1

EPJ manuscript No.
(will be inserted by the editor)

Parity Violation in Deep Inelastic Scattering at JLab 6 GeV

Xiaochao Zheng[1] for the JLab E05-007 Collaboration

Lab for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received: date / Revised version: date

Abstract. The parity-violating asymmetry in $\boldsymbol{e}-{}^2$H deep inelastic scattering (DIS) can be used to extract the weak neutral-current coupling constants C_{2q}. A measurement of this asymmetry at two Q^2 values is planned at Jefferson Lab. Results from this experiment will provide a value of $2C_{2u}-C_{2d}$ to a precision of ± 0.03, a factor of eight improvement over our current knowledge. If all hadronic effects can be understood, this result will provide information on possible extensions of the Standard Model, complementary to other experiments dedicated to new physics searches. Presented here are the physics motivation, experimental setup, potential hadronic effects and their implications, and the future of PV DIS at Jefferson Lab.

PACS. 13.60.-r Photon and charged-lepton interactions with hadrons – 12.15.-y Electroweak interactions – 12.15.Mm Neutral currents – 12.60.-i Models beyond the standard model

1 Introduction

A measurement of the parity-violating (PV) asymmetry of $\boldsymbol{e}-{}^2$H deep inelastic scattering (DIS) is planned [1] at the Thomas Jefferson National Accelerator Facility (JLab) in Virginia, USA. The measurement will be performed at two Q^2 values of 1.1 and 1.9 GeV^2 and a fixed $x = 0.3$. The high Q^2 measurement will be used to extract the effective weak coupling constants $(2C_{2u} - C_{2d})$. The low Q^2 measurement may provide the first observation of the hadronic higher-twist contribution to the PV DIS asymmetry, which at JLab energies is the most likely source of a large deviation from the Standard Model prediction. Using the Standard Model value of $2C_{1u} - C_{1d}$ which will be tested by combining the results from Cs atomic parity violation (APV) and the future Qweak experiment, the expected uncertainty on $(2C_{2u}-C_{2d})$ is ± 0.03. This result will improve the current knowledge on this quantity by a factor of eight. It will help to extract the couplings C_{3q} from high-energy data, and might reveal possible physics beyond the Standard Model.

Results from this experiment (E05-007) will provide an important guidance for the future DIS-parity program, of which the ultimate goals are two-fold: by choosing a kinematics where hadronic effects are negligible, we can extract $\sin^2\theta_W$ and study possible extensions of the Standard Model to a high precision. By choosing kinematics where hadronic effects are expected to be large, various interesting phenomena can be studied, such as higher-twist effects, charge-symmetry violation (CSV), and the parton distribution function ratio d/u. These results may also have implications for the interpretation of existing neutrino scattering data.

2 Parity Violation in Deep Inelastic Scattering off a Deuterium Target

Historically, PV DIS was one of the first tests of the Standard Model and an early measurement of the PV DIS asymmetry off a deuterium target [2,3] served to establish the value of $\sin^2\theta_W$ at $\sin^2\theta_W \approx 1/4$. Since this groundbreaking experiment, parity violation has become an important tool not only for probing the Standard Model [4–6] but also for probing the structure of the nucleon [7–9].

2.1 PV DIS Asymmetry

In electron scattering, the weak neutral current can be accessed by measuring a parity-violating asymmetry caused by the interference term between weak and electromagnetic scattering amplitudes [10]. The scattering amplitude, $\mathcal{M}$, for the scattering process is a product of the current for the electron with the photon or the Z^0 propagator and the hadron current: $\mathcal{M}_\gamma = j_\mu(1/q^2)J^\mu$ and $\mathcal{M}_Z = j_\mu(1/M_Z^2)J^\mu$. The cross section for scattering right- and left-handed electrons off an unpolarized target is proportional to the square of the total amplitudes: $\sigma^{l,r} \propto (\mathcal{M}_\gamma + \mathcal{M}_Z^{l,r})^2$, where only a longitudinally polarized electron beam was considered and $\mathcal{M}_Z^r$ and $\mathcal{M}_Z^l$ represent the incident right- and left-handed electrons, respectively. The parity-violating asymmetry may be expressed as [10]

$$A_{LR} \equiv \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \approx \frac{\mathcal{M}_Z^r - \mathcal{M}_Z^l}{\mathcal{M}_\gamma}. \qquad (1)$$

