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Neutron orbital structure from generalized parton distributions of ^{3}He

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The generalized parton distribution H and E of the ^{3}He nucleus, which can be measured in hard exclusive processes such as coherent deeply virtual Compton scattering, are thoroughly analyzed in impulse approximation, within the Av18 interaction. It is found that their sum, at low momentum transfer, is dominated to a large extent by the neutron contribution: the peculiar spin structure of ^{3}He makes this target unique for the extraction of the neutron information. This observation allows access, in dedicated experiments, to the orbital angular momentum of the partons in the neutron.

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The measurement of generalized parton distributions (GPDs) [1–3], parametrizing the nonperturbative hadron structure in hard exclusive processes, will be a major achievement for Hadronic physics in the next few years. H, a target helicity-conserving quantity, and E, a target helicity-flip one, are two of the GPDs occurring at leading twist. Their measurement will offer possibilities, such as a picture of the three-dimensional nucleon structure [4], and the access to the parton orbital angular momentum (OAM) [3]. For the latter aim, it is mandatory to measure both the GPDs H and E. The most natural process to observe them is deeply virtual Compton scattering (DVCS) (i.e., $eH \longrightarrow e'H'\gamma$ when $Q^2 \gg M^2$) (here and in the following, $Q^2 = -qq$ is the momentum transfer between the leptons e and e', Δ^2 the one between the hadrons H and H', and M is the nucleon mass) [3,5]. DVCS data are being analyzed (recent results can be found in Ref. [6]) and, despite severe difficulties, GPDs are being extracted from them (see Ref. [7] and references therein).

The issue of measuring GPDs for nuclei to unveil medium modifications of bound nucleons has been addressed in several papers [8,9]. Great attention has to be paid to avoid confusing unusual effects with conventional ones. To this respect, a special role can be played by few-body nuclear targets, for which realistic studies are possible and exotic effects can be therefore distinguished. To this aim, in Ref. [10], an impulse approximation (IA) calculation of the flavor q GPD of ^{3}He, H_q^3, has been presented, valid for $\Delta^2 \ll Q^2, M^2$. The approach permits the investigation of the coherent, no breakup channel of DVCS off ^{3}He, which can be hardly studied at large Δ^2, due to the vanishing cross section. It was found that the properties of nuclear GPDs should not be trivially inferred from those of nuclear parton distributions (PDFs), measured in deep inelastic scattering (DIS).

In this Rapid Communication, the approach of Ref. [10] is extended to evaluate the GPD E_q of ^{3}He, E_q^3 to study the possibility of accessing the neutron information. In fact, the properties of the free neutron are being investigated through experiments with nuclei, taking nuclear effects properly into account. ^{3}He, thanks to its particular spin structure, is extensively used as an effective polarized neutron target [11]. ^{3}He is therefore a serious candidate to study the polarization properties of the free neutron, such as its helicity-flip GPD E_q. To fully understand the importance of measuring the neutron GPDs and the advantages of ^{3}He, let us first summarize the main properties of GPDs. For a spin 1/2 hadron target, with initial (final) momentum and helicity $P(P')$ and $s(s')$, respectively, the GPDs $H_q(x,\xi,\Delta^2)$ and $E_q(x,\xi,\Delta^2)$ are defined through the light cone correlator

$$\begin{aligned} F^q_{s's}&(x,\xi,\Delta^2) \\ &= \int \frac{dz^-}{4\pi} e^{ix\bar{P}^+z^-} \langle P's'|\hat{O}_q|Ps\rangle|_{z^+=0,z_\perp=0} \\ &= \frac{1}{2\bar{P}^+}\Big[H_q(x,\xi,\Delta^2)\bar{u}(P',s')\gamma^+u(P,s) \\ &\quad + E_q(x,\xi,\Delta^2)\bar{u}(P',s')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(P,s)\Big], \end{aligned} \tag{1}$$

where $\hat{O}_q = \bar{\psi}_q(-\frac{z}{2})\gamma^+\psi_q(\frac{z}{2})$, being $\bar{P} = (P+P')/2$, ψ_q the quark field, m the hadron mass, and $q^\mu = (q_0,\vec{q})$. The skewedness variable, ξ, is defined as $\xi = -\Delta^+/(2\bar{P}^+)$ (here and in the following, $a^\pm = (a^0 \pm a^3)/\sqrt{2}$. In addition to the variables x,ξ and Δ^2, GPDs depend on the scale Q^2. This dependence, not important in this investigation, is not shown in the following. Among the constraints satisfied by GPDs, the ones relevant here are: i) in the forward limit, $P' = P$ (i.e., $\Delta^2 = \xi = 0$) DIS is recovered, and $H_q(x,\xi,\Delta^2)$ yields the usual PDF, $H_q(x,0,0) = q(x)$, while $E_q(x,0,0)$ is not accessible; ii) the integration over x yields, for H_q (E_q), the contribution of the flavor q to the Dirac (Pauli) form factor (FF) of the target,

