Strange Quark Contributions to Parity-Violating Asymmetries in the Backward Angle G0 Electron Scattering Experiment

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Abstract. The G0 collaboration has measured parity-violating asymmetries in elastic electron-proton and quasielastic electron-deuteron scattering at $Q^2 = 0.22$ and 0.63 GeV$^2$. They are sensitive to strange quark contributions to currents in the nucleon, and to the nucleon axial current. The results indicate strange quark contributions of $< 10\%$ of the charge and magnetic nucleon form factors at these four-momentum transfers. They also provide the first measurement of anapole moment effects in the axial current at these four-momentum transfers.


INTRODUCTION

Due to the nature of the strong interaction, as described by QCD, the properties of bound systems of quark are successfully described by perturbation theory at small distance scales. However, at the scale of $\sim 1$ fm (roughly the size of a nucleon) the QCD coupling constant becomes large and the effects of the color fields (gluons) are no longer reliably calculable, even with the most modern lattice techniques. The quark model which describes hadrons as bound systems of valence quarks, $uud$ for the proton, does a surprisingly good job of categorizing the mesons and baryons observed in nature, however when explored in detail the sea of gluons and $q\bar{q}$ pairs also plays an important role. For example, the bare masses of quarks alone only accounts for $\sim 1\%$ of the total mass of the proton.

Since the nucleons themselves have no valance strangeness, measuring the effects of the strange ($s\bar{s}$) quarks on nucleon properties provides one method for studying the $q\bar{q}$ sea. Ongoing studies of the mass, momentum and spin of the nucleon have revealed that the $s$ quarks contributes at non-negligible levels [1, 2, 3]. Additionally, the strange quark contributions to nucleon vector currents can be determined assuming the coupling of both photons and $Z$ bosons to the point-like quarks is well defined [4]. Neglecting the very small contribution from heavier flavors, the charge and magnetic form factors of the proton and neutron can be written ($i = \gamma, Z$)

\begin{align}
G_{E,M}^{p,i} &= e^{u}G_{E,M}^{u} + e^{d}(G_{E,M}^{d} + G_{E,M}^{s}), \\
G_{E,M}^{n,i} &= e^{d}G_{E,M}^{d} + e^{s}(G_{E,M}^{u} + G_{E,M}^{s}),
\end{align}

assuming the proton and neutron are related by a simple exchange of $u$ and $d$ quarks (as well as $\bar{u}$ and $\bar{d}$) [5]. For the ordinary electromagnetic form factors the charges are $e^u = +2/3$, $-1/3$ for $u$ and $d/s$ quarks, respectively, while the weak form factors couple with charges, $e^d = 1 - 8/3 \sin^2 \theta_W$, $-1 + 4/3 \sin^2 \theta_W$ (with $\theta_W$ the weak mixing angle) for the $u$ and $d/s$ quarks, respectively. Solving this system using the proton neutral weak form factors

\begin{align}
G_{E,M}^{e,p} = (1 - 4 \sin^2 \theta_W)G_{E,M}^{\gamma,p} - G_{E,M}^{Z,p}.
\end{align}

The ordinary electromagnetic form factors at four-momentum transfer values $< 1$ GeV$^2$ and $\theta_W$ in Eq. 2 are precisely known, however $G_{E,M}^{Z,p}$ requires additional effort. Measurements of electron-proton elastic scattering cross-sections are dominated by the electromagnetic interaction. However, the parity violating nature of the weak interaction allows one to write an asymmetry observable for longitudinally polarized electrons ($R$ and $L$) scattered elastically from

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1 see [26]
TABLE 1. Measured and raw elastic asymmetries (Eq. 6). \( f_{el} \) is the background fraction for the dominant contribution (Al target cell) to the yield. Misidentified \( \pi^- \) (\( f_{pi} \) fraction) and other small backgrounds \( f_{other} \) (with 100% error) are also given. \( \Delta A_{corr} \) are the contributions to the overall point-to-point and global systematic uncertainties (Table 2) due to these background corrections.

