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Parity-violating Electron Deuteron Scattering and the Proton's Neutral Weak Axial Vector Form Factor

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We report on a new measurement of the parity-violating asymmetry in quasielastic electron scattering from the deuteron at backward angles at $Q^2 = 0.038$ (GeV/c)^2. This quantity provides a determination of the neutral weak axial vector form factor of the nucleon, which can potentially receive large electroweak corrections. The measured asymmetry $A = -3.51 \pm 0.57$ (stat) ± 0.58 (sys) ppm is consistent with theoretical predictions. We also report on updated results of the previous experiment at $Q^2 = 0.091$ (GeV/c)^2, which are also consistent with theoretical predictions.

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Parity-violating electron scattering provides a unique probe of the electroweak structure of the nucleon. It has been well established that elastic scattering studies yield new and interesting information on the strange vector matrix elements [1, 2]. This is the basis for a substantial program of experiments at modern electron accelerator facilities, beginning with the SAMPLE experiment [3, 4] at MIT-Bates.

The primary goal of SAMPLE is to determine the proton's strange magnetic form factor G_M^s through parity-violating electron scattering from the proton at backward angles. However, the parity-violating asymmetry – the asymmetry in the scattering cross section with respect to the helicity of the incident electron – is not only sensitive to G_M^s, but is also sensitive to the proton's neutral weak axial form factor. As pointed out in Ref. [5], the neutral weak axial form factor as measured in electron scattering, G_A^e, can potentially receive large electroweak corrections that are absent in neutrino scattering. These corrections include the anapole moment, which is identified as the effective parity-violating coupling of a photon to the nucleon. Determining G_A^e is important not only for a reliable extraction of G_M^s, but also because of its sensitivity to the hadronic effects on the electroweak radiative corrections. The adequate understanding of such effects is essential to proper interpretation of other precision electroweak measurements such as neutron and nuclear β decay [6]. Parity-violating quasielastic electron-deuteron scattering at backward angles is predominantly sensitive to G_A^e and thus can be used to determine G_A^e [7].

The SAMPLE collaboration previously performed an experiment on a deuterium target (SAMPLE II) as well as on a hydrogen target (SAMPLE I) at 200 MeV [$Q^2 \sim 0.1$ (GeV/c)^2]. Combining the results from these two experiments allows separate determination of G_M^s and G_A^e. Our data [4] indicated that, while the overall contribution from strange quarks to the proton's magnetic form factor is small, the size of the electroweak radiative corrections to the axial form factor is significantly larger than anticipated from theory [8].

These results stimulated considerable interest among theorists. Many different processes and effects were studied for their potential contributions to the axial form factor or to the parity-violating asymmetry in electron-deuteron scattering. These include the anapole moment [8, 9, 10], nuclear effects including two-body currents [11], and the parity-violating hadronic interaction [12, 13]. None of the effects studied here were significant enough to explain the discrepancy.

In order to experimentally confirm these results, we performed a third SAMPLE experiment (SAMPLE III), with a deuterium target at a lower beam energy of 125 MeV [$Q^2 = 0.038$ (GeV/c)^2]. As was the case for SAMPLE II, the dominant scattering process is quasielastic scattering, and the asymmetry is predominantly sensitive to G_A^e. Since the parity-violating asymmetry in the cross section is proportional to Q^2 to first order, the expected asymmetry was roughly 3 times smaller than that for 200 MeV. The cross section, however, is larger by a factor of 2 with the same background level, resulting in an experiment sensitive to the same physics with roughly the same sensitivity but with very different systematics.

The experiment was carried out at the MIT Bates Linear Accelerator Center. The experimental method and apparatus were identical to SAMPLE II, except for the incident beam energy. A 125 MeV longitudinally polarized electron beam was incident on a 40 cm long liquid deuterium target, and electrons scattered at backward angles were detected by an air Čerenkov detector covering angles between 130° and 170° (solid angle ~ 1.5 sr). The detector consists of the radiator air volume and 10 detector elements, each with an ellipsoidal mirror to focus Čerenkov light onto a corresponding 8-inch photomultiplier tube (PMT).

A remotely controlled light shutter was used to cover each PMT for the background measurements. About 10% of the data were taken with the shutters closed. In addition, in order to further study the background, an additional measurement of the shutter closed asymmetry was made with a plate of plastic scintillator placed in front of each PMT to enhance the statistics. Also, the non-Čerenkov sources of light in the detector signal, mostly due to scintillation light in the air, were studied by covering the mirrors. The background level was the same as SAMPLE II, consistent with bremsstrahlung radiation in the target being the dominant origin of all the different background components.

