Polarization Transfer in ^{4}He$(\vec{e}, e'\vec{p})^3$H: Is the Ratio G_{Ep}/G_{Mp} Modified in the Nuclear Medium?

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Polarization observables in the ^{4}He$(\vec{e}, e'\vec{p})^3$H reaction are calculated using accurate three- and four-nucleon bound-state wave functions, a realistic model for the nuclear electromagnetic current operator, and a treatment of final-state interactions with an optical potential. In contrast to earlier studies, no significant discrepancies are found between theory and experiment both for the ratio of transverse to longitudinal polarization transfers and for the induced polarization, when free-nucleon electromagnetic form factors are used in the current operator. The present results challenge the current interpretation of the experimental data in terms of medium-modified form factors.

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The recent measurement, carried out at Jefferson Lab (JLab) [1] (E93-049), of the ratio of transverse, P'_x, to longitudinal, P'_z, polarization transfer parameters in the ^{4}He$(\vec{e}, e'\vec{p})^3$H reaction has generated considerable interest. In the elastic process $\vec{e}p \rightarrow e\vec{p}$, the P'_x/P'_z ratio is proportional to that of electric to magnetic form factors of the proton [2], and therefore its measurement in a nucleus by quasielastic proton knockout can shed light, in principle, on the question of whether these form factors are modified in medium.

The issue of medium modifications of the nucleon is a long-standing and controversial one. The increase of nucleon size has been advocated to explain the depletion of the nuclear structure functions measured by deep inelastic scattering (EMC effect) [3], as well as the quenching of the quasielastic longitudinal response [4]. However, theoretical calculations in which binding effects are taken into account using realistic spectral functions provide a quantitative account of both the size and density dependence [5] of the EMC effect, thus showing that it can be explained by conventional nuclear physics. Moreover, stringent limits on the change of nucleon size due to the nuclear environment have been obtained from the y-scaling analysis of inclusive data [6].

In all instances, the answer to the question of whether bound nucleons are indeed modified is model dependent. In the case under discussion here the modification is inferred from a comparison of the experimental data with theoretical predictions of the $(\vec{e}, e'\vec{p})$ cross sections *in nuclei*. Therefore, it is crucial for a proper interpretation of the experimental data that the theoretical calculations include contributions from final-state interactions (FSI) between the knocked out proton and residual system, as well as from many-body terms in the nuclear electromagnetic current and from correlation effects in both the initial and final bound nuclear clusters. At issue then is whether these contributions have so far been accounted for and reliably estimated. For example, the studies of Refs. [7,8], based on relativistic mean field theory, ignore correlation effects in the bound-state wave functions and many-body terms in the electromagnetic operator. Furthermore, FSI are treated with a relativistic optical potential in the work of Udias and collaborators [7], in which the contributions associated with charge-exchange processes are neglected—they will turn out to play an important role in the reaction under consideration; see below. In the work of the Ghent group [8], FSI are described in a Glauber framework, which may not be reliable at the low end of the Q^2 range covered by E93-049, since the ejected proton energies are too low. In addition and more importantly, the charge-exchange mechanism referred to earlier is also not included in this study—indeed, it is not obvious how to incorporate it within the context of a Glauber approach. Lastly, Laget's calculations [9], a full account of which is yet to be published, treat FSI by retaining S, P, and D waves in the nucleon-nucleon (NN) scattering amplitude at low energy, and by using a standard parametrization of the latter in terms of a central term at higher energies. Charge-exchange as well as spin-dependent effects beyond those implicit in the use of the low-energy NN amplitudes are neglected. Two-body terms in the current operator are shown to lead to a quenching of $\simeq$ 2–2.5% in the ratio P'_x/P'_z relative to that in plane-wave-impulse approximation (PWIA); note, however, that in Ref. [1] no quenching is reported in the result at $Q^2 = 0.5$ (GeV$/c)^2$ (the only one shown) for the calculation from the same author. Approximations are made in the numerical evaluations of the loop integrals occurring in Laget's diagrammatic approach.