* *Present address:* Department of Physics, University of Virginia, Charlottesville, VA 22904, USA

Thus, measuring the parity-violating asymmetry gives access to the weak neutral current in a ratio of amplitudes rather than the square of this ratio, greatly enhancing its relative contribution. The size of the asymmetry can be *estimated* based on the ratio of the propagators:

$$A_{LR} \approx \frac{Q^2}{M_Z^2} \approx 120 \text{ ppm at } \langle Q^2 \rangle = 1 \text{ GeV}^2 \quad (2)$$

with $M_Z = 91.2$ GeV [11].

Following this formalism, the parity-violating asymmetry for scattering longitudinally polarized electrons from an unpolarized isoscalar target such as deuterium, assuming isospin symmetry, is given by [10,12]

$$A_d = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right) \times \frac{(2C_{1u} - C_{1d})\left[1 + R_s\right] + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}. \quad (3)$$

Here, the kinematic variable Y is defined as

$$Y = \frac{1 - (1-y)^2}{1 + (1-y)^2 + f(y, R_{LT})} \quad (4)$$

with $y = \nu/E$ and $\nu = E - E'$ is the energy lost by an incident electron of energy E scattering to an electron of energy E'. The ratio $R_{\rm LT}(x, Q^2) = \sigma_L/\sigma_T \approx 0.2$ measures the virtual photon-absorption cross-section ratio from longitudinally and transversely polarized photons, and $f(y, R_{\rm LT})$ is a function describing the effect of longitudinally polarized photons to the asymmetry and vanishes when $R_{\rm LT} = 0$. In a work by Blumlein *et al.* [13] it was derived that $f(y, R_{\rm LT}) = -y^2 R_{\rm LT}/(1 + R_{\rm LT})$ when $\nu^2 \ll Q^2$. At JLab energies both Eqs. (3) and (4) need to be modified to take into account terms proportional to ν^2/Q^2. The ratios R_s and R_v depend on the parton distribution functions:

$$R_s(x) = \frac{s(x) + \bar{s}(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \quad \text{and} \quad (5)$$

$$R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}\ , \quad (6)$$

where we have neglected contributions from the charm quark. The weak couplings C_{1q} and C_{2q} with $q \in u, d$ are defined as:

$$C_{1u} = g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W), \quad (7)$$

$$C_{1d} = g_A^e g_V^d = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W), \quad (8)$$

$$C_{2u} = g_V^e g_A^u = -\frac{1}{2} + 2\sin^2(\theta_W), \quad (9)$$

$$C_{2d} = g_V^e g_A^d = \frac{1}{2} - 2\sin^2(\theta_W), \quad (10)$$

where the second equality is valid at the tree-level of the Standard Model. These coupling constants, along with the Weinberg angle θ_W itself, are fundamental parameters of the Standard Model.

In an approximation of moderately large x where sea quark contributions vanish, $R_v \approx 1$ and $R_s \approx 0$. The uncertainty in $2C_{2u} - C_{2d}$ extracted from measured asymmetry is then approximately:

$$\frac{\delta(2C_{2u} - C_{2d})}{2C_{2u} - C_{2d}} \approx \frac{\delta A_d}{A_d}\left[1 - \frac{1}{Y}\frac{2C_{1u} - C_{1d}}{2C_{2u} - C_{2d}}\right] \quad (11)$$

2.2 Exploring New Physics Beyond the Standard Model from PV DIS

Although there exists a large amount of data confirming the electroweak sector of the Standard Model at the level of a few parts per thousand, there also exist strong conceptual reasons (*e.g.*, the so-called high-energy desert from $M_{\rm weak} \approx 250$ GeV up to the Planck scale $M_P \approx 2.4 \times 10^{18}$ GeV) to believe that the Standard Model is only a piece of some larger framework [14]. This framework should provide answers to the conceptual puzzles of the Standard Model; but must also leave the $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ symmetry of the Standard Model intact at $M_{\rm weak} \approx 250$ GeV. Hence, there exists intense interest in the search for physics beyond the Standard Model.