<table>
<thead>
<tr>
<th>Target</th>
<th>( Q^2 ) (GeV(^2))</th>
<th>( A_{meas} ) (ppm)</th>
<th>( f_{el} )</th>
<th>( f_{pi} ) (ppm)</th>
<th>( f_{other} ) (ppm)</th>
<th>( A_e )</th>
<th>( \Delta A_{corr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.221</td>
<td>-9.72</td>
<td>0.13 ± 0.064</td>
<td>0 ± 0.001</td>
<td>0.003</td>
<td>-9.22</td>
<td>±0.11 ± 0.40</td>
</tr>
<tr>
<td>D</td>
<td>0.221</td>
<td>-13.50</td>
<td>0.099 ± 0.050</td>
<td>0 ± 0.002</td>
<td>0.005</td>
<td>-13.57</td>
<td>±0.02 ± 0.08</td>
</tr>
<tr>
<td>H</td>
<td>0.628</td>
<td>-36.9</td>
<td>0.11 ± 0.050</td>
<td>0 ± 0.001</td>
<td>0.023</td>
<td>-37.0</td>
<td>±0.61 ± 0.86</td>
</tr>
<tr>
<td>D</td>
<td>0.628</td>
<td>-37.4</td>
<td>0.061 ± 0.031</td>
<td>0.04 ± 0.015</td>
<td>0.029</td>
<td>-39.4</td>
<td>±0.48 ± 0.23</td>
</tr>
</tbody>
</table>

unpolarized protons, as [6]

\[
A = \frac{\frac{d \sigma_R - d \sigma_L}{d \sigma_R + d \sigma_L}}{4 \sqrt{2} \alpha} = -\frac{G_F Q^2 \epsilon G_E L^2 + \tau G_M G_E - (1 - 4 \sin^2 \theta W)e' G_M' G_E'}{\epsilon (G_M'^2 + \tau (G_M'^2))}
\]  

where \( \tau = Q^2/4M^2 \), \( \epsilon = 1/(1 + 2(1 + \tau) \tan^2 \theta / 2) \), \( \epsilon' = \sqrt{\tau (1 + \tau) (1 - \epsilon^2)} \). \( Q^2 \) is the squared four-momentum transfer \( (Q^2 > 0) \), \( G_F \) and \( \alpha \) the usual weak and electromagnetic couplings, \( \theta \) the laboratory electron scattering angle, \( M \) the proton (neutron) mass and \( G_E', G_M', \) etc. the proton (neutron) electromagnetic and neutral weak form factors, respectively. Extracting \( G_E'^P \) and \( G_M'^P \) from the asymmetry, requires measurements at two different angles along with a third measurement to determine the effective axial form factor, \( G_A' \).

In addition to the strange quark vector currents, the parity violating asymmetry in Eq. 3 is also sensitive to the axial form factor of \( G_A' \), defined via

\[
G_A' = G_{A,T=1}^{e,T=0} = G_{A,cc}^{e,T=0} = G_{A,cc}^{e,T=0} + R_{ana} + G_{A}^{e,T=0}.
\]

To lowest order \( G_{A,T=1}^{e,T=1} \) is the same as that measured in charged current neutrino scattering \( (G_{A,cc}^{e,T=0}) \) [6, 7, 8]. The isoscalar contribution to \( G_A' \), \( G_{A,T=0}^{e,T=0} \), is small (<10%) [9, 2, 3]. However, the radiative corrections, \( (R_{ana}) \), associated with electron scattering are expected to be significant (~30%) and distinct from those measured in neutrino scattering [9]. They include the effect of the anapole moment, the effective parity-violating coupling of the photon to the nucleon [10].

The parity violating asymmetry from quasielastic scattering off the deuteron is largely sensitive \( G_A' \). This asymmetry is, to a good approximation, the sum of those for the proton and neutron,

\[
A_D = \frac{G_F Q^2 N_n + N_p}{4 \sqrt{2} \alpha D_n + D_p}
\]

where \( N_n(p) \) and \( D_n(p) \) are the numerator and denominator from Eq. 3. For the results reported here, we use a complete model of the electroweak deuteron response [11].

The SAMPLE [12], HAPPEX [13], PVA4 [14] and G0 [15] experiments have previously reported measurements of these parity-violating asymmetries. Using the combined forward angle asymmetries and the SAMPLE backward angle proton and deuteron measurements, a complete experimental determination of the strange quark vector currents and the axial current (see discussion below) has been made at a four-momentum transfer \( Q^2 = 0.1 \) GeV\(^2\) [16]. The G0 collaboration is reporting the first backward angle asymmetry measurements from both hydrogen and deuterium since the SAMPLE experiment, at the four-momentum transfers of 0.221 and 0.628 GeV\(^2\). Together with G0 forward angle measurements [15], the first experimental separation of \( G_M \) and \( G_E \) for \( Q^2 > 0.1 \) GeV\(^2\) has before performed. Additionally, the results give the first indication of the \( Q^2 \) dependence of \( G_{A,T=1}^{e,T=1} \).

