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Higher twist effects in parity-violating electron deuteron scattering

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Summary. — Parity-Violating Deep Inelastic Scattering (PVDIS) of polarized electrons from deuterium can in principle probe higher twist quark-quark correlations beyond the parton model. As first observed by Bjorken and Wolfenstein, the dominant contribution to the electron polarization asymmetry, proportional to the axial vector electron coupling, receives corrections at twist-four from the matrix element of a single four-quark operator. In particular, because the contribution of the relevant twist four operator satisfies the Callan-Gross relation, the ratio of parity-violating longitudinal and transverse cross sections, $R^{\gamma Z}$, is identical to that for purely electromagnetic scattering, R^{γ}, up to perturbative and power suppressed contributions. This result simplifies the interpretation of the asymmetry for experiments planned at the Thomas Jefferson National Accelerator Facility (JLab). The results of MIT Bag Model calculations are used to give benchmark estimates of the relevant twist four operator contribution to the leading term in the asymmetry as a function of Bjorken x and Q^2. These are compared with corrections to the asymmetry due to violation of charge symmetry in the parton distribution functions.

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Parity-violating deep inelastic scattering (PVDIS) of longitudinally polarized electrons from deuterium played a central role in establishing the theory of weak neutral currents in the 1970s [1-3]. Since then the parity violating asymmetry

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}\,, \tag{1}$$

where $\sigma_{R,L}$ correspond to the scattering cross-sections with positive and negative helicity electrons, respectively, has been studied extensively for various targets. Furthermore, the recently approved 12 GeV upgrade of CEBAF at JLab, expected to be completed by 2014, aims to begin the next generation Moller and electron-deuteron scattering experiments. The SOLID proposal [4] for precision parity-violating electron-deuteron scattering, approved as part of the 12 GeV upgrade, will measure A_{RL} over a wide kinematic range in Q^2 and Bjorken-x to within 1% at each kinematic point. In addition, one high-precision PVDIS experiment with deuterium has completed data taking at selected kinematic points with the 6 GeV [5] beam. Substantial uncertainties in the theoretical interpretation of the deep inelastic asymmetries will remain unless various effects contributing to the asymmetry such as new physics beyond the SM, sea quark distributions, Charge Symmetry Violation (CSV), and higher twist contributions are well understood and disentangled from each other.

The SM parity-violating interactions of the electron with the quarks, obtained after integrating out the Z-boson, are parameterized as

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\Big[\bar{e}\gamma^\mu\gamma_5 e\big(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\big) + \bar{e}\gamma^\mu e\big(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\big)\Big], \tag{2}$$

where at lowest order, the Wilson coefficients in the SM are given by

$$\begin{aligned} C_{1u}^{\text{tree}} &= -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W, \qquad & C_{1d}^{\text{tree}} &= \frac{1}{2} - \frac{2}{3}\sin^2\theta_W, \\ C_{2u}^{\text{tree}} &= -\frac{1}{2} + 2\sin^2\theta_W, \qquad & C_{2d}^{\text{tree}} &= \frac{1}{2} - 2\sin^2\theta_W. \end{aligned} \tag{3}$$

The reason for the sensitivity of the asymmetry to such parity-violating interactions is that in the limit of good isospin and negligible sea quark effects, all hadronic structure functions cancel at leading order in the twist expansion. The resulting expression at tree-level, known as the Cahn-Gilman (CG) formula is given by

$$A_{CG}^{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\left(1 - \frac{20}{9}\sin^2\theta_W\right) + \left(1 - 4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]. \tag{4}$$

Here y is the kinematic variable defined as $y = \frac{2P\cdot(\ell-\ell')}{2P\cdot\ell}$ where P_μ, ℓ_μ, and ℓ'_μ denote the four momenta of the deuteron, the incoming electron, and the outgoing electron respectively. The corrections to this Cahn-Gilman formula can be parameterized by writing the asymmetry as

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right], \tag{5}$$

where the parameters $\tilde{a}_j$ $(j = 1, 2)$ are schematically written as

$$\tilde{a}_j = -\frac{2}{3}\left(2C_{ju} - C_{jd}\right)\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right] \tag{6}$$

and $R_j(\text{new})$, $R_j(\text{sea})$, $R_j(\text{CSV})$, $R_j(\text{TMC})$, and $R_j(\text{HT})$ denote, respectively, corrections arising from possible new physics, sea quark effects, CSV, target mass corrections (TMC), and higher twist (HT) contributions. Addressing the nature of higher twist corrections to the CG formula is subject of this work.