The value of $\sin^2\theta_W$ at the Z-pole ($Q^2 = M_Z^2$) is measured to remarkable precision, $\sin^2\theta_W[M_Z]_{\overline{MS}} = 0.23120 \pm 0.00015$ [11]; however, a careful comparison of measurements involving purely leptonic and semi-leptonic electroweak currents shows a large inconsistency. This strongly suggests additional physics not included in the Standard Model or that one or more of the experiments has significantly understated its uncertainties [15,16]. Below the Z-pole, there are only three precise measurements: Atomic parity violation (APV) in Cs atoms [5] yields a result which, while in agreement with Standard Model predictions, has somewhat large uncertainties, and a difficult theoretical calculation is necessary to extract $\sin^2\theta_W$ from the measured asymmetry. The NuTeV experiment at Fermilab measured $\sin^2\theta_W$ through a careful comparison of neutrino and anti-neutrino deep inelastic scattering (DIS). Their result is approximately three standard deviations from Standard Model predictions [18]; however, the NuTeV result is not without considerable controversy. Most recently, the SLAC E-158 [4] experiment used the asymmetry in Møller scattering to determine a precise value of $\sin^2\theta_W$ that is consistent with the Standard Model prediction. A fourth measurement, the Qweak experiment [6], is planned at JLab, and will determine $\sin^2\theta_W$ to 0.3% by measuring the weak charge of the proton.

Among various experimental efforts to search for new physics, PV DIS involves the exchange of a Z^0 between electrons and quarks and thus is sensitive to physical processes that might not be seen in purely leptonic observables, such as the precision A_{LR} at SLC and A_{FB}^l at LEP. The recent NuTeV [18] result on $\sin^2\theta_W$ at low Q^2 involves a particular set of semi-leptonic charged and neutral current reactions and disagrees with the Standard Model prediction by three standard deviations. A precision measurement of DIS-Parity will provide a clean semi-leptonic observable to the world data below the Z-pole and will

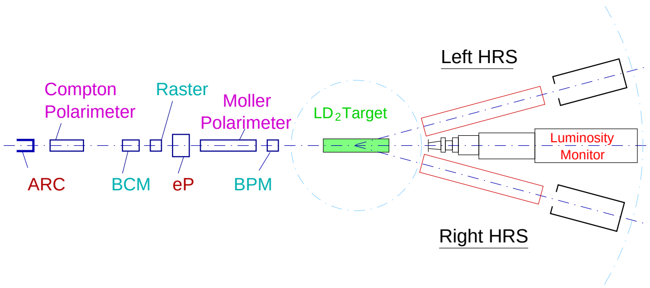

Fig. 1. Hall A floor plan for the proposed measurement.

provide essential clues as to the source of these discrepancies.

The values of C_{1q} have been determined to a reasonable precision [17]. However, our present knowledge of C_{2q} is poor: $\delta(2C_{2u} - C_{2d}) = \pm 0.24$. This also affect the extraction of $C_{3q} \equiv g_A^e g_A^q$ from neutrino scattering data. A precision measurement of C_{2q} is highly desirable to explore possible extensions of the Standard Model. PV DIS is a semi-leptonic process and is sensitive to the C_{2q}'s, therefore it is complementary to other Standard Model test experiments including the Qweak experiment – which studies semi-leptonic processes but is only sensitive to C_{1q}'s. For example, a large axial quark coupling could cause the NuTeV effect, but cannot be seen in C_{1q}. Quark and lepton compositeness is accessible only through C_{2q} but not C_{1q} if a particular symmetry, SU(12), is respected. A precision PV DIS measurement will significantly strengthen the constraints on these possible extensions to the Standard Model. Possible new physics that PV DIS may be sensitive to are Z' Searches, quark and lepton compositeness, leptoquarks and supersymmetry. We are currently working with theorists on an updated list of new physics limits achievable from the measurement described here [19,20]. The "mass scale" for which PV DIS is sensitive to physics beyond the Standard Model would be [20]

$$\frac{\Lambda}{g} = \frac{1}{\sqrt{2\sqrt{2}G_F\ \delta(2C_{2u} - C_{2d})}} \approx 1.0 \text{ TeV}. \qquad (12)$$

