New Measurement of Parity Violation in Elastic Electron-Proton Scattering and Implications for Strange Form Factors

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We have measured the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from the proton. The result is $A = -14.60 \pm 0.94(stat) \pm 0.54(syst)$ ppm at the kinematic point $\langle\theta_{\rm lab}\rangle = 12.3°$ and $\langle Q^2\rangle = 0.477$ (GeV/c)^2. The measurement implies that the value for the strange form factor $(G_E^s + 0.392 G_M^s)/(G_M^p/\mu_p) = 0.091 \pm 0.054 \pm 0.039$, where the first error is experimental and the second arises from the uncertainties in electromagnetic form factors. This measurement is the first fixed-target parity violation experiment that used either a "strained" GaAs photocathode to produce highly polarized electrons or a Compton polarimeter to continuously monitor the electron beam polarization.

13.60.Fz, 11.30.Er, 13.40.Gp, 14.20.Dh

It is well known that strange quarks and antiquarks are present in the nucleon. An important open question is the role that sea (non-valence) quarks in general and strange quarks in particular [1] play in the fundamental properties of the nucleon. For example, do strange quarks contribute to the charge radius or magnetic moment of the proton? If so, the strange form factors G_E^s and G_M^s are significant. A number of papers have suggested that indeed these form factors may be large [1–10]. Others models suggest small contributions [11–14].

Strange form factors can be isolated from up and down quark form factors by measuring the parity-violating asymmetry $A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ in the elastic scattering of polarized electrons from protons [15,16]. The experiments are challenging since $A \approx A_0 \tau \approx 10$ parts per million (ppm) for typical kinematics. Here $A_0 = (G_F M_p^2)/(\sqrt{2}\pi\alpha) = 316.7$ ppm, where G_F is the Fermi constant for muon decay and M_p is the proton mass. Also $\tau = Q^2/4M_p^2$ where Q^2 is the square of the four-momentum transfer. Nevertheless, several experiments have recently published significantly non-zero values for A [17–19]. In this letter, we present the most precise measurement to date for A of the proton and determine new limits for the possible contribution of strange form factors.

Measurements of elastic electromagnetic and electroweak nucleon scattering provide three sets of vector form factors. ¿From this information, the form factors for each flavor may be determined [20]: $G_{E,M}^u$, $G_{E,M}^d$, and $G_{E,M}^s$. A convenient alternate set, which is directly accessible in experimental measurements, is the electromagnetic form factors $G_{E,M}^{p\gamma}$, $G_{E,M}^{n\gamma}$, plus $G_{E,M}^0$. Here $G^0 = (G^u + G^d + G^s)/3$, $G^{p\gamma} = \frac{2}{3}G^u - \frac{1}{3}G^d - \frac{1}{3}G^s$, and $G^{n\gamma} = \frac{2}{3}G^d - \frac{1}{3}G^u - \frac{1}{3}G^s$, where the last expression assumes charge symmetry. G^0 cannot be accessed in electromagnetic scattering and thus represents new information on nucleon dynamics that can be accessed only via measurements of the weak neutral current amplitude.

The theoretical asymmetry in the Standard Model has a convenient form in terms of G^0:

$$A_{th} = -A_0 \tau \rho'_{eq} \left(2 - 4\hat{\kappa}'_{eq} \sin^2\theta_W - \frac{\varepsilon \eta_p}{\varepsilon \eta_p^2 + \tau \mu_p^2} \frac{G_E^0 + \tau \mu_p G_M^0/(\varepsilon \eta_p)}{(G_M^{\gamma p}/\mu_p)} \right) - A_A \tag{1}$$

where $\mu_p(\mu_n) \approx 2.79(-1.91)$ is the proton(neutron) magnetic moment in nuclear magnetons, $\eta_p = \eta_p(Q^2) = G_E^{p\gamma}(Q^2)/(G_M^{p\gamma}(Q^2)/\mu_p)$, and $\varepsilon = (1 + 2(1+\tau)\tan^2\theta/2)^{-1}$, the longitudinal photon polarization. The scattering angle of the electron in the laboratory is θ. The contribution from the proton axial form factor, A_A, is small for our kinematics [21,22]. The parameters $\rho'_{eq} = 0.9879$ and $\hat{\kappa}'_{eq} = 1.0029$ include the effect of electroweak radiative corrections [23], and $\sin^2\theta_W = 0.2314$.