The electron-deuteron scattering asymmetry is conventionally written in the form

$$A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + \frac{g_V^e}{2} Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]. \tag{7}$$

Here, g_V^e (g_A^e) are the vector (axial vector) couplings of the Z-boson to the electron; F_1^{γ}, $F_1^{\gamma Z}$, and $F_3^{\gamma Z}$ are the structure functions arising, respectively, from hadronic matrix elements of the vector electromagnetic (EM) current, interference of the vector EM and vector weak neutral current (WNC), and interference of the vector EM current and axial vector WNC; and $Y_{1,3}$ are functions of kinematic variables and the ratios R^{γ} and $R^{\gamma Z}$ of longitudinal and transverse cross sections for purely EM and WNC-EM vector current interference cross sections

$$R^{\gamma(\gamma Z)} \equiv \frac{\sigma_L^{\gamma(\gamma Z)}}{\sigma_T^{\gamma(\gamma Z)}} = r^2 \frac{F_2^{\gamma(\gamma Z)}}{2x F_1^{\gamma(\gamma Z)}} - 1, \qquad r^2 = 1 + \frac{4M^2 x^2}{Q^2}, \tag{8}$$

where x is the momentum fraction of the initial state parton in the deuteron. In the SM, at leading twist and in the absence of CSV effects, the Y_1 term in eq. (7) is independent of y and depends only on g_A^e and the vector current coupling of the Z-boson to quarks [3]. Since $g_V^e = -1 + 4\sin^2\theta_W \sim -0.1$, the Y_1-term dominates the asymmetry, making its scrutiny particularly important for the interpretation of the Jefferson Lab PVDIS program.

We draw on the observations of [6, 7] that the twist-four contribution to the Y_1 term in A_{RL} for deuterium, given in eq. (7), arises from a single four-quark operator involving up- and down-quark fields

$$\mathcal{O}_{ud}^{\mu\nu}(x) = \frac{1}{2}[\bar{u}(x)\gamma^{\mu}u(x)d(0)\gamma^{\nu}d(0) + (u \leftrightarrow d)], \tag{9}$$

to recast its effect on the asymmetry, in a manner suitable for interpretation of experiments at JLab. Noting that the contribution of $O_{ud}^{\mu\nu}(x)$ to the electroweak structure functions satisfies the Callan-Gross relation at leading order in the strong coupling, we find that

$$R^{\gamma Z} = R^{\gamma}, \qquad Y_1 = 1, \tag{10}$$

at twist-four up to perturbative corrections. The possibility of differences between $R^{\gamma Z}$ and R^{γ} as large as 20% was recently considered in ref. [8]. Using eq. (10), the twist-four effect entering the dominant term in the asymmetry resides entirely in the ratio $F_1^{\gamma Z}/F_1^{\gamma}$ so that one can write

$$\left[\frac{F_1^{\gamma Z}}{F_1^{\gamma}}\right]_{CG+HT} = \frac{9}{5}\left(1 - \frac{20}{9}\sin^2\theta_W\right)\Big[1 + R_1(\mathrm{HT})\Big],$$

where the first term corresponds to the CG limit and the second term gives the twist-four correction. The twist-four correction takes the form [9]

$$R_1(\mathrm{HT}) = \left[\frac{-4}{5(1 - \frac{20}{9}\sin^2\theta_W)}\right]\frac{F_1^{du}}{u_p(x) + d_p(x)}. \tag{11}$$