3 Experimental Setup

3.1 Overview

The floor plan for our experimental setup is shown in Fig. 1. We will use an 85 μA polarized beam and a 25 cm long liquid deuterium target. The scattered electrons will be detected by the two standard Hall A High Resolution Spectrometers (HRS). In the following we will describe some details of the experimental setup, focusing on two major upgrades required by the measurement.

3.2 Beam Line and the Compton Polarimetry Upgrade

We plan to use a 6.0 GeV 85 μA beam with an 85% polarization. To reduce the heat impact on the target, the beam will be circularly rastered such that the beam spot size at the target is $\sim$ 4mm in diameter. The beam energy can be measured to $\Delta E/E = 2 \times 10^{-4}$ using either the ARC or eP devices [21]. The helicity-dependent asymmetry of the electron beam will be controlled by a DAQ specially developed in Hall A for parity-violation experiments [7]. A luminosity monitor will be used downstream of the target to monitor helicity-dependent target-density fluctuations and other possible false asymmetries.

We need 1% precision in the beam polarization measurement in order to achieve an acceptable systematic uncertainty on the final results. The current Compton polarimetry in Hall A measures the asymmetry of Compton scattering between the electron beam and a high-power IR laser (1 kW, 1064 nm) achieved by a Fabry-Perot cavity. The current systematic uncertainty of the Compton polarimeter is about 1.9% for a 6 GeV beam. In order to achieve a $\leqslant 1\%$ precision, we will upgrade the current IR laser to a green laser (532 nm), and replace the current 600 μm micro-strips used in the electron detector by 300 μm strips. With these upgrades the total systematic uncertainty is expected to be reduced to $\leqslant 0.9\%$. These upgrades are presently being carried out at JLab and we expect to install and commission the new Compton polarimeter by late 2007.

3.3 Spectrometers and the DAQ Upgrade

We will use the standard Hall A HRSs [21] to detect the scattered electrons. For each HRS the effective solid-angle acceptance for an extended target is 5.4 msr and the momentum acceptance is $\pm 4.5\%$. The HRS central momentum can be calculated from the dipole field magnitude to 5×10^{-4} and the central angle can be determined to ± 0.2 mrad, giving an uncertainty of $\pm 0.004/Q^2$ on $2C_{2u} - C_{2d}$ where Q^2 is in GeV^2. Particle identification (PID) in each HRS will be done with a CO_2 Čerenkov detector and a double-layered lead-glass shower detector. We expect to achieve a pion rejection factor of $\geq 10^4$ at an electron efficiency of $\geq 99\%$.

Because of the need to separate the pion background we must use a counting method instead of an integrating DAQ. The detector signals we will use include those from the two PID detectors and scintillators (for crude directional information). To process this information we are considering a Flash ADC (FADC) -based DAQ presently being designed by the Fast Electronics Group at JLab. This design will allow for the possibility of counting experiments at approximately 1 MHz with a low and precisely measurable dead time, *e.g.* a 1% dead time measured with a 0.3% absolute accuracy. The FADC fills an on-board memory at 250 MHz with $\sim 4\ \mu$s latency (buffer size). An on-board processor (FPGA) will analyze the digitized data and perform the PID. The DAQ will be flexible enough to accommodate a variety of experiments. A first version of the FADC is expected to be ready by 2007.

