THE STRANGENESS CONTENT OF THE PROTON FROM PARITY VIOLATING ELECTRON SCATTERING AT JLAB

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We have measured the parity violating asymmetry in the cross section for elastic scattering of longitudinally polarized electrons from protons at 3.36 GeV incident energy and 0.48 $\mathrm{GeV}^2/\mathrm{c}^2$ momentum transfer at JLab. From our 1998 run, this asymmetry is -14.5 $\pm$ 2.2 ppm, consistent with the Standard Model with no contribution from strange quarks. We extract the combination of strange form factors $G_E^s + 0.39 G_M^s = 0.023 \pm 0.034(\mathrm{stat}) \pm 0.022(\mathrm{syst}) \pm 0.026(\delta G_E^n)$, where the last error arises from the neutron electric form factor.

1 Strangeness in the Proton

A common view of proton structure is that protons contain one down and two up quarks bounded by gluons and "dressed" by sea quarks. Since the mass of the strange quarks is comparable to the strong interaction scale, it is not unreasonable to expect that strange quarks may contribute to the form factors. A rather clean probe of vector strange matrix elements comes from parity violation in electron scattering which arises from Z^0 boson exchange [1]. The Hall A Proton Parity Experiment (HAPPEX) measures the parity violating asymmetry $\mathrm{A}^{\mathrm{PV}} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ where $\sigma_{R(L)}$ is the elastic cross section for Right(Left) handed longitudinally polarized electrons from protons.

The usefulness of this asymmetry can be seen by comparing to purely electromagnetic scattering, which measures the following four linear combinations of the Sachs form factors:

$$G^{\gamma \mathrm{p}}_{[\mathrm{E,M}]} = \frac{2}{3} G^{\mathrm{u}}_{[\mathrm{E,M}]} - \frac{1}{3} G^{\mathrm{d}}_{[\mathrm{E,M}]} - \frac{1}{3} G^{\mathrm{s}}_{[\mathrm{E,M}]}$$

$$G^{\gamma \mathrm{n}}_{[\mathrm{E,M}]} = \frac{2}{3} G^{\mathrm{d}}_{[\mathrm{E,M}]} - \frac{1}{3} G^{\mathrm{u}}_{[\mathrm{E,M}]} - \frac{1}{3} G^{\mathrm{s}}_{[\mathrm{E,M}]}$$

where the superscripts are for the proton (p) and neutron (n), the subscripts are for the electric (E) and magnetic (M) form factors, and the quark flavors assumed to contribute are u, d, and s. Also isospin invariance between neutron and proton was assumed in the above, i.e. that for the quark form factors

$$G^{\mathrm{u}}_{\mathrm{p}} = G^{\mathrm{d}}_{\mathrm{n}} \quad ; \quad G^{\mathrm{d}}_{\mathrm{p}} = G^{\mathrm{u}}_{\mathrm{n}} \quad ; \quad G^{\mathrm{s}}_{\mathrm{p}} = G^{\mathrm{s}}_{\mathrm{n}}$$

where now the subscripts p and n are for proton and neutron. From these four combinations of six unknown quark form factors, one has insufficient information to extract $G^s_{[E,M]}$.

Parity violating electron scattering measures a new pair of combinations which can be written as follows, using the Standard Model for the vector hadronic weak neutral currents:

$$G^{Zp}_{[E,M]} = (\frac{1}{4} - \frac{2}{3}\sin^2\theta_W)G^u_{[E,M]} + (-\frac{1}{4} + \frac{1}{3}\sin^2\theta_W)[G^d_{[E,M]} + G^s_{[E,M]}]$$

where the superscript Z stands for the Z^0 boson intermediary for the weak interaction. Thus by measuring these neutral weak form factors, in conjunction with the electromagnetic form factors, we can extract the strange quark contribution. The explicit dependence of the parity violating asymmetry on the strangeness content is written as follows in terms of the Sachs form factors, the Weinberg angle θ_W, Fermi constant G_F, fine structure constant α, and kinematic factors Q^2, ϵ, τ, and ϵ' [2]:

$$\begin{aligned} A^{PV}(\vec{e},P) &= -\frac{G_F|Q|^2}{4\pi\alpha\sqrt{2}} \times [(1-4\sin^2\theta_W) - \\ &\quad \frac{\epsilon G^p_E(G^n_E + G^S_E) + \tau G^p_M(G^n_M + G^S_M) - (1-4\sin^2\theta_W)\epsilon' G^p_M G^p_A}{\epsilon(G^p_E)^2 + \tau(G^p_M)^2}] \end{aligned}$$

The expression also contains a term with the neutral weak axial form factor G^p_A which is obtainable by combining information from neutron beta decay and polarized deep inelastic scattering [3]; it is suppressed in the HAPPEX kinematics and only contributes 2.4 ± 1.2%.