G0 BACKWARD ANGLE MEASUREMENT

The G0 experiment was conducted [17] in Hall C at Jefferson Lab. Polarized electron beams with currents up to \( I = 60 \) \( \mu \)A and energies of 359 and 684 MeV were generated with a strained GaAs polarized source [18]. The average beam polarization was 85.8 ± 2.1(1.4)% at the lower (higher) incident energy. The helicity of the beam was changed every
an aerogel Čerenkov detector allowed pions to be distinguished from electrons with a rejection factor efficiency of about 85%.

Electrons from elastic (inelastic) scattering are in the upper right (lower left) on figure. b) (Right) The yield versus magnet current for a toroid field sweep in CED 6/FPD 11 with data shown in (green) and simulation: elastic (blue), aluminum (light blue) inelastic (pink), π0 (orange), π- (purple) total(red). The dashed line is placed at the nominal setting with red line indicating ∼ ± 20% change in magnetic current.

![Example of counting rates – LH2, 0.684 GeV.](image)

**FIGURE 1.** Example of counting rates – LH2, 0.684 GeV. a) (Left) Various CED - FPD combinations (FPDs 1 and 2 not used). b) (Right) The yield versus magnet current for a toroid field sweep in CED 6/FPD 11 with data shown in (green) and simulation: elastic (blue), aluminum (light blue) inelastic (pink), π0 (orange), π- (purple) total(red). The dashed line is placed at the nominal setting with red line indicating ∼ ± 20% change in magnetic current.

**TABLE 2.** Corrections to the raw elastic asymmetries (Table 1), and the resulting final physics asymmetries. Rate and “Other” corrections are additive; beam polarization corrections, (1/0.858) ± 0.02 ± 0.01, and electromagnetic radiative corrections are multiplicative. “Other” corrections include those for helicity-correlated beam parameters, the small transverse component of beam polarization, and two-boson exchange. The uncertainties for the corrections are point-to-point and global systematic; for the physics asymmetry the uncertainties are statistical, point-to-point and global systematic.

<table>
<thead>
<tr>
<th>Target</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>Rate (ppm)</th>
<th>Other (ppm)</th>
<th>EM Radiative</th>
<th>$A_{\text{phys}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.221</td>
<td>−0.31 ± 0.08 ± 0</td>
<td>0.22 ± 0.08 ± 0.01</td>
<td>1.037 ± 0.002 ± 0</td>
<td>−11.25 ± 0.86 ± 0.27 ± 0.43</td>
</tr>
<tr>
<td>D</td>
<td>0.221</td>
<td>−0.58 ± 0.21 ± 0</td>
<td>0.06 ± 0.10 ± 0.01</td>
<td>1.032 ± 0.004 ± 0</td>
<td>−16.93 ± 0.81 ± 0.41 ± 0.21</td>
</tr>
<tr>
<td>H</td>
<td>0.628</td>
<td>−1.28 ± 0.18 ± 0</td>
<td>0.29 ± 0.11 ± 0.01</td>
<td>1.037 ± 0.002 ± 0</td>
<td>−45.9 ± 2.4 ± 0.8 ± 1.0</td>
</tr>
<tr>
<td>D</td>
<td>0.628</td>
<td>−7.0 ± 1.8 ± 0</td>
<td>0.34 ± 0.21 ± 0.01</td>
<td>1.034 ± 0.004 ± 0</td>
<td>−55.5 ± 3.3 ± 2.0 ± 0.7</td>
</tr>
</tbody>
</table>

1/30 sec (MPS). A pseudo-random helicity structure was imposed on every four MPS, a quartet, with either LRRL or RLLR being chosen, where R/L represent the helicity state of the electron. Helicity-correlated current changes were corrected with active feedback to about 0.3 parts-per-million (ppm). Corrections to the measured asymmetry for residual helicity-correlated beam current, position, angle and energy variations of at most 0.2 ± 0.07 ppm were applied via linear regression.

A superconducting toroidal spectrometer, consisting of an eight-coil magnet, and eight detector sets, detected the electrons scattered at an angle of about 110° from 20 cm liquid hydrogen and deuterium targets [19]. Each detector set included two arrays of scintillators, one near the exit of the magnet (“CED”), and the second along its focal surface (“FPD”). These detectors allowed us to separate electrons from elastic and inelastic scattering (Fig. 1a). Additionally, an aerogel Čerenkov detector allowed pions to be distinguished from electrons with a rejection factor ≥ 85% and electron efficiency of about 85%.