As an alternative, a scaler-based DAQ using fast NIM electronics is also being considered. We plan to build both

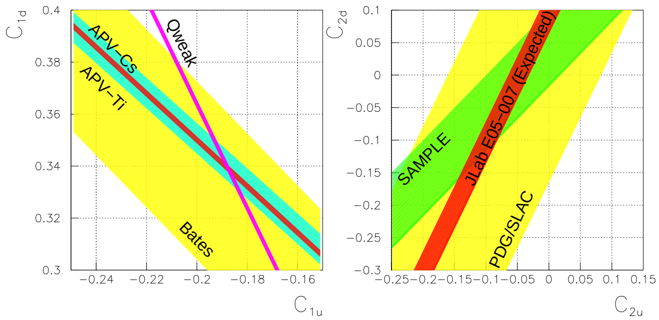

Fig. 2. The effective couplings C_{1q} (left) and C_{2q} (right) . The future Qweak experiment combined with the APV-Cs result will provide the most precise data and the best Standard Model test on C_{1q}. For C_{2q}, the SAMPLE result for $C_{2u} - C_{2d}$ at $Q^2 = 0.1$ GeV^2 [22] and the current PDG value for $2C_{2u} - C_{2d}$ are shown. Assuming the SM prediction of $2C_{1u} - C_{1d}$, the value of $2C_{2u} - C_{2d}$ can be determined from this experiment to $\Delta(2C_{2u} - C_{2d}) = \pm 0.03$.

systems such that the FADC-based DAQ can be cross-checked with the regular HRS counting DAQ at a low rate (<4 kHz) and with the scaler-based DAQ at a high rate (up to 1 MHz).

3.4 Expected Results

The asymmetry A_d will be extracted from the measured raw counting asymmetry as

$$A_d = \frac{A_{raw}}{P_{beam}} + \Delta A_{EM}^{RC} \tag{13}$$

where P_{beam} is the beam polarization. A_{EM}^{RC} is the electromagnetic radiative correction and can be calculated to 0.2% (relative to A_d). Provided that all uncertainties related to hadronic structure are well under control, one can then extract $2C_{2u} - C_{2d}$ from A_d using Eq.(3). The expected total uncertainty in $2C_{2u} - C_{2d}$ is shown in Fig. 2 along with existing world data. For illustration, current knowledge of C_{1q}'s and their expected results from the Qweak experiments are also shown. We expect to run E05-007 in early 2009 and first results may become available within one year of its completion.

4 Interpretation of the Data and Discussions on Hadronic Effects

While we can extract $2C_{2u} - C_{2d}$ from the measured asymmetry, there are uncertainties coming from hadronic physics which may complicate the interpretation of this asymmetry in terms of Standard Model parameters. This section will describe some of these interesting issues.

4.1 Uncertainty from Parton Distributions and $R_{\rm LT}$

The uncertainties due to R_s and R_v in Eq. (3) can be estimated using CTEQ [23,24] and MRST [25,26] PDF parameterizations. We find that our current knowledge of PDFs gives an uncertainty at the level of $\delta(2C_{2u} - C_{2d}) \leqslant \pm 0.0025$. The ratio $R_{\rm LT} = \sigma_L/\sigma_T$ is taken from a global fit, R1998 [27]. Propagation of the uncertainty from the this fit yields an uncertainty of $\delta(2C_{2u} - C_{2d}) \leqslant \pm 0.0017$.

4.2 Higher-Twist Effects

Among all hadronic effects that could contribute to PV electron-scattering observables, higher-twist (HT) effects are expected to be the most probable for kinematics at JLab. Here higher-twist effects refer to the fact that the strong interactions between the quarks become observable at low Q^2 and the process cannot be described by the $\gamma(Z)$ exchange between the electron and a *single* quark (the leading-twist process). For electromagnetic scattering processes, these interactions introduce a scaling violation to the structure functions for $Q^2 < 1$ GeV^2 that is stronger than the $\ln(Q^2)$-dependence of the DGLAP equations of perturbative QCD (pQCD). For PV $\boldsymbol{e}-{}^2$H scattering, HT effects start from twist-four terms which diminish as $1/Q^2$. Hence, observation of any Q^2-dependent deviation from the expected asymmetry would strongly imply a contribution from HT.