The present study is based on variational wave functions for the bound three- and four-nucleon systems, derived from a realistic Hamiltonian consisting of the Argonne v_{18} two-nucleon [10] and Urbana-IX three-nucleon [11] interactions (AV18/UIX) with the hyperspherical-harmonics (HH) technique, with (^{3}He$/^3$H) [12] and without (^{4}He) [13] the inclusion of pair correlations. The high accuracy of the HH wave functions is well documented [14], as is the quality of the AV18/UIX Hamiltonian in successfully and quantitatively accounting for a wide variety of three- and four-nucleon bound-state properties and reactions, from zero to several hundred MeV energies [14,15].

The polarization transfer measurement in the JLab experiment E93-049 was performed in a quasielastic regime: the momentum of the recoiling ^{3}H nucleus was kept close to zero. The proton lab kinetic energies were (0.29, 0.55, 0.88, 1.42) GeV for the Q^2 values (0.5, 1.0, 1.6, 2.6) $(\mathrm{GeV}/c)^2$, respectively. These energies are obviously beyond the range of applicability of NN interaction models, such as the AV18, which are constrained to reproduce NN elastic scattering data up to the pion production threshold. At higher energies, NN scattering becomes strongly absorptive with the opening of particle production channels. Indeed, the pp inelastic cross section at 0.5 GeV increases abruptly from about 2 mb to 30 mb and remains essentially constant for energies up to several hundred GeV [16].

In view of these considerations, FSI in the p^3H scattering state are described in the present work via an optical potential [17,18]. Of course, this approximation has limitations as to the energy range where it is expected to be valid; see discussion below. The p^3H wave function is then written as

$$\psi^{(-)}_{\mathbf{k}\sigma;\sigma_3}(p+{}^3\mathrm{H}) = \frac{1}{\sqrt{4}}\sum_{\mathrm{perm}}(-)^{\mathrm{perm}}[\eta^{(-)}_{\mathbf{k}\sigma}(i;p)\phi_{\sigma_3}(jkl;{}^3\mathrm{H}) + \eta^{(-)}_{\mathbf{k}\sigma}(i;n)\phi_{\sigma_3}(jkl;{}^3\mathrm{He})],$$

where σ and σ_3 are the spectator nucleon and bound cluster spin projections, $\mathbf{k}$ is their relative momentum, and the sum over permutations ensures the antisymmetry of the wave function $\psi^{(-)}$. The spectator wave functions $\eta(i;p/n)$ are given by the linear combinations $[\eta(i;T=1) + / - \eta(i;T=0)]/2$, where $T = 0, 1$ denotes the total isospin of the $1+3$ clusters. The latter are taken to be the scattering solutions of a Schrödinger equation containing a complex, energy-dependent optical potential of the form

$$v^{\mathrm{opt}}_T(T_{\mathrm{rel}}) = [v^c(r;T_{\mathrm{rel}}) + (4T-3)v^{c\tau}(r;T_{\mathrm{rel}})] + [v^b(r;T_{\mathrm{rel}}) + (4T-3)v^{b\tau}(r;T_{\mathrm{rel}})]\mathbf{l}\cdot\mathbf{s},$$

where T_{rel} is the relative energy between clusters i and jkl, and $\mathbf{l}$ and $\mathbf{s}$ are the orbital and spin angular momenta of nucleon i, respectively. The imaginary part of v^{opt}_T accounts for the loss of flux in the p^3H and n^3He states due to their coupling to the dd, three- and four-body breakup channels of ^{4}He. Note that the $n + {}^3$He component in the scattering wave function $\psi^{(-)}(p+{}^3\mathrm{H})$ vanishes unless the isospin-dependent (charge-exchange) terms in v^{opt} are included. In the results presented below, all partial waves are retained in the expansion of $\eta(i;T)$, with full account of interaction effects in those with relative orbital angular momentum $l \le 17$. It has been explicitly verified that the numerical importance of FSI in higher partial waves is negligible.