$$\int_{-1}^{1} dx\, H_q(E_q)(x,\xi,\Delta^2) = F^q_{1(2)}(\Delta^2). \tag{2}$$

A fundamental result is Ji's sum rule (JSR) [3], relating the forward limit of the second moment of the unpolarized GPDs to the total angular momentum of the quark q in the

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target, $\langle J_q \rangle$,

$$\langle J_q \rangle = \int_{-1}^{1} dx\, x[H_q(x,0,0) + E_q(x,0,0)]. \quad (3)$$

The combination $H_q + E_q$ is therefore needed to study the angular momentum content of the nucleon, through the JSR. In particular the OAM part could be obtained from $\langle J_q \rangle$, being the helicity one measurable in DIS and semi-inclusive DIS (SiDIS). The relevance of this information to understand the cumbersome spin structure of the nucleon is apparent and, as for any other parton observable, the neutron data are crucial to obtain, together with the proton ones, a u and d flavor decomposition of the GPDs. It is important therefore to measure the neutron H_q and E_q, and the advantages of ^{3}He are evident being this system, among the light nuclei, is the only one for which the nuclear combination $H_q + E_q$ can be dominated by the neutron one. In fact, ^{4}He is scalar and it does not show up any E_q. ^{2}H is also useless in this respect. As it is easily seen in the forward limit, relevant for the JSR, according to Eq. (2) the size of E_q^A for a given target A can be related to its FFs, whose normalization is $F_1^A(0) = Z_A$, $F_1^A(0) + F_2^A(0) = \mu_A$, being Z_A and μ_A the charge and the magnetic dipole moment of the target, respectively. Using the experimental data, one gets, for ^{2}H, $F_2^2(0) \simeq -0.14\mu_N$, reflecting a small E_q^2 (in the analysis of Ref. [8], this contribution has been indeed neglected). On the contrary, in the ^{3}He case, $F_2^3(0)$ is not only sizable ($\simeq -4.13\mu_N$), but, if summed to $F_1^3(0)$, yields $\mu_3 \simeq -2.13\mu_N$, a value rather close to the neutron one, $\mu_n \simeq -1.91\mu_N$. As it is well known, μ_3 and μ_n would be equal (i.e., there would be no proton contribution to μ_3) if ^{3}He could be described in an independent particle model with central forces only. Although this scenario is too crude, realistic calculations show that the wave function lies in this configuration with a probability close to 90%, a fact that made it possible to safely extract the neutron DIS structure functions from ^{3}He data, as suggested in Ref. [11], estimating carefully nuclear corrections. In the case under investigation here, the situation is somehow different, because GPDs are not densities. This is the case at least in the forward limit, where the JSR holds: in that situation, static ^{3}He properties can be advocated. The aim of the present analysis is precisely to establish to what extent, close to the forward limit and slightly beyond it, the measured GPDs of ^{3}He can be used to extract the neutron information and, in turn, its OAM content. This study is a prerequisite for any experimental program of coherent DVCS off ^{3}He, a topic that is under consideration at JLab.

Let us then generalize the approach of Ref. [10], where the GPD H_q^3 of ^{3}He has been obtained in IA. In addition to the kinematical variables x and ξ, one needs the corresponding ones for the nucleons in the target nuclei, x' and ξ'. The latter quantities can be obtained defining the + components of the momentum k and $k + \Delta$ of the struck parton before and after the interaction, with respect to $\bar{p}^+ = \frac{1}{2}(p + p')^+$, being $p(p')$ the initial (final) momentum of the interacting bound nucleon [10]. Using the standard procedure developed in IA studies of DIS off nuclei [12], the following relations for H_q^3, E_q^3, in terms of the nucleon ones, H_q^N, E_q^N, are found

$$H_q^3(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p}\, \overline{\sum_S} \sum_s P^N_{SS,ss}(\vec{p},\vec{p}\,',E) \times \frac{\xi'}{\xi} H_q^N(x',\xi',\Delta^2), \quad (4)$$

$$(H_q^3 + E_q^3)(x,\xi,\Delta^2) = \sum_N \int dE \int d\vec{p}\,[P^N_{+-,+-}(\vec{p},\vec{p}\,',E) - P^N_{+-,-+}(\vec{p},\vec{p}\,',E)] \times \frac{\xi'}{\xi}(H_q^N + E_q^N)(x',\xi',\Delta^2). \quad (5)$$

