New Results from the HAPPEX Experiments at $Q^2 = 0.1 \text{ GeV}/c^2$

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Abstract. The nucleon's strange electric and magnetic form factors G_E^s and G_M^s can be probed via parity-violating electron scattering. The HAPPEX collaboration has made new measurements of the parity-violating asymmetry A_{PV} in elastic scattering of 3 GeV electrons off hydrogen and ^4He targets with $\langle\theta_{lab}\rangle \approx 6.0^\circ$. For ^4He the preliminary result is $A_{PV} = (+6.43 \pm 0.23 \text{ (stat)} \pm 0.22 \text{ (syst)}) \times 10^{-6}$. For hydrogen the preliminary result is $A_{PV} = (-1.60 \pm 0.12 \text{ (stat)} \pm 0.05 \text{ (syst)}) \times 10^{-6}$. From these values we extract $G_E^s = 0.004 \pm 0.014 \pm 0.013$ at $\langle Q^2 \rangle = 0.077 \text{ GeV}/c^2$, and $G_E^s + 0.09 G_M^s = 0.004 \pm 0.011 \pm 0.005$ at $\langle Q^2 \rangle = 0.109 \text{ GeV}/c^2$, both consistent with zero, providing stringent new limits on the role of strange quarks in the vector structure of the nucleon.

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1 Introduction

Although QCD is widely accepted as the correct theory of the strong interaction, it is not yet possible to describe precisely all the properties of the nucleon in terms of quarks and gluons, the fundamental degrees of freedom appearing in the Lagrangian. Measurements of deep-inelastic lepton scattering give information on quark distribution functions and the quark spin structure. These data indicate that the sea quarks, in particular strange quarks in the form of $s\bar{s}$ pairs, may contribute significantly to certain observables in the perturbative regime. However, the contribution of the sea quarks in the non-perturbative realm is far from being understood. Strange quarks effects provide a direct probe of the sea in the nucleon. Although the up and down quarks and anti-quarks also contribute to the sea, at low momentum transfer they are also intimately connected with the special role of the pion as the Goldstone Boson of chiral symmetry breaking. In particular, there is relatively little known about the contribution of strange quarks to vector matrix elements (*i.e.*, to the electric and magnetic form factors of the nucleon).

Much of the original impetus for examining strange quark form factors of the nucleon arose when initial attempts to understand the “spin-crisis” appeared to indicate that Δs was large, *i.e.*, that a large fraction of the proton's spin might be due to strange quarks (for an update, see [1]). This suggested that other (*e.g.* vector) strange quark matrix elements could also be sizable. Indeed, many calculations, using a variety of nucleon models, were found to allow (or even prefer) large vector strange form factors (for reviews, see [2]).

Parity-violating electron scattering opens a unique experimental window into the strange quark vector form factors. The differing couplings of the quark flavors to the γ and the Z^0 allow one to separate the contributions from the various flavors, using the electroweak $\gamma - Z^0$ interference term. This interference leads to a parity-violating asymmetry in the scattering cross section, proportional to the neutral-current amplitude. Precise measurements of this asymmetry can be interpreted in terms of the strange electric (G_E^s) and magnetic (G_M^s) form factors of the nucleon. For elastic scattering from the proton, the parity-violating asymmetry between cross-sections for positive and negative helicity electrons has contributions from weak electric, magnetic and axial vector currents, and is given in the Standard Model by [3]

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \times \left\{ (1 - 4\sin^2\theta_W) - \frac{\epsilon G_E^{\gamma p} G_E^{\gamma n} + \tau G_M^{\gamma p} G_M^{\gamma n}}{\epsilon(G_E^{\gamma p})^2 + \tau(G_M^{\gamma p})^2} - \frac{\epsilon G_E^{\gamma p} G_E^s + \tau G_M^{\gamma p} G_M^s}{\epsilon(G_E^{\gamma p})^2 + \tau(G_M^{\gamma p})^2} - \frac{(1 - 4\sin^2\theta_W) \epsilon' G_M^{\gamma p}}{\epsilon(G_E^{\gamma p})^2 + \tau(G_M^{\gamma p})^2} \times \left[-2(1 + R_A^{T=1}) G_A^{T=1} + (\sqrt{3} R_A^{T=0}) G_A^{T=0} \right] \right\}, \quad (1)$$