The central v^c and $v^{c\tau}$, and spin-orbit v^b and $v^{b\tau}$ terms have standard Woods-Saxon and Thomas functional forms. The parameters of v^c, $v^{c\tau}$, and v^b were determined by fitting $p + {}^3$H elastic cross section data in the lab energy range $T_{\mathrm{lab}} = (160\text{–}600)$ MeV, and $p + {}^3\mathrm{H} \to n + {}^3\mathrm{He}$ charge-exchange cross section data at $T_{\mathrm{lab}} = 57$ MeV and 156 MeV (see Refs. [17,18] for a listing of their values). The charge-exchange spin-orbit term is taken to be purely real, with a depth parameter depending logarithmically on T_{lab}, $15.0 - 1.5\log[T_{\mathrm{lab}}(\mathrm{MeV})]$ in MeV, and with radius and diffuseness having the values 1.2 fm and 0.15 fm, respectively. The isospin-independent and isospin-dependent spin-orbit terms of v^{opt}_T are not well constrained by the data, since these consist exclusively of differential cross sections [17,19,20]. However, they significantly affect the induced polarization P_y measured in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$, as will be shown below.

The nuclear electromagnetic current includes one- and two-body terms. The one-body current and charge operators have the form recently derived by Jeschonnek and Donnelly [21] [specifically, Eqs. (23) and (25) of Ref. [21]] from an expansion of the covariant single-nucleon current, in which only quadratic and higher order terms are neglected in its dependence on the initial nucleon momentum. This form of the one-body currents is well suited for dealing with processes in which the energy transfer may be large (i.e., the ratio of four- to three-momentum transfer $(Q/q)^2$ is not close to 1) and the initial momentum of the struck nucleon is small. Thus, its use is certainly justified in the quasielastic kinematics of the E93-049 experiment under consideration.

The two-body charge and current operators (MEC) consist of a '''model-independent'' part that is constructed from the NN interaction (the AV18 in the present case), and a '''model-dependent'' one, associated with the excitation of intermediate Δ resonances and the $\rho\pi\gamma$ and $\omega\pi\gamma$ transition mechanisms (for a review, see Carlson and Schiavilla in Ref. [15] and references therein).

Finally, the Höhler parametrization [22] is used for the electromagnetic form factors of the nucleon, except at the highest Q^2 values of 1.6 $(\mathrm{GeV}/c)^2$ and 2.6 $(\mathrm{GeV}/c)^2$, for which the proton electric and magnetic form factors are taken from the parametrization obtained in Ref. [23] by fitting G_{Mp} data and the ratio G_{Ep}/G_{Mp} recently measured at JLab [2]. Incidentally, E93-049 also reported measurements of the polarization transfer ratio on hydrogen in the same kinematics as for helium [1]. The results for $(P'_x/P'_z)_{^1\mathrm{H}}$ are in agreement with the Höhler-Brash parametrization, except at $Q^2 = 1.6$ $(\mathrm{GeV}/c)^2$: Strauch *et al.* measure -0.395 ± 0.013 while the Brash fit, based on Ref. [2], gives -0.415. However, this difference is due to finite detector acceptances [24].

The matrix elements $^{(-)}\langle p + {}^3\mathrm{H}; \mathbf{k}\sigma, \sigma_3 | j^\mu(\mathbf{q},\omega) | {}^4\mathrm{He}\rangle$ are computed with Monte Carlo (MC) techniques without making any further approximations beyond those inherent to the treatment of FSI and nuclear electromagnetic currents, discussed above. The resulting theoretical predictions for the super-ratio $R = (P'_x/P'_z)/(P'_x/P'_z)_{\rm PWIA}$ and for the induced polarization P_y are compared with the experimental data [1] in Figs. 1 and 2. The ratio of transverse to longitudinal polarizations in PWIA is proportional to G_{Ep}/G_{Mp} as obtained in the Höhler-Brash parametrization. In Fig. 1 the hydrogen data [1] are also shown, for which, as expected, R is very close to 1, except for the point at $Q^2 = 1.6$ $({\rm GeV}/c)^2$ (see comment above, however).