In Eqs. (4) and (5), proper components appear of the spin-dependent nondiagonal spectral function of the nucleon N in ^{3}He,

$$P^N_{SS',ss'}(\vec{p},\vec{p}\,',E) = \frac{1}{(2\pi)^6}\frac{M\sqrt{ME}}{2}\int d\Omega_t \times \sum_{s_t} \langle \vec{P}'S'|\vec{p}\,'s',\vec{t}s_t\rangle_N \langle \vec{p}s,\vec{t}s_t|\vec{P}S\rangle_N, \quad (6)$$

where S, $S'(s,s')$ are the nuclear (nucleon) spin projections in the initial (final) state, respectively, and $E = E_{\min} + E_R^*$, E_R^* being the excitation energy of the two-body recoiling system and $E_{\min} = |E_{^3\mathrm{He}}| - |E_{^2H}| = 5.5$ MeV. The main quantity appearing in the definition Eq. (6) is the intrinsic overlap integral

$$\langle \vec{p}s,\vec{t}s_t|\vec{P}S\rangle_N = \int d\vec{y}\, e^{i\vec{p}\cdot\vec{y}} \langle \chi_N^s, \Psi_t^{s_t}(\vec{x}) | \Psi_3^S(\vec{x},\vec{y})\rangle \quad (7)$$

between the wave function of ^{3}He, Ψ_3^S, with the final state, described by two wave functions: i) the eigenfunction $\Psi_t^{s_t}$, with eigenvalue $E = E_{\min} + E_R^*$, of the state s_t of the intrinsic Hamiltonian pertaining to the system of two interacting nucleons with relative momentum $\vec{t}$, which can be either a bound or a scattering state, and ii) the plane wave representing the nucleon N in IA.

As discussed in Ref. [10], where Eq. (4) has been obtained and evaluated, the accuracy of this calculation, since a NR spectral function will be used to evaluate Eqs. (4) and (5), is of order $O(\vec{p}\,^2/M^2, \vec{\Delta}^2/M^2)$. The interest of the present calculation is indeed to investigate nuclear effects at low values of $\vec{\Delta}^2$, for which measurements in the coherent channel may be performed.

Equation (5) shows a much richer spin structure than Eq. (4). Equation (5) has been evaluated in the nuclear Breit frame, using the exact nuclear overlaps described above, obtained along the line of Ref. [13], using the wave function [14] corresponding to the Av18 interaction [15]. For the nucleonic GPDs, the model of Ref. [16] has been used, which, despite its simplicity, fulfills the general properties of GPDs. The model has been minimally extended to parametrize also the GPD E_q, assuming that it is proportional to the charge of q (this natural choice is used, e.g., in Ref. [17]).

The only real possibility to establish the validity of the approach is the comparison with experiments. Unfortunately, data for the GPDs are not available and for E_q^3, in particular,

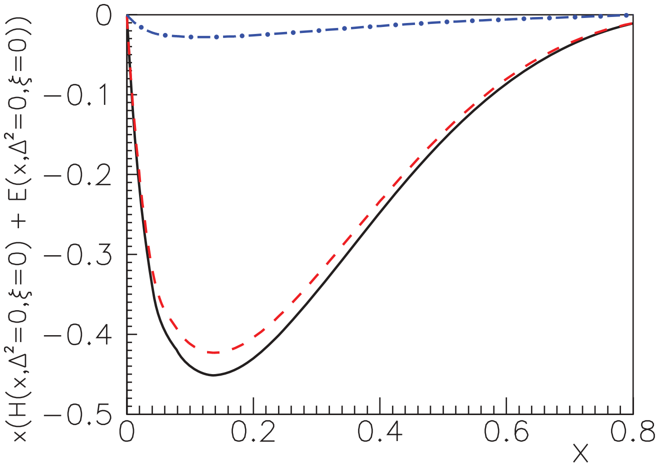

FIG. 1. (Color online) The quantity $x\sum_q(H_q^3 + E_q^3)$, shown in the forward limit (full), together with the neutron (dashed) and the proton (dot-dashed) contribution.