where $G_{E(M)}^{\gamma p(n)}$ are the proton (neutron) electric (magnetic) form-factors, $G_A^{T=1(0)}$ is the isovector (isoscalar) proton axial form factor, G_F is the Fermi constant, α is the fine structure constant, and θ_W is the electroweak mixing angle. All form factors are functions of Q^2 , the square

of the four-momentum transfer; for the hydrogen experiment the kinematical quantities are $\epsilon = 0.994$, $\tau = 0.028$, $\epsilon' = 0.018$. The vector electroweak radiative corrections are well-known, and are not shown, for clarity; the R_A factors parametrize the axial electroweak radiative corrections [3]. In deriving Eq. 1, the usual assumption of charge symmetry has been adopted [4]; recent work has re-examined this assumption, and has shown that the present experimental precision is approaching the level at which charge symmetry violating effects become important (see ref. [5] and R. Lewis, these proceedings).

Forward-angle scattering is used in the present experiments, which suppresses the final term involving the axial form factors. Thus, given adequate knowledge of the ordinary electromagnetic form factors, a measurement of A_{PV} at a given Q^2 will yield a linear combination of the strange form factors G_E^s and G_M^s . In order to disentangle G_E^s from G_M^s at a given Q^2 , we have chosen to make a separate measurement on a ^4He target, which is solely sensitive to G_E^s .

Elastic electron scattering from ^4He is an isoscalar $0^+ \rightarrow 0^+$ transition and therefore has no contributions from magnetic or axial-vector currents. The same one-body transition densities appear in the matrix elements of the weak and electromagnetic operators. When the ratio comprising an asymmetry is formed, these transition densities cancel out, as long as two-body (meson-exchange) currents are negligible. Thus the nuclear many-body physics divides out and only the single nucleon form factors G_E^s and $G_E^{\gamma T=0}$ remain; the parity-violating asymmetry at tree-level is therefore given by [3]

$$A_{PV}^{\text{He}} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left(4\sin^2\theta_W + \frac{G_E^s}{G_E^{\gamma T=0}} \right), \quad (2)$$

where $G_E^{\gamma T=0} = (G_E^p + G_E^n)/2$ is the isospin-zero electric form factor (adequately known from other experiments). Nuclear model-dependence in A_{PV}^{He} due to isospin-mixing [8] and D-state admixtures [6] in the ^4He ground state is negligible, as are meson exchange current contributions at the low Q^2 chosen here [7].

2 Experiment Overview

The present measurements represent another step in the HAPPEX program in Hall A at the Thomas Jefferson National Accelerator Facility. Results from the first round of measurements at the present kinematics, taken in 2004, have been published [10,9]. Here we report results from a significantly higher statistics data set ($\times 10$ for ^4He and $\times 3$ for hydrogen) obtained in 2005. The experimental approach has been documented in detail elsewhere [11]. In brief, the twin high-resolution spectrometers (HRS) in Hall A are used for independent measurements of the asymmetry for forward-angle elastic scattering of longitudinally polarized electrons. The focal-plane detectors, situated in heavily-shielded detector huts in each HRS, are

Fig. 1. Sketch of a HAPPEX focal plane detector, consisting of a layered brass-quartz calorimeter viewed by photomultiplier tubes. The ‘L’-shaped configuration shown was used for hydrogen experiment; for helium only a single segment and PMT was used.

total absorption calorimeters consisting of alternating layers of brass and synthetic quartz, viewed by photomultiplier tubes (PMTs). For the hydrogen experiment a two segment detector was used to cover the full flux of elastically scattered electrons (see fig. 1); for helium, the elastic locus is smaller, and a single detector segment was used in each arm. The spectrometers are arranged to create an approximately left-right symmetric acceptance. New septum magnets were installed to allow detection of electrons with small ($\langle\theta_{lab}\rangle \sim 6^\circ$) scattering angles, in order to reach down to $Q^2 \sim 0.1 \text{ GeV}/c^2$.