The calculated results in Figs. 1 and 2 are labeled as follows. The curves OPT(no CH-EX) and OPT both use one-body currents and the optical potential to describe FSI effects, the only difference being that in the OPT(no CH-EX) calculation the charge-exchange components $v^{c\tau}$ and $v^{b\tau}$ of $v_T^{\rm opt}$ are ignored. The curve labeled OPT + MEC includes the full $v_T^{\rm opt}$ (as the curve OPT) and one- and two-body currents. The statistical errors associated with the MC integrations are only shown for the OPT + MEC predictions; they are similar for the other predictions. Finally, the results of a calculation including one- and two-body currents, in which the sign of the charge-exchange spin-orbit term $v^{b\tau}$ in $v_T^{\rm opt}$ had been artificially flipped, were found to be numerically close to those obtained in the OPT approximation, except for P_y at $Q^2 = 0.5$ $({\rm GeV}/c)^2$, i.e., $P_y = -0.0060 \pm 0.0090$. They are not shown in Figs. 1 and 2.

It should be stressed once more that the calculations may not describe reliably FSI effects for the last two Q^2 values since the relevant proton kinetic energies, 0.88 GeV and 1.42 GeV, represent uncontrolled extrapolations of the present optical model, which is fit to data up to 0.6 GeV. For the low Q^2 values, however, the P_y results obtained in the OPT approximation indicate that, while the spin-orbit terms v^b and $v^{b\tau}$ may not be well constrained by the p^3H elastic and charge-exchange differential cross sections, they seem nonetheless to be quite realistic.

The OPT + MEC calculation reproduces well the measured super-ratio R at low Q^2 values, and is also consistent with the measured induced polarization P_y, although the experimental data for this latter quantity have rather large systematic errors. The charge-exchange components $v^{c\tau}$ and, particularly, $v^{b\tau}$ in the optical potential play a crucial role—see curves OPT(no CH-EX) and OPT in Fig. 1—as do two-body terms in the electromagnetic current operator. The inability to reproduce the observed quenching of the super-ratio had been a persistent problem in all earlier studies we are aware of [7–9]. Indeed, the results of these studies are similar to those obtained here in the OPT(no CH-EX) calculation.

In the parallel kinematics of E93-049 P'_x and P'_z are proportional, in the notation of Ref. [25], to the response functions $R^t_{LT'}$ and $R^l_{TT'}$, respectively, involving interference between matrix elements of charge-current and current-current operators. In fact, it turns out that $R^l_{TT'} = R_T$ exactly (again, in parallel kinematics), where R_T is the ordinary transverse response. The charge-exchange mechanism affects both $R^t_{LT'}$ and $R^l_{TT'}$: for example, at $Q^2 = 0.5$ $({\rm GeV}/c)^2$, $R^t_{LT'} = 0.251$ fm^3 and 0.227 fm^3, and $R^l_{TT'} = 0.183$ fm^3 and 0.174 fm^3 in the OPT(no CH-EX) and OPT calculations, respectively. However, the resulting polarization transfer parameters are: $P'_x = -0.116$ and -0.115, and $P'_z = 0.130$ and 0.136 in the same approximations.

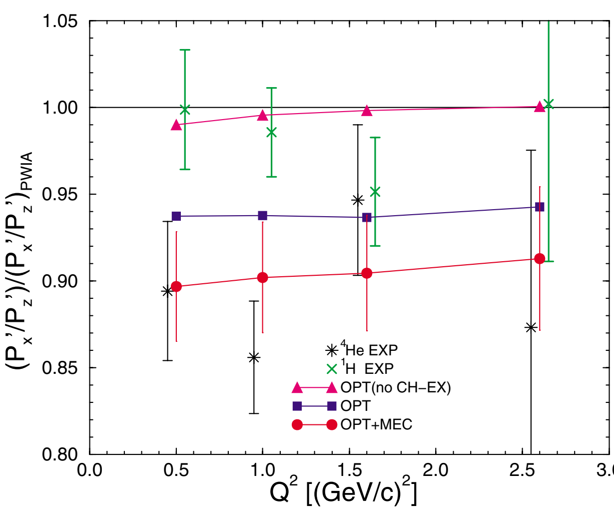

FIG. 1 (color). The super-ratios measured for ^{4}He are compared to theoretical predictions, obtained in various approximation schemes (see text for an explanation of the notation). The solid lines are to guide the eye only. Also shown are the super-ratios measured for ^{1}H. Note that the ^{4}He (^{1}H) data have been shifted to the left (right) by 0.05 $({\rm GeV}/c)^2$ in order to reduce clutter.