even the forward limit is unknown. One check is in any case possible and it is therefore very important: The quantity $H_q^3 + E_q^3$, summed over the active flavors, can be integrated over x to give the experimentally well-known magnetic FF of ^{3}He, $G_M^3(\Delta^2) = F_1^3(\Delta^2) + F_2^3(\Delta^2)$ [cf. Eq. (2)]. The result we found by using this procedure is in quantitative agreement with the Av18 one-body calculation presented in Ref. [18], and with the nonrelativistic part of the calculation in Ref. [19]. For the values of Δ^2 that are relevant for the coherent process under investigation here (i.e., $-\Delta^2 \lesssim 0.2\ \text{GeV}^2$) our results compare well also with the data. For higher values, the agreement is lost. This is a well-known problem: to get a good description of the magnetic FF of trinucleons, three-body forces and two-body currents have to be introduced in the dynamical description of the process (see, e.g., Ref. [18]). If measurements were performed at high values of $-\Delta^2$, our calculations could be improved by allowing for these effects, a standard although lengthy procedure. Anyway, since coherent DVCS cannot be measured at high $-\Delta^2$ for nuclear targets, the good description

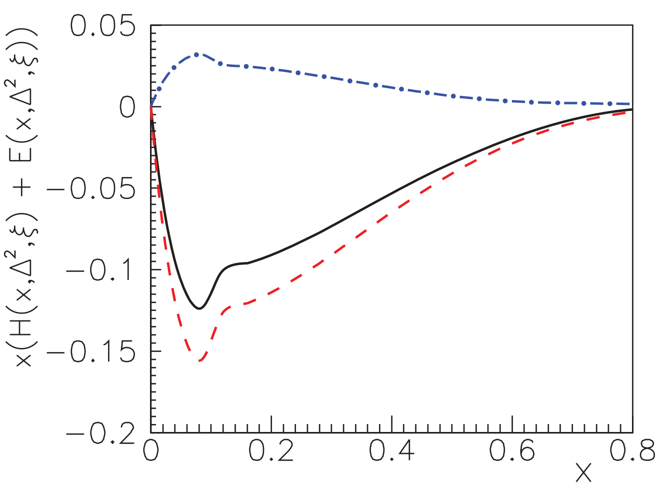

FIG. 2. (Color online) The same as in Fig. 1, but at $\Delta^2 = -0.1\ \text{GeV}^2$ and $\xi = 0.1$.

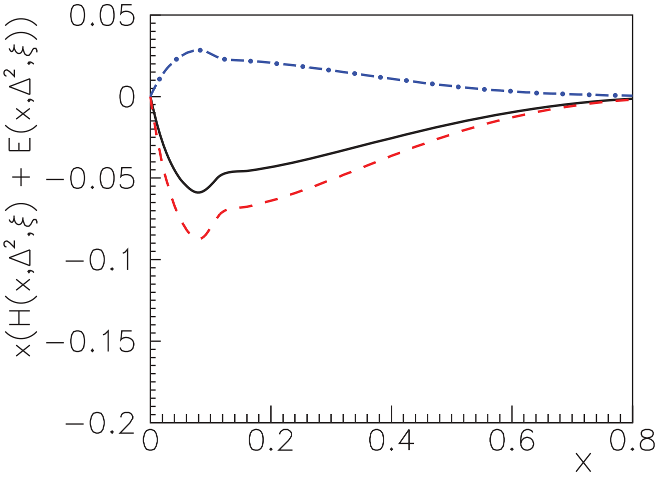

FIG. 3. (Color online) The same as in Fig. 1, but at $\Delta^2 = -0.15\ \text{GeV}^2$, and $\xi = 0.1$.

obtained close to the static point is quite satisfactory for the aim of the present investigation. With the comfort of this successful check, one can have eventually a look at the nuclear GPDs. Results are shown in Figs. 1–4. The quantity $x(H_q^3 + E_q^3)$ summed over the flavors q, which, in the forward limit, yields the integrand of the JSR [cf. Eq. (3)], is shown in Figs. 1–3, in the forward limit (Fig. 1), and at $\Delta^2 = -0.1, -0.15\ \text{GeV}^2$ and $\xi = 0.1$ (Figs. 2 and 3). The shapes of the curves are very dependent on the nucleonic model of Ref. [16], used as input in the calculation, but one should not forget that the aim of this analysis, for the moment, is that of getting a clear estimate of the proton and neutron contribution to the nuclear observable, a feature rather independent on the nucleonic model. The difference in size of the curves in Figs. 1–3 reflects the dramatic effect of increasing Δ^2, a behavior basically governed by the FF. The most evident and interesting result is actually that the contribution of the neutron is impressively dominating the nuclear GPD at low Δ^2, with the proton contribution