The incident electron beam was pulsed at 600 Hz, and the average beam current was 40 μA. The polarized electron beam was generated by directing a circularly polarized laser beam onto a GaAs crystal. The helicity of the beam was pseudorandomly chosen for each pulse. The helicity of the beam with respect to the electronic signal was manually reversed every 2-3 days by inserting and removing a halfwave plate in the laser beam path to check for and reduce possible systematic effects. (These two configurations are called "IN" and "OUT".) The polarization of the electron beam was measured daily with a transmission polarimeter, and occasionally with the Møller polarimeter on the beam line.

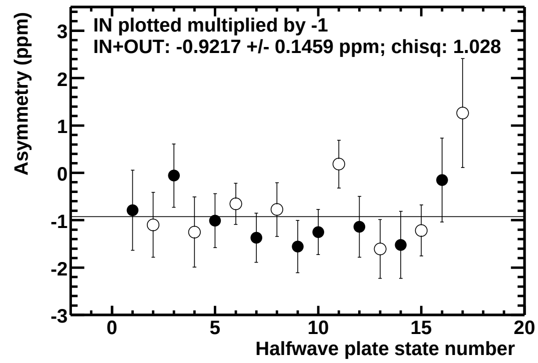

FIG. 1: Results for the detector yield asymmetry (average of 10 detectors). Each data point represents the average between two halfwave plate state changes. The OUT data are plotted as filled circles and the IN data as open circles. The sign of the IN data is reversed to give the correct sign.

Various beam parameters, including the intensity, energy, position, and angle, were monitored continuously for helicity correlated differences. Four Lucite Čerenkov counters (luminosity monitors) downstream of the target at the forward angles ($\sim 12°$) detected low Q^2 scattering which has negligible parity-violating asymmetry, thus serving as monitors for false asymmetries.

As in the past, the yield for each detector for each beam pulse (integrated over the duration of the pulse) was normalized to the beam charge measured in front of the target, and then was corrected for the beam position, angle, and energy. A linear regression technique was used to determine the dependence of the detector yields on each parameter. Then, the asymmetry was computed for the appropriate pulse pairs. In addition, the normalized detector yields were also corrected for transmission of the beam (defined as the ratio of the beam intensities at the target and at the end of the accelerator) to account for an observed beam intensity asymmetry caused by differential scraping at an energy-defining slit. The results of this analysis are shown in Fig. 1, where the detector asymmetry is plotted as a function of time.

The asymmetry was further corrected for the beam polarization, the background dilution, and electromagnetic radiative effects (effects due to the bremsstrahlung radiation of the incident and scattered electrons) to obtain the physics asymmetry. The average beam polarization during the experiment was $P_e = 38.9 \pm 1.6\%$. The background dilution factor, determined for each detector from the ratio between the shutter open and closed detector yields and the mirror covered studies, was typically $1.4 \sim 1.7$ with a relative uncertainty of 4.5%. Electromagnetic radiative effects were evaluated using a spindependent modification to Ref. [15] within the context of a GEANT [16] simulation of the detector geometry. In the simulation, scattered electron events were generated uniformly in energy, angle, and along the length of the 40 cm target. The scattered electron kinematics were selected after accounting for energy loss in the target. Each event was weighted according to the scattering cross section and the detector efficiency, and was assigned an asymmetry according to its kinematics. The correction factor for electromagnetic radiative effects was evaluated for each detector by comparing the (weighted) asymmetry with and without the radiative effects included in the simulation, and was typically 1.09 with a relative uncertainty of 3%.

The systematic error in the corrections procedure was estimated by comparing results from two different methods that are mathematically equivalent for normally distributed infinite data: one computes the dependence of the detector signal on the beam parameters for normalized yields, and the other for asymmetries. We assign a relative systematic error of 11.2% for OUT and 2.1% for IN, the larger error for OUT naturally reflecting the larger correction due to the larger beam intensity asymmetry.

Additional uncertainties were assigned to the resulting physics asymmetry to account for two systematic effects observed during the experiment. The first is the residual asymmetry in the luminosity monitors. Some of the luminosity monitors showed non-zero asymmetries even after the corrections procedure was applied, potentially indicating the existence of a helicity correlated difference in some unmeasured beam parameter(s) that caused false asymmetries in the luminosity monitor signal. The size of the false asymmetry that this effect could cause in the Čerenkov detector signal was estimated from the observed luminosity monitor asymmetries and the correlation between the Čerenkov detector asymmetry and the luminosity monitor asymmetry, and was assigned as the systematic error. Relative systematic errors of 20.0% and 19.2% were assigned for the OUT and IN data, respectively, and the errors were treated as uncorrelated when combining the two data sets.