The beam helicity was flipped in a pseudorandom pattern at 30 Hz. The PMT response was integrated separately for each arm, along with the response of beam current and beam position monitors, during the 33.3 ms periods of constant beam helicity. To help to control systematic effects, the standard technique was adopted of periodically inserting a half-wave ($\lambda/2$) plate in the laser optical path at the electron source, which thereby passively reverses the sign of the beam polarization. Each such subset of data is referred to as a “slug”; there were 41 slugs of data for hydrogen and 121 for ^4He .

The cryogenic targets used 20 cm long cells with transverse flow of the cryogenic fluid (liquid hydrogen, and cold ^4He gas at 6.7 K and 200 psi, respectively) and was capable of operating with 400 W of deposited beam power. Average beam currents of $55 \mu\text{A}$ (hydrogen) and $35 \mu\text{A}$ (^4He) 3 GeV electrons were used; the beam current was limited by beam-induced heating of the septum magnets. Target density fluctuations did not contribute significantly to the statistical width of the measured asymmetry in either case. The electron beam polarization was continuously monitored using the Hall A Compton polarimeter; the run-averaged polarization was $(86.7 \pm 2)\%$ for the hy-

Table 1. Averaged Helicity-Correlated Beam Parameters.

Parameter of Error	Hydrogen	Helium
Intensity asymmetry	0.406 ppm	-0.377 ppm
Energy asymmetry	0.2 ppb	3 ppb
x-position difference	0.5 nm	-0.2 nm
x-angle difference	-0.2 nrad	4.4 nrad
y-position difference	1.7 nm	-26 nm
y-angle difference	0.2 nrad	-4.4 nrad

drogen data and $(84.0 \pm 2.5)\%$ for ^4He . Periodic measurements using the Hall A Møller polarimeter and the 5 MeV Mott polarimeter were consistent with these results.

Loose cuts were placed on the data to remove periods of poor beam quality, or when a particular spectrometer was not functioning; no cuts were placed based on any helicity-dependent quantities. In the setup of the electron source, careful attention was paid to the laser optics that brings the light on the ‘superlattice’ GaAs photocathode, so as to minimize helicity-correlated changes in beam parameters such as intensity, energy, and horizontal (x) and vertical (y) positions and angles at the target. These procedures are extensively discussed in K. Paschke’s contribution to these proceedings.

For the hydrogen data, the run-averaged values for the helicity-correlated beam parameters sets a new standard in the field (see Table 1). For the helium data the results were not as impressive, while still quite acceptable (see Table 1). A problem was uncovered mid-way through the helium data-taking, in which an in-time helicity signal was found to be ‘picked up’ by devices at an early stage in the accelerator. This electronics cross-talk caused significant helicity-correlated steering of the beam, and thus large (of order 400 nm) position differences at the target. While the effect largely cancelled out with half-wave plate insertion, and also largely cancelled between the right and left spectrometers, it was still large enough to be of concern. The problem was diagnosed about 1/3 of the way through the data-taking by reversing the sign of the helicity driver signal (whereupon it also reversed, adding another layer of cancellation), and the offending signal cable was removed about 2/3 of the way through the data-taking and the problem disappeared. The effect is visible in the ‘raw’ asymmetry data for one arm as shown in fig. 2. However, the effect on the asymmetry is essentially invisible if one averages data from the right and left spectrometers. Note that dedicated tests showed that any helicity-correlated electronics noise in the DAQ was below the 1 parts per billion (ppb) level and thus negligible.

Correction of the raw asymmetry for the effects of the five correlated beam parameter differences listed in Table 1 requires determination of the sensitivity of the detected signal rates to these beam parameters. Two independent methods were used to calculate these sensitivities. The first relied on linear regression of the observed response of the detector PMTs to natural beam fluctuations. The other used calibration data in which the beam was deliberately modulated (by amounts large compared

Table 2. Systematic Uncertainties.