2 Experimental Technique

The experiment was performed in Hall A at the Thomas Jefferson National Accelerator Facility at an incident electron beam energy of 3.36 GeV and a Q^2 of 0.48 GeV^2/c^2, with a 100μA CW beam scattering elastically at $< \theta_{lab} > =$ 12.3° from a 15 cm long liquid hydrogen target. Figure 1 shows a layout of the experimental setup.

The polarized electron beam originated from photoemission from a GaAs crystal using a circularly polarized laser with a 30 Hz reversal frequency of the polarization line–locked to the 60 Hz frequency of AC power. The helicity was structured into pairs of 33.3 msec periods of opposite helicity, where the sign of the helicity of the first in the pair was determined pseudorandomly. We call these 33 msec periods "windows". The electrons were accelerated to 3.36 GeV in the Continuous Electron Beam Accelerator Facility (CEBAF). Because of the excellent stability of the beam and the small beam loading effects of the CW superconducting RF cavities, we are able to place strict limits on helicity correlated beam position differences, intensity differences, and energy differences. The window-to-window jitter in the intensity was typically 300 ppm and the window-to-window jitter in the position was a few microns.

In Hall A two identical 5.5 msr spectrometers situated at a 12.5° angle detected the scattered electrons in total-absorption detectors in their focal planes. With their 10^{-4} momentum resolution, the spectrometers focused inelastic events well away from our detectors. Custom-built electronics integrated and digitized the data from the focal-plane detectors, as well as analog signals from beam position and current monitors on the beamline.

A major challenge for measuring such small asymmetries is maintaining helicity correlated systematics at a level much smaller than the statistical error. Helicity correlated electronic cross–talk was monitored from voltage–source and current–source signals, and made a less than 2×10^{-8} systematic effect on our asymmetry. In controlling the electron beam systematics, the two goals were: 1) To make the two electron beams for the two helicities as identical as possible; and 2) To calibrate our apparatus by modulating the beam position, angle, and energy, thus allowing us to compute corrections due to these parameters.

To achieve the first goal, we applied a feedback loop on the helicity correlated charge asymmetry which averaged it below 1 ppm. To provide complete control over helicity correlated differences, one could imagine providing feedback on several parameters of the laser beam used to produce polarized electrons, such as the position and angle of the beam, and the Stokes parameters that define its polarization. However, for the HAPPEX experiment, feedback on the intensity alone was sufficient to maintain adequately small helicity correlations in the other parameters of the electron beam – the energy, position, and angle. For more precise future experiments, a more complete control of the optics may be necessary, as is foreseen for the E158 experiment at SLAC [4].

For the second goal of computing the systematic errors, we used a system of beam monitoring and beam modulation to compute corrections to the asymmetry due to the parameters of the beam. On the beamline was various instrumentation for measuring the beam position, current, and energy. We had two RF cavity beam current monitors (BCM) in Hall A, and several RF stripline beam position monitors (BPM) at positions upstream, downstream, and in the middle of the string of dipole magnets that transported the beam