If, in addition to $G_{E,M}^0$, the proton and neutron electromagnetic form factors $G_{E,M}^{p\gamma}$ and $G_{E,M}^{n\gamma}$ are known, the strange form factors may be determined from

$$G_{E,M}^s = G_{E,M}^0 - G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma}. \tag{2}$$

It is convenient to normalize the form factors to $G_M^{p\gamma}/\mu_p$ since the normalized form factors depend less on experimental uncertainties and tend to vary less with τ. Then the quantities extracted are $G_E^s/(G_M^{p\gamma}/\mu_p) \to \tau\rho_s$ and $G_M^s/(G_M^{p\gamma}/\mu_p) \to \mu_s$ for the limit $\tau \to 0$. Models [2,3,5,8] suggest that the radius parameter ρ_s could be of the order of ±2 and the strangeness contribution to the magnetic moment μ_s could be of the order of -0.3. If the strange form factors are indeed of this scale, our experiment along with other experiments in progress should be able to establish their presence.

This experiment took place in Hall A at the Thomas Jefferson National Accelerator Facility. An approximately 35μA beam of 67-76% polarized electrons with an energy of 3.3 GeV scattered from a 15 cm liquid hydrogen target. Elastic events were detected by integrating the signal in total-absorption counters located at the focal plane of a pair of high-resolution magnetic spectrometers.

It is important that the signal be purely elastic, since background processes may have large asymmetries. For example, the production of the prominent $\Delta-$resonance has 3 times the asymmetry of elastic scattering. [20] To measure the rejection of unwanted events by our system, we measured the response of the detector, both in counting and integrating mode, as a function of the mismatch between the spectrometer setting and the momentum of elastic events. The result, shown in Fig. 1, is that the integrated response drops many orders of magnitude as the momentum mismatch increases. Based on this data, we determined that only 0.2% of our signal arises from background processes.

A new feature of the experiment is that the beam polarization $P_e \approx 70\%$. This was achieved by using photoemission by circularly polarized laser light impinging on a "strained" GaAs crystal. A plot of the polarization versus time for part of the run is given in Fig. 2. The starred points are from Møller scattering and the dots are preliminary data from the recently commissioned Compton polarimeter. The Compton device continuously monitored the polarization of the beam on target and ruled out possible significant variations in polarizations between the daily Møller measurements. Both devices have an overall systematic error $\Delta P_e/P_e \sim 3.2\%$.

To study possible systematic errors in our small asymmetry, we inserted a half-wave ($\lambda/2$) plate in the laser beam at the source to reverse the sign of the helicity. Data were obtained in sets of 24-48 hour duration, and the state of the $\lambda/2$ plate was reversed for each set. The resulting asymmetries are shown in Fig. 3a. The asymmetries reverse as expected but otherwise behave statistically.

The strained GaAs crystal, in contrast to the bulk GaAs used for our previous result, has a large analyzing power for linearly polarized light. The analyzing power tends to promote helicity-correlated differences in beam parameters such as position, energy, and intensity. The intensity asymmetry was nulled with a feedback system. In addition, the intensity asymmetry in the beam in another hall also had to be nulled. The position and energy differences were measured with precision microwave monitors. One example of monitor data is shown in Fig. 3b. The effect of these beam differences on the asymmetry was measured by calibrating the apparatus with beam correction coils and an energy vernier. The resultant correction, shown in Fig. 3c, proved to have an average of 0.02 ± 0.02 ppm.