Source of Error	Hydrogen (ppb)	Helium (ppb)
Beam Polarization	37	192
Q^2 Determination	16	58
Detector Linearity	15	58
False Asymmetries	17	48
Target Wall Background (Al)	15	32
Quasielastic scattering		24
Transverse Asymmetry	4	8
Radiative Corrections	3	6

to the intrinsic beam fluctuations) using steering magnets and an accelerating cavity. The differences between the sensitivities calculated using these two methods were much smaller than corresponding statistical errors on the corrections. The net helicity-correlated correction to the helium data set was 120 ppb (compared to a statistical error of 191 ppb) and for hydrogen was 11 ppb (compared to a statistical error of 105 ppb).

The data were found to be perfectly behaved statistically under a number of tests. For example, the results agreed within errors for both settings of the half-wave plate, the results were consistent for right and left arm spectrometers, the asymmetry distributions of individual helicity pairs, after the correction for helicity-correlated beam parameters discussed above, were perfectly Gaussian over four orders of magnitude. Subdividing the data into slugs or into one-hour long runs gave consistent distributions with a reduced χ^2 close to one in each case.

An important feature of the HAPPEX apparatus is the fact that the spectrometers focus the elastically scattered electrons onto a compact region in the focal plane, where the detectors are located. Backgrounds from inelastic scattering are essentially not intercepted by the detectors and thus contributed less than 1% to the detected signal rate. The thin aluminum walls of the target cells lead to only a modest background from aluminum (0.76% for hydrogen and 1.8% for helium). A detailed discussion of the determination of the small background contributions and of the central kinematics (Q^2) is available in B. Moffit’s contribution to these proceedings; their effects on the systematic errors are given in Table 2.

Dedicated measurements of the transverse beam spin asymmetry were made for both targets (see L.J. Kaufman, these proceedings). Combined with limits placed on the degree of transverse polarization, obtained using the Møller polarimeter, the results indicate only a small background to A_{PV} in each case (see Table 2). The smallness of the effect is due both to the fact that the production beam was almost perfectly longitudinal, and to the large cancellation in the effect of the transverse asymmetry between the left and right arm spectrometers.

Fig. 2. Left: Measured raw asymmetry in the left HRS for ^4He , for both settings of the insertable half-wave plate (HWP), as a function of “slug” of data. The helicity driver signal was reversed at slug 37, and the electronics cross-talk fixed at slug 77, whereupon the data stabilize; Right: Same data after correction for helicity-correlated beam parameters. Results for the right HRS are similar.

3 Results

For ^4He the preliminary result is

$$A_{PV} = +6.43 \pm 0.23 \text{ (stat)} \pm 0.22 \text{ (syst)} \text{ ppm}$$

at $\langle Q^2 \rangle = 0.077 \text{ GeV}/c^2$. The expected asymmetry in the absence of strange form factors is 6.37 ppm. For hydrogen the preliminary result is

$$A_{PV} = -1.60 \pm 0.12 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ ppm}$$

at $\langle Q^2 \rangle = 0.109 \text{ GeV}/c^2$. The expected asymmetry in the absence of strange form factors is -1.64 ppm. This latter includes the small contribution from the axial form factor (See eq. 1) of -0.037 ± 0.018 ppm, determined using the the axial radiative corrections calculated by Zhu *et al.* [17]. In interpreting our asymmetries, we adopt the Friedrich and Walcher parameterization of the electromagnetic form factors [12], supplemented by the recent BLAST data for G_E^n [13].

The contributions to the systematic error in each case are listed in Table 2. The dominant systematic for both targets is the knowledge of the beam polarization, which at present has an error of 2% for hydrogen and 2.5% for helium; continued refinement of the data-analysis techniques for the Compton polarimeter promises to reduce these errors significantly for the final results.