The theory for HT is not well established. In a naive picture, HT is expected to vanish in the asymmetry A_d because the strong coupling between the struck quark and other spectator quarks (the origin of HT) should not depend on what type of the gauge boson (γ or Z^0) is probing the quark, hence the HT contributions cancel in the ratio. In less hand-waving pictures, most of existing HT models show that the HT contribution to A_d is below $1\%/Q^2$ level (see *e.g.* Ref. [1]), which is acceptable for interpreting our expected data in terms of Standard Model tests. However, these models were developed primarily during and after the previous PV DIS experiment in the 1970's. A modern calculation of the HT from QCD is needed and we hope such calculation will become available in the next 1-2 year(s) [19].

On the other hand, HT provides information on non-perturbative aspects of the strong interaction, which by itself has its own value. So far first-hand information on HT comes primarily from experimental data, *e.g.* by observing the non-$\ln Q^2$ dependence of DIS structure functions. However, such an extraction is complicated by the determination of the leading-twist term, which has a large uncertainty from the truncation of higher order terms in α_S. By contrast, the prospects for observing HT contributions in PV-DIS are relatively uncomplicated because the QCD higher order terms are expected to cancel in the asymmetry. Thus our PV DIS experiment will provide valuable insights into the study of the non-perturbative side of strong interactions.

One interesting remark is that it has been shown that although the NuTeV measurement was performed at $\langle Q^2 \rangle$ =20 GeV^2, the HT contribution to the typically measured Paschos-Wolfenstein (P-W) ratio could be of the same magnitude as that of the PV DIS observable at $Q^2 \approx 2$ GeV^2 [28]. If the NuTeV deviation from the Standard

Model is fully due to the HT, then this would imply a contribution to our expected results much above their uncertainties. Although this is a model-dependent calculation, it underscores the uncertainty in determination of HT effects in other contexts. The precision measurement proposed here would clearly be sensitive to this magnitude of the HT correction.

5 Future PV DIS Program at JLab

More PV DIS measurements are being planned at the 12 GeV Upgrade of JLab [29] using the current high momentum spectrometer (HMS) and the planned baseline Super-HMS in Hall C. From this measurement we expect to extract the value of $\sin^2\theta_W$ to a precision of $\delta\sin^2\theta_W/\sin^2\theta_W = \pm 0.0025(stat.) \pm 0.0032(syst.)$ and the weak coupling C_{2q}'s to $\delta(2C_{2u} - C_{2d}) = \pm 0.015$. In addition, measurements of PV DIS asymmetries over a wide range of x and Q^2 are possible, provided a large-acceptance solenoid spectrometer [30] is built. If such a device is possible, we can measure HT effects to great precision. By measuring the PV DIS asymmetry on the proton, we can extract the unpolarized PDF ratio d/u at large x without contamination of the deuteron nuclear (EMC) effect and thus provide a clean test on various predictions of this ratio from *e.g.* pQCD and relativistic constituent quark models. By comparing the PV DIS asymmetry on the deuteron with that on the proton, we will be sensitive to charge-symmetry violation which implies that the $u(d)$ distributions in the proton differ from the $d(u)$ distributions in the neutron. This effect not only violates one of the known discrete fundamental symmetries (isospin symmetry) and has profound implications for our understanding of hadronic structure and the strong interaction, but is also one of the leading candidates for the cause of the NuTeV anomaly [31] and hence the picture of Standard Model test below the Z-pole will change dramatically should this effect be large.

