers asymmetries off \(^3\text{He}\).

Preliminary promising results (in IA) of the relativistic effects in SIDIS processes were obtained
through an evaluation of the LF effective polarizations. The next step will be the introduction of the
FSI through the GEA within the LFHD.

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