From our 2005 data alone, we extract $G_E^s = 0.004 \pm 0.014 \pm 0.013$ and $G_E^s + 0.09 G_M^s = 0.004 \pm 0.011 \pm 0.005$. These results are shown in fig. 3. The results are in excellent agreement (but much more precise than) our previously published data from the runs in 2004 [9,10]. To extrapolate to a common $Q^2 = 0.1 \text{ GeV}/c^2$, we assumed that $G_E^s \propto Q^2$ and that G_M^s was constant over this small range of Q^2 . A fit to the present data combined with our 2004 results yields

$$G_E^s = -0.002 \pm 0.017$$

and

$$G_M^s = 0.12 \pm 0.24$$

Also shown in fig. 3 is a simple-minded fit to the world data at this Q^2 , including the SAMPLE [14], PV-A4 [15], and G0 [16] results, as well as our 2004 results, which gives $G_E^s = -0.006 \pm 0.016$ and $G_M^s = 0.28 \pm 0.20$. Notice that the HAPPEX results dominate the precision of the world fit. Correlated errors and correlated assumptions have not been taken into account in this global fit. A more sophisticated combined fit, which makes different assumptions about the axial form factors and incorporates data up to $Q^2 = 0.3 \text{ GeV}/c^2$ was presented by R. Young at this meeting (see also [19]); the results of that fit agree within errors with ours, however the central value for G_M^s is much closer to zero in that fit.

4 Interpretation and Conclusion

The present high-precision results place significant constraints on the strange vector form factors of the nucleon. In particular, the HAPPEX- ^4He experiment is the *first* measurement made to date that is sensitive to only a single, isolated strange form factor (G_E^s). The results obtained at low Q^2 are gratifyingly consistent with the data the other the collaborations (SAMPLE, PV-A4, G0) that have contributed measurements at or near this kinematic point, using a variety of different experimental approaches. While a number of model calculations are ruled out by the present data, a number are still consistent with the result. Going beyond models, the HAPPEX data are in spectacular agreement with the predictions if Leinweber *et al.* (ref. [18], and R. Young, these proceedings), which adopt charge symmetry, and combine input from lattice gauge calculations with hyperon data to yield the results that are also shown in fig. 3. The excellent mutual consistency of all the data, and the high precision, are good news for the

Fig. 3. The results, with 1σ error bands, of the 2005 HAPPEX data-taking on hydrogen and helium targets, expressed in the G_M^s vs. G_E^s plane. Also shown are the 68% and 95% confidence level allowed regions from a combined fit to the world data at this Q^2 (see text). Shown as vertical and horizontal bands are the theoretical predictions of Leinweber *et al.* [18] using charge symmetry, hyperon data, and lattice QCD input.

Q_{weak} experiment (S. Page, these proceedings), as they indicate that the form factor uncertainty in interpreting that measurement is under adequate control.

The present results for G_E^s indicate that, to a remarkable degree, the spatial distribution of strange quarks in the nucleon mirrors that of the anti-strange quarks; there appears to be little tendency (if any) for one or the other to preferentially appear at larger radii, unlike what one expects in a naive model in which the nucleon has a significant Fock space component as a hyperon-kaon state. The result for G_M^s is consistent with zero, although the central value is positive. This slight favoring of a positive value is in agreement with the (less precise) indications from earlier experiments (*e.g.* ref. [14]). While the new data significantly improve constraints on G_M^s , there is still room for non-trivial values; at the 1σ level the HAPPEX results allow as much as 4.3% of the nucleon's magnetic moment to arise from strangeness, or a decidedly significant 27% of the isoscalar part of magnetic moment.

The HAPPEX collaboration has an approved experiment planned to measure forward-angle parity violating electron scattering at $Q^2 = 0.63 \text{ GeV}^2$, which, when combined with the G0 backward-angle measurement at the same Q^2 , will allow a similarly precise separation of the strange form factors at this larger Q^2 . The measurements underway now (PV-A4, G0) at backward angles and intermediate Q^2 should provide a third kinematic point with separated form factors, as well as valuable information on the axial form factor; together these results should pro-

vide a comprehensive picture of the strange quark contributions to the vector structure of the nucleon. The present results show that these contributions remain stubbornly elusive.

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