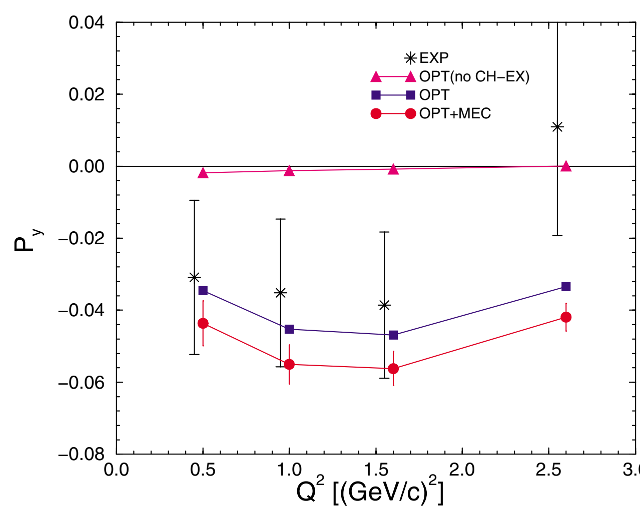

FIG. 2 (color). The induced polarizations measured for ^{4}He are compared to theoretical predictions, obtained in various approximation schemes (see text for an explanation of the notation). The solid lines are to guide the eye only. Note that the ^{4}He data have been shifted to the left by 0.05 $({\rm GeV}/c)^2$ in order to reduce clutter.

Two-body terms in the current operator (those in the charge operator give tiny contributions) also affect $P_x^{\prime}$ and $P_z^{\prime}$ differently. Both response functions $R_{LT'}^{t}$ and $R_{TT'}^{l} = R_T$ are increased by two-body current contributions, but the increase for R_T, about 8%, is twice as large as for $R_{LT'}^{t}$ (as one would naively expect), and therefore the ratio $P_x^{\prime}/P_z^{\prime}$ is suppressed by about 4% with respect to that obtained with one-body currents only. The enhancement of R_T is consistent with that calculated for the transverse response function, measured in inclusive $^4\mathrm{He}(e, e')$ scattering in quasielastic kinematics (Carlson *et al.* in Ref. [15]), although it is important to emphasize that the total $p^3\mathrm{H}$ contribution to the inclusive response involves an integral over the missing momentum p_m, while here this contribution is evaluated at a single kinematical point, namely $p_m \simeq 0$. Lastly, among the two-body terms, the π-like and ρ-like currents, derived from the isospin-dependent static part of the AV18, and the Δ-excitation current give the leading contributions.

To conclude, the observed suppression of the super-ratio in ^{4}He is explained by FSI effects and two-body current contributions. In contrast to earlier suggestions made in the literature [1], no in-medium modification of the proton electromagnetic form factors is needed to reproduce the experimental data. The present results corroborate the conclusions derived from analyses of the Coulomb sum rule (CSR) in few-nucleon systems [26], which show that there is no missing strength in the longitudinal response of these nuclei when the free-proton electric form factor is used. The CSR situation for medium-weight nuclei remains controversial to this day [27,28], although there are rather strong indications that even there no quenching of longitudinal strength is observed [27,29]. Therefore, the quark-meson coupling model of nucleon and nuclear structure [30], which leads to the notion of medium-modified nucleon form factors, seems to be at variance with a number of experimental observations. It is interesting to note that this notion is not an inevitable consequence of the quark substructure of the nucleon. For example, a recent study [31] of the two-nucleon problem in a flux-tube model of six quarks interacting via single gluon and pion exchanges suggests that the nucleons retain their individual identities down to very short separations, with little distortion of their substructures.

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