The measured asymmetry is formed for each helicity quartet, e.g. $A_{\text{meas}} = \frac{Y_r - Y_L}{Y_r + Y_L + Y_0} + fY$ for LRRL. This measured asymmetry has multiple components written generically as

$$A_{\text{meas}} = (1 - f) A_e + f A_b$$

where $A_e$ is the raw elastic asymmetry, $A_b$ the background asymmetry and $f$ the background fraction. The backgrounds in the region of the elastic locus (see Fig. 1a) amount to 10-15% of the signal. In the elastic locus, the aluminum target windows dominate the backgrounds with misidentified π− and electrons from π$^0$ conversion also contributing (Table 1). The aluminum fraction was measured using runs with gaseous hydrogen in the target and the pion contamination was determined from dedicated time-of-flight runs and pulse shape analysis. Additionally, an acceptance study was performed by sweeping the field of the toroid ±40% of the nominal setting and comparing the yield in each coincidence cell with Monte Carlo simulation using GEANT [20] (Fig. 1b). The aluminum asymmetry was taken to
be the same as that of the deuteron (both effectively quasielastic scattering only) with an additional uncertainty of 5% for nuclear effects. The pion asymmetry (∼0 ppm) was measured concurrently with that for the electrons. The background corrections are small because the background asymmetries generally have values close to those of the elastic asymmetry, or otherwise, the fraction is small.

All asymmetries were corrected for measured rate dependent effects (Table 2). For elastic scattering, dead-time corrections generally dominated those from accidentals and amounted to ∼15% of the yield based on the measured beam current dependence, and led to an uncertainty of about 0.5 ppm in the asymmetries. In the high-energy deuteron measurement, accidentals from pion signals in the scintillators in coincidence with random signals from the Čerenkov dominated the correction. In this case, the correction to the asymmetry was −7.0 ± 1.8 ppm. Electromagnetic radiative corrections [21] of (3−3.5) ±0.3% and small two boson exchange effects (1%) [22] were also applied to the asymmetries. Table 2 shows the corrections to the raw elastic asymmetry, $A_{el}$, as well as the final asymmetries $A_{phys}$ and their statistical and systematic uncertainties.

RESULTS

Fig. 2 shows the three new elastic form factors, $G_E^s$, $G_M^s$, and $G_A^{s,T=1}$, extracted from $A_{phys}$, at $Q^2 = 0.221$ and 0.628 GeV$^2$ [25, 26]. These results utilize a simple interpolation of the G0 forward angle measurements [27]. The Kelly [28] electromagnetic nucleon form factors, $G_{EM}^{p,n}$, are used as the basis for these determinations to be consistent with the deuteron model [11]. Fig. 2 also shows an extraction of $G_E^s$ and $G_M^s$ at $Q^2 = 0.1$ GeV$^2$ using a low $Q^2$ fit to previous data [16]. Also the PVA4 points shown [14], in contrast to the G0 results, did not measure on deuterium and assume a value for $G_A^{s,T=1}$ determined by the normalization of Ref. [9] (shown in Fig. 2c), and a dipole form factor with a mass parameter of 1.032 GeV.
In conclusion, the G0 collaboration has measured backward angle parity-violating asymmetries in elastic electron-proton and quasielastic electron-deuteron scattering at $Q^2 = 0.221$ and 0.628 GeV$^2$. These asymmetries determine the neutral weak interaction analogs of the ordinary charge and magnetic form factors of the nucleon, together with the effective axial form factor. From the asymmetries we have determined $G_E^s$, $G_M^s$ and $G_E^{T=1}$, which indicate that the strange quark contributions to the nucleon form factors are <10%, and provide the first information on the $Q^2$ dependence of $G_E^{T=1}$ and the nucleon anapole moment. Future forward angle experiments at $Q^2 = 0.63$ GeV$^2$ at Jefferson Lab and Mainz will further improve the precision of these determinations.

ACKNOWLEDGMENTS

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REFERENCES

26. More detailed tables may be found at http://www.npl.uiuc.edu/exp/G0/Backward.
27. From Ref. [15]: A linear fit was made to $A_{phys} - A_{NVS}$ values (see text) from $Q^2 = 0.177$ to 0.997 GeV$^2$; the uncertainty of the interpolated values taken to be 70% of the statistical uncertainty at the nearest measured point.