The second is that, although the measured shutter closed asymmetry for all 10 detectors combined was consistent with zero, the individual detectors showed a non-zero shutter closed asymmetry. The detector-by-detector distribution showed a definite pattern dependent on the azimuthal angle, indicating that this asymmetry is of parity-conserving nature, and hence cancels out when averaged over all 10 detectors that are symmetrically arranged azimuthally. The shutter closed asymmetry was estimated from the "high-statistics" shutter closed data taken with plastic scintillator and was subtracted from the shutter open asymmetry for each detector. The value of the final asymmetry is very insensitive to this procedure because of the symmetry of the detector arrangement, and the associated systematic error was estimated to be 5%.

TABLE I: Summary of relative uncertainties on the measured asymmetry.

Source	$\delta A/A$ (%)
Dilution factor	5
Background asymmetry subtraction	5
Luminosity monitor asymmetry	14
Corrections procedure	5
Total systematic (added in quadrature)	17

The resulting physics asymmetry is

$$A(Q^2 = 0.038) = -3.51 \pm 0.57 \pm 0.58 \ \text{ppm}, \qquad (1)$$

where the first uncertainty is statistical and the second is the estimated systematic error as summarized in Table I.

Since the SAMPLE detector does not have energy resolution for the scattered electrons, the measured asymmetry contains contributions not only from quasielastic scattering but also from elastic scattering and threshold breakup. In order to construct the theoretical expression of the asymmetry as a function of the quantities of interest, *i.e.*, G_M^s and G_A^e of the nucleon, we did the following. First we performed a full nuclear calculation according to Ref. [12] to obtain the parity-conserving and parity-violating response functions for the total inelastic processes (quasielastic scattering and threshold breakup) for selected kinematics. The dependence on G_M^s and G_A^e was explicitly kept track of in the calculation. Electroweak radiative corrections were included. In particular, the isoscalar axial radiative correction was taken to be $R_A^0 = 0.03 \pm 0.05$ from Ref. [8]. We use $\sin^2\theta_W = 0.23113(15)$ [14].

The parity-violating asymmetry was computed on an event-by-event basis in the GEANT simulation, and separately for the elastic (from Ref. [17]) and inelastic (using the above obtained response functions) processes. The resulting asymmetry distributions represented an average over the detector acceptance and incident electron energies. The physics asymmetry was then computed as a combined average of the elastic and inelastic distributions weighted by the appropriate cross sections. The resulting theoretical asymmetry is

$$A(Q^2 = 0.038) = -2.14 + 0.27 G_M^s + 0.76 G_A^{e\,(T=1)}, \quad (2)$$

where the asymmetry is in parts per million and the form factor is in nuclear magnetons (n.m.). In this expression, we retain explicitly the isovector ($T = 1$) component of G_A^e. The small isoscalar component is absorbed into the first term. The dependence on the nuclear model is small.

The radiative corrections and theoretical asymmetry for the SAMPLE II data were also re-evaluated with the GEANT simulation. In addition, background dilution factors coming from pion photoproduction were re-examined

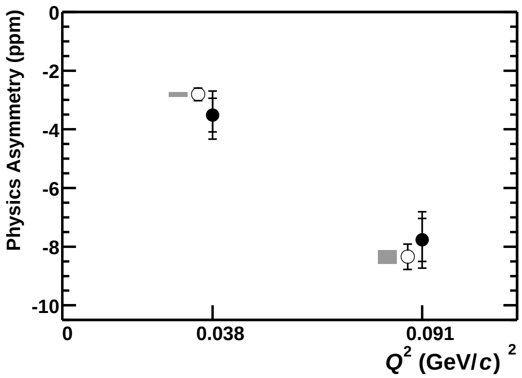

FIG. 2: The physics asymmetries measured in SAMPLE II (updated results) and SAMPLE III are plotted as a function of Q^2 (solid circles). Also plotted (with offset Q^2 for visibility) are the theoretical predictions with the value of G_A^e taken from Ref. [8], and $G_M^s = 0.15$ n.m. (open circles). The height of the gray rectangles represents the change in the physics asymmetry corresponding to a 0.6 n.m. change in G_M^s.