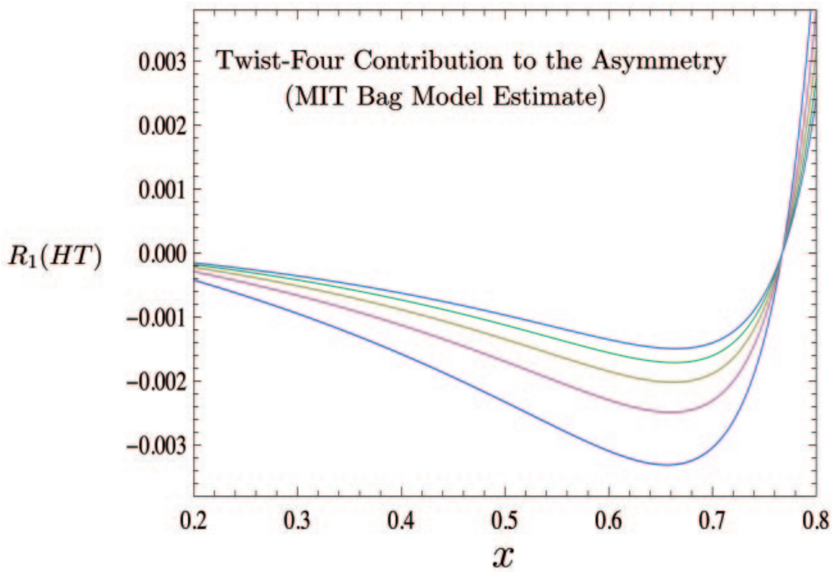

Fig. 1. – The estimate of $R_1(HT)$ as a function of the Bjorken variable x for different values of Q^2 in the MIT Bag Model. The curves from the bottom to top correspond to the values $Q^2 = 4, 6, 8, 10, 12\,\mathrm{GeV}^2$, respectively.

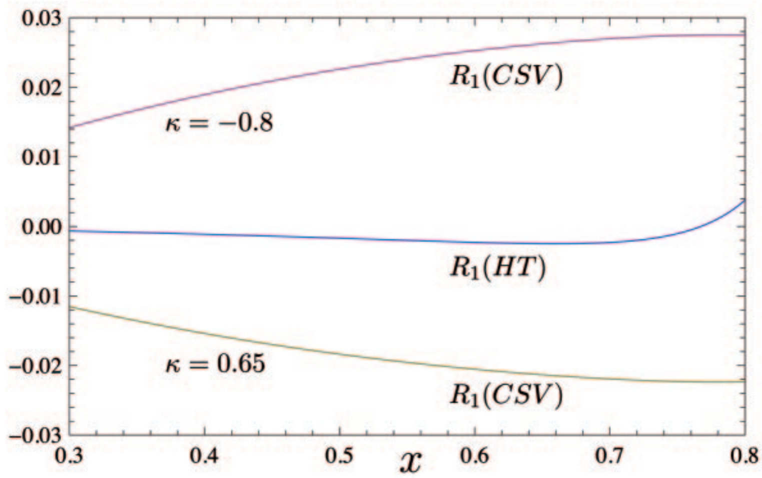

Fig. 2. – The relative magnitudes of $R_1(HT)$ and $R_1(CSV)$ as a function of the Bjorken-x variable for a representative value of $Q^2 = 6\,\mathrm{GeV}^2$. We use the parameterization [8] $\delta u - \delta d = 2\kappa f(x)$, where $f(x) = x^{-1/2}(1-x)^4(x-0.0909)$. The top curve and bottom curves give $R_1(CSV)$ for the choices $\kappa = -0.8$ and $\kappa = 0.65$. The middle curve is the MIT Bag Model estimate for $R_1(HT)$.

The twist-four structure function F_1^{du} is related to the standard structure functions as [9]

$$F_1^{du} = \Big[(9 - 20\sin^2\theta_W)F_1^{\gamma} - 5F_1^{\gamma Z}\Big]. \tag{12}$$

Using the power law dependence in Q^2 of the twist-four effects to the Y_1-term it may be possible, with the precision and the wide kinematic range of the PVDIS program at JLab and its possible extension at an electron-ion collider, to separate this twist-four effect from CSV effects depending on their relative overall sizes. To provide theoretical guidance for such a program, we utilize the MIT Bag Model to estimate [9] the size and variation of the twist-four contribution F_1^{du} with Bjorken-x and Q^2. These estimates extend the earlier work of ref. [10] by allowing for the x-dependences of the twist-two and twist-four contributions to $F_1^{\gamma(\gamma Z)}$ to differ. As seen in fig. 1, we find that if the MIT Bag Model reasonably estimates the magnitude of the twist-four contribution from $O_{ud}^{\mu\nu}(x)$, the impact on the asymmetry would likely be too small to be extracted without further improvements in experimental precision. In this case, as seen in fig. 2, the planned PVDIS experiments could in principle provide a theoretically clean probe of possible contributions from CSV and/or physics beyond the SM. Conversely, the observation of significant power corrections to the Y_1 term would signal the presence of relatively large and theoretically interesting quark-quark correlation contributions to the electroweak structure functions. Similar conclusions were obtained more recently [11] using nucleon multiparton light-cone wave functions to estimate higher twist effects.

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