The experimental asymmetry, corrected for the measured beam polarization, is $A_{exp} = -14.6$ ppm for the 1999 data. We also include the 1998 data, which gives $A_{exp} = -14.5$ ppm when extrapolated to the same Q^2 value. In addition, two small corrections were made to the 1998 data. The background contribution was added, and the Q^2 value was corrected from 0.479 to 0.474 (GeV/c)^2. An increase of 1% in Q^2 is expected to increase the magnitude of the asymmetry by 1.5%. The errors for all the data are given in Table I. Systematic errors in the beam polarimetry and in the measurement of the spectrometer angle were the most significant sources. The combined result is $-14.60 \pm 0.94(stat) \pm 0.54(syst)$ ppm at the average kinematics Q^2=0.477 (GeV/c)^2 and $\theta = 12.3°$. The experiment averaged over the finite solid angle of the spectrometers, increasing the asymmetry by 0.7%. We use $A_A = (0.56 \pm 0.23)$ ppm [23,21,22], where the uncertainty comes from weak radiative corrections.

The result is $(G_E^0 + 0.392 G_M^0)/(G_M^{p\gamma}/\mu_p) = 1.550 \pm 0.046 \pm 0.026 \pm 0.011$, where the first error is statistical, the second systematic, and the last error arises in the uncertainty from A_A. The sensitivity to η_p is negligible. To determine the contribution due to strange form factors, we use Eq. 2 and data for the electromagnetic form factors. The values we use [24–31] are summarized in the first three lines of Table II. Thus we have $(G_E^s + 0.392 G_M^s)/(G_M^{p\gamma}/\mu_p) = 0.091 \pm 0.054 \pm 0.039$, where the first error is the errors in G^0 combined in quadrature and the second due to the electromagnetic form factors.

If we assume that the $\tau \to 0$ limit for the ratio of form factors is valid at our Q^2, we obtain $\rho_s + 2.9\mu_s = 0.67 \pm 0.41 \pm 0.30$. This result is plotted in Fig. 4, together with various predictions. A more conservative assumption, suggested by the Galster approximation [20] to $G_E^{n\gamma}$, is that $G_E^s/(G_M^{p\gamma}/\mu_p) = \tau\rho_s/(1 + \lambda_E^s \tau)$, where $\lambda_E^s \approx 5.6$. This would reduce our sensitivity to ρ_s by about a factor of two. We have a new experiment approved for a point at $Q^2 \sim 0.1$ (GeV/c)^2 that will significantly reduce our sensitivity to λ_E^s.

The electromagnetic form factors are a major source of uncertainty for $(G_E^s + 0.392 G_M^s)$. Moreover, there exist for G_M^n data [32], also given in Table II, that are inconsistent with the value we chose. With this choice, $(G_E^s + 0.392 G_M^s)/(G_M^{p\gamma}/\mu_p) = 0.143 \pm 0.054 \pm 0.047$. Fortunately, there are experiments in progress that will significantly improve the accuracy of the electromagnetic form factors. These new electromagnetic measurements could have significant impact on the conclusions that we can draw about strange form factors.

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Source	Correction	$\delta A/A(\%)$:1998	$\delta A/A(\%)$:1999
Statistics	–	13.3	7.2
P_e	–	7.0	3.2
Q^2	–	1.8	1.8
Backgrounds	1.2	0.6	0.6

TABLE I. Summary of corrections and contributions to the errors in % for the measured asymmetry.

Form Factor	Value	Ref.
$G_E^p/(G_M^p/\mu_p)$	0.99 ± 0.02	[24,25]
$G_E^n/(G_M^p/\mu_p)$	0.16 ± 0.03	[27–31]
$(G_M^n/\mu_n)/(G_M^p/\mu_p)$	1.05 ± 0.02	[26]
$(G_M^n/\mu_n)/(G_M^p/\mu_p)$	1.12 ± 0.04	[32]

TABLE II. Electromagnetic form factors normalized to G_M^p/μ_p.