in light of recently published data [18]. Such processes contribute to the detector yield through their decay products, but have negligible parity-violating asymmetry [19]. The largest contribution is from coherent π^0 photoproduction on the deuteron, which had been neglected in Ref. [4], but was found in Ref. [18] to be significantly enhanced relative to the corresponding incoherent process. Including this effect increased the background dilution factor by 9%. The re-evaluated electromagnetic radiative corrections resulted in an additional 2% increase in the background dilution factor. Finally, improved determination of the scintillation component of the detector signal resulted in another 2% increase. Thus, the final physics asymmetry increased by 13% in magnitude compared with our previously published results [4], giving

$$A(Q^2 = 0.091) = -7.77 \pm 0.73 \pm 0.62 \text{ ppm}, \quad (3)$$

where the first error is statistical and the second is the estimated systematic error. (Note that this asymmetry value contains the contribution from the non-quasielastic processes, which was estimated to be $\sim 1.5\%$ and removed in Ref. [4].) The re-evaluated theoretical value for the asymmetry, using the nuclear calculation as described above, has resulted in an expected value that is 2% smaller:

$$A(Q^2 = 0.091) = -7.06 + 0.77 G_M^s + 1.66 G_A^{e\,(T=1)}. \quad (4)$$

In Fig. 2, the physics asymmetries measured in SAMPLE II (updated results) and SAMPLE III are plotted as a function of Q^2. Also plotted are the theoretical predictions with the value of G_A^e taken from Ref. [8] [$G_A^e(Q^2 = 0.038) = -0.91 \pm 0.28$ and $G_A^e(Q^2 = 0.091) = -0.84 \pm 0.26$], and $G_M^s = 0.15$ n.m. The dependence of the theoretical values on G_M^s is small.

The results from SAMPLE III (125 MeV deuterium run) and the updated results from SAMPLE II (200 MeV deuterium run) both agree with the theoretical prediction on the electroweak radiative correction on the neutral weak axial form factor of the nucleon by Zhu *et al.* [8]. In addition to these two experimental results, various theoretical efforts also support the theoretical prediction by Zhu *et al.* The confirmation on the theoretical value of G_A^e not only allows us to extract G_M^s reliably from the data from SAMPLE I (200 MeV hydrogen run), but also is important for interpreting results from future parity-violating electron scattering experiments at JLab and Mainz.

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[1] D. Kaplan and A. Manohar, Nucl. Phys. **B310**, 527 (1988).
[2] R. D. McKeown, Phys. Lett. B **219**, 140 (1989); D. H. Beck, Phys. Rev. D **39**, 3248 (1989).
[3] B. A. Mueller *et al.*, Phys. Rev. Lett. **78**, 3824 (1997); D. T. Spayde *et al.*, *ibid.* **84**, 1106 (2000).
[4] R. Hasty *et al.*, Science **290**, 2117 (2000).
[5] M. J. Musolf and B. R. Holstein, Phys. Lett. B **242**, 461 (1990).
[6] R. D. McKeown, Mod. Phys. Lett. A **18** 75 (2003); M. J. Ramsey-Musolf in *Proceedings of PAVI02 the International Workshop on Parity Violation, Mainz, Germany, 2002,* edited by F. Maas *et al.* (World Scientific, Singapore, in press) (nucl-th/0302049).
[7] E. J. Beise and R. D. McKeown, Comment Nucl. Part. Phys. **20**, 105 (1991).
[8] S.-L. Zhu *et al.*, Phys. Rev. D **62**, 033008 (2000).
[9] C. M. Maekawa and U. van Kolck, Phys. Lett. B **478**, 73 (2000); C. M. Maekawa, J. S. Veiga, and U. van Kolck, Phys. Lett. B **488**, 167 (2000).
[10] D. O. Riska, Nucl. Phys. **A678**, 79 (2000).
[11] L. Diaconescu, R. Schiavilla, and U. van Kolck, Phys. Rev. C **63**, 044007 (2001).
[12] R. Schiavilla, J. Carlson, and M. Paris, Phys. Rev. C **67**, 032501(R) (2003).
[13] C.-P. Liu, G. Prézeau, and M. J. Ramsey-Musolf, Phys. Rev. C **67**, 035501 (2003).
[14] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
[15] L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).
[16] GEANT Version 3.21, CERN program library.
[17] S. J. Pollock, Phys. Rev. D **42**, 3010 (1990).
[18] J. C. Bergstrom, *et al.*, Phys. Rev. C **57**, 3203 (1998).
[19] J.-W. Chen and X. Ji, Phys. Lett. B **501**, 209 (2001);

J.-W. Chen (private communication).