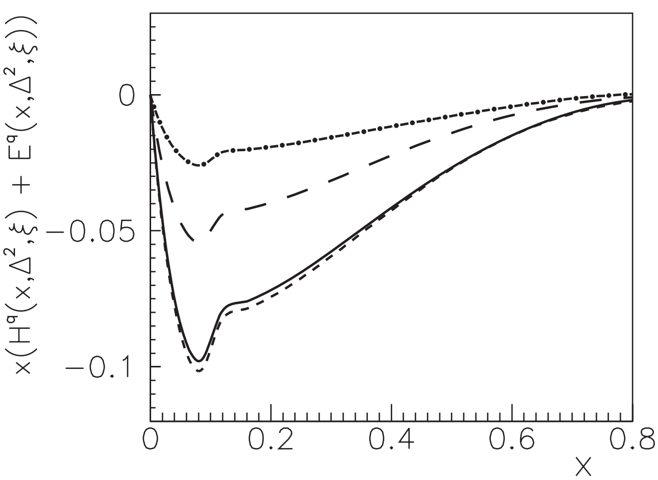

FIG. 4. The quantity $x(H_q^3 + E_q^3)$ for the d (full) and u (dot-dashed) flavor, at $\Delta^2 = -0.1\ \text{GeV}^2$, and $\xi = 0.1$. The neutron contributions for the d (dashed) and u (long-dashed) flavor are also shown.

growing fast with increasing Δ^2, ranging from a few percent in the forward limit, to 15% at most at $\Delta^2 = -0.1$ GeV^2 but being already 30% at $\Delta^2 = -0.15$ GeV^2. On the contrary, as shown in Fig. 4, for the flavor d the impressive dominance of the neutron contribution varies slowly with increasing Δ^2. All these features can be understood qualitatively looking at Eq. (5) which, being rather involved, can be usefully sketched as follows

$$H_q^3 + E_q^3 \approx P_p^3 \otimes \left(H_q^p + E_q^p\right) + P_n^3 \otimes \left(H_q^n + E_q^n\right), \quad (8)$$

where $P^3_{p(n)}$ describes the proton (neutron) dynamics in ^{3}He, while $(H_q^{p(n)} + E_q^{p(n)})$ is the contribution of the flavor q to the GPDs of the proton (neutron). As already explained, due to the spin structure of ^{3}He, P_n^3 is quite larger than P_p^3, justifying the relevance of the neutron contributions in Fig. 1. With increasing Δ^2, for the u flavor, the term $H_u^p + E_u^p$ gets much larger than $H_u^n + E_u^n$, explaining the growth with Δ^2 of the relative size of the proton contribution with respect to the neutron one, shown in Figs. 2–4. This does not occur for the d flavor, and the dominance of the neutron contribution is not hindered by increasing Δ^2 as for the u flavor (cf. Fig. 4). This happens also because one half of the d content of ^{3}He comes from the neutron, while only one fifth of the u one comes from it. In any case, the fact that the proton contribution gets sizable going toward less forward situations should not hinder the extraction of the neutron properties close to the forward limit, where the most important information, related to the OAM of the partons in ^{3}He and then in the neutron, is expected.

A comment is in order concerning the possibility of accessing neutron GPDs in incoherent DVCS off the neutron in nuclear targets (i.e., the process when the interacting neutron is detected together with the scattered electron and the produced photon). An experiment of this type has been approved at the 12 GeV program of JLab [20] for a ^{2}H target. Although these kinds of processes are hindered by final state interactions of the detected neutron, important information, complementary to that obtained with the coherent process proposed here, will be collected. In the near future, we plan therefore to investigate also incoherent DVCS off the neutron in ^{3}He.

In this Rapid Communication, a calculation of the GPDs H_q, E_q of ^{3}He has been presented, proposing coherent DVCS off ^{3}He at low Δ^2 as a key process to obtain the neutron information. If high values of Δ^2 are reached, two-body currents and three-body forces can be included into the approach and, at the same time, a light-front analysis of the process, which already started in SiDIS [21], can be performed to have, from the beginning, a relativistic framework for the investigation.

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