6 Summary

We are planning to measure the parity-violation asymmetry A_d in $\boldsymbol{e}-{}^2$H deep inelastic scattering at $Q^2 = 1.1$ and 1.9 GeV^2 and similar $x(=0.3)$ using a 85 μA polarized beam and a 25 cm long liquid deuterium target in Hall A of JLab. Two major instrumentational upgrades are required by this experiment and both are being developed at JLab. Assuming an 85% beam polarization and 46 days of beam time, we expect to extract the weak coupling constant combination to $\Delta(2C_{2u} - C_{2d}) = \pm 0.03$ from A_d at 1.9 GeV^2, a factor of eight improvement compared to our current knowledge of this quantity. This result will help to extract C_{3q} from high-energy data, and has the potential to reveal possible new physics beyond the Standard Model. The additional point at 1.1 GeV^2 will help to investigate the non-perturbative hadronic physics contribution to PV DIS asymmetry and may provide the first precision observation of this effect. This result may have implications for the interpretation of existing data from other Standard Model test experiments using semi-leptonic processes. This experiment will provide the first crucial guidance for the future PV DIS program with the JLab 12 GeV Upgrade.

Acknowledgement The author would like to thank the PAVI06 organizers for their invitation to the beautiful Milos Island. The work was developed when the author was working for the Medium Energy Physics Group at Argonne National Lab, Argonne, IL 60439, USA, under the U. S. Department of Energy contract no. W-31-109-ENG-38. The Jefferson Science Associates, LLC operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-06OR23177.

References

1. X. Zheng, P.E. Reimer, R. Michaels *et al.*, JLab Experiment E05-007 (2005).
2. C.Y. Prescott *et al.*, Phys. Lett. B **77** (1978) 347.
3. C.Y. Prescott *et al.*, Phys. Lett. B **84** (1979) 524.
4. P.L. Anthony *et al.*, Phys. Rev. Lett. **95** (2005) 081601.
5. S.C. Bennett and C.E. Wieman, Phys. Rev. Lett. **82** (1999) 2484.
6. D. Armstrong *et al.*, The $Q_{\rm weak}$ Experiment, JLab E02-020 (2001).
7. K.A. Aniol *et al.*, Phys. Rev. Lett. **96** (2006) 022003.
8. D.S. Armstrong *et al.*, Phys. Rev. Lett. **95** (2005) 092001.
9. R. Hasty *et al.*, Science **290** (2000) 2117.
10. R.N. Cahn and F.J. Gilman, Phys. Rev. D **17**, (1978) 1313.
11. S. Eidelman *et al.*, Phys. Lett. B **592** (2004) 1.
12. R. Arnold *et al.*, SLAC-PROPOSAL E149 (1993).
13. J. Blumlein, M. Klein, T. Naumann and T. Riemann, DESY Theory Workshop 1987, HERA Pub. PHE-88-01.
14. M.J. Ramsey-Musolf, Phys. Rev. C **60** (1999) 015501.
15. M.S. Chanowitz, Phys. Rev. Lett. **87** (2001) 231802.
16. M.S. Chanowitz, Phys. Rev. D **66** (2002) 073002.
17. J. Erler and M.J. Ramsey-Musolf, Prog. Part. Nucl. Phys. **54** (2005) 351.
18. G.P. Zeller *et al.*, Phys. Rev. Lett. **88** (2002) 091802.
19. M.J. Ramsey-Musolf, private communication.
20. J. Erler, private communication.
21. J. Alcorn *et al.*, Nucl. Instrum. Meth. A **522** (2004) 294.
22. E.J. Beise, M.L. Pitt and D.T. Spayde, Prog. Part. Nucl. Phys. **54** (2005) 289.
23. D. Stump *et al.*, Phys. Rev. D **65** (2002) 014012.
24. J. Pumplin *et al.*, Phys. Rev. D **65** (2002) 014013.
25. A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C **28** (2003) 455.
26. A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C **35** (2004) 325.
27. K. Abe *et al.*, Phys. Lett. B **452** (1999) 194.
28. M. Gluck and E. Reya, Phys. Rev. Lett. **47** (1981) 1104.
29. X. Zheng, P.E. Reimer, K. Paschke *et al.*, JLab 12 GeV Letter-of-Intent (2006)
30. *"Initiatives of a large acceptance solenoidal spectrometer for Hall A at the JLab 12 GeV Upgrade for studying parity and spin", Informal discussions* (2006).
31. J.T. Londergan, D.P. Murdock and A.W. Thomas, Phys. Rev. D **72** (2005) 036010.