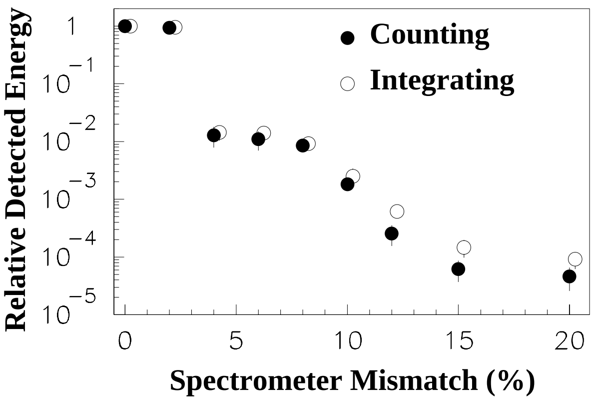

FIG. 1. Fraction of energy deposited in the detector as a function of spectrometer mismatch. The inelastic threshhold is about 4.5%, where the response of the detector is already reduced by a factor of 100.

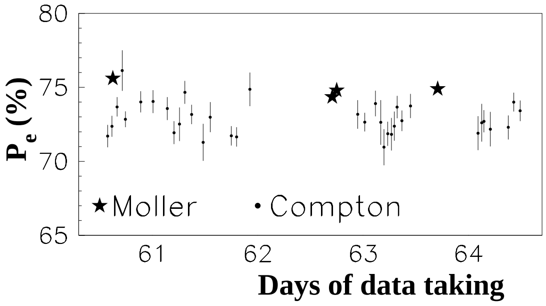

FIG. 2. Electron beam polarization for part of the run. The statistical errors on the Møller data are smaller than the points.

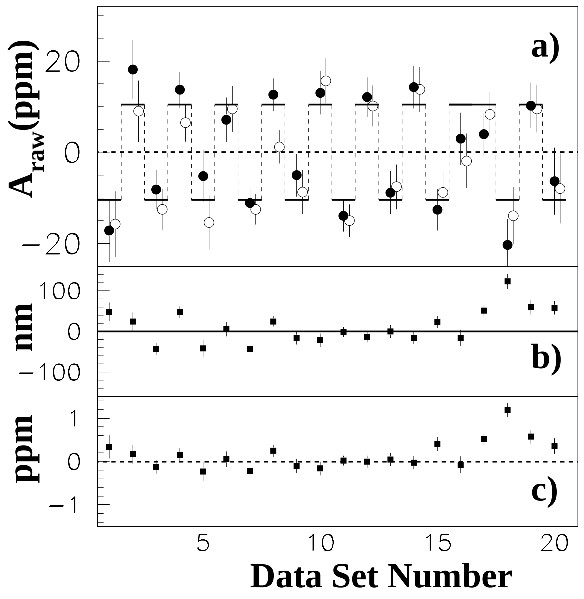

FIG. 3. a) Raw asymmetry versus data set. The $\chi^2 = 33.7$ for 39 degrees of freedom. b) Helicity-correlated horizontal position difference measured near the target. c) Correction to left spectrometer data due to all of the beam parameter differences.

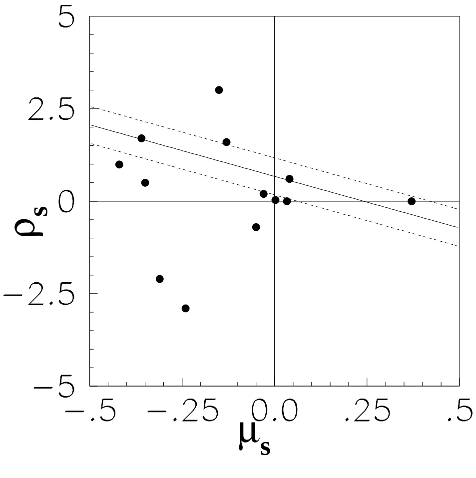

FIG. 4. Band: allowed region from our results with assumptions listed in text. Points: various estimates from models. [1–14]