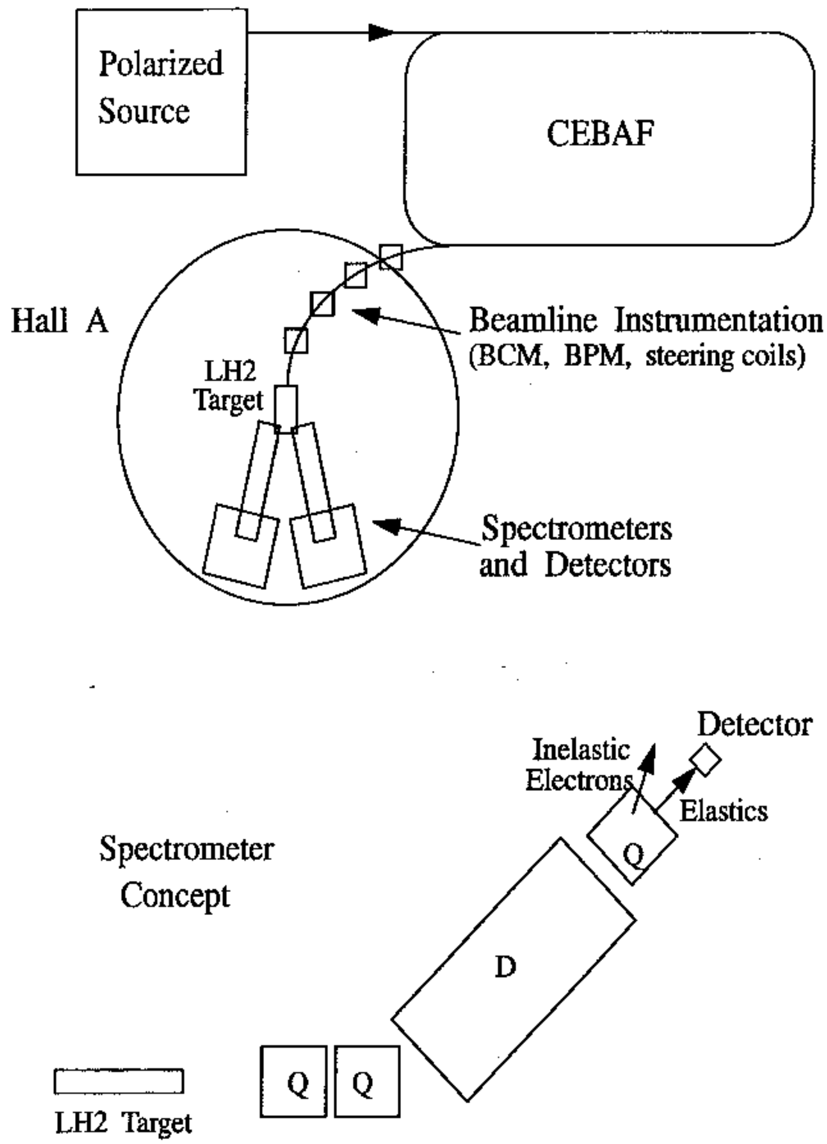

Figure 1: Layout of the HAPPEX experiment and spectrometer. The bottom plot shows the spectrometer QQDQ design, which focuses elastic events on our detector while inelastic events are well separated.

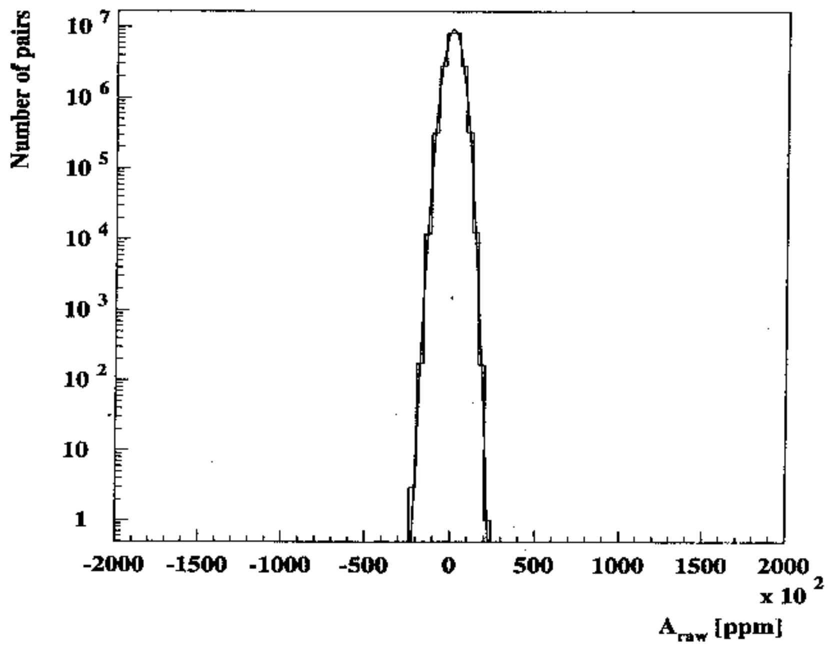

Figure 2: The parity violating asymmetry for events with $\geq 80\mu A$ beam on target

possible dipole scattering. The results of tests 3 and 4 for dipole scattering was that it contributes a less than 10^{-8} systematic error to our asymmetry.

The cuts applied to the data had negligible bias. Data were cut only when there was $\leq 3\mu A$ of beam current or when some equipment like magnets was not functioning.

Insertion of a half-wave plate in the laser beam was an important test of false asymmetries. The half-wave plate reverses the sign of the electron beam helicity, and hence the physics asymmetry, while leaving several other kinds of systematics such as electronic cross talk unchanged. The half-wave plate was inserted and withdrawn repeatedly during the experiment, and data taken in 1-2 day intervals with each state. Fig. 3 shows a clear correlation between the half-waveplate state and the raw asymmetry, for which the average was -5.64 $\pm$ 0.75 ppm. The beam polarization of 38.8 $\pm$ 2.7% was measured with into the hall. The energy was monitored with a BPM at a point of high dispersion in the middle of the string of dipoles. One needs two pieces of information to compute the systematic errors: the helicity correlated differences in these monitors, and the sensitivity (derivatives) of the apparatus to the beam parameters. To compute the sensitivity to position and angle, we had upstream of the dipole magnet string several dipole air-core steering coils for modulating the beam. In addition, we had an energy vernier, with which we made small adjustment to an RF accelerating cavity, for modulating the energy by $\pm 1.5 \times 10^{-4}$. These parameters were modulated by small amounts such that they did not add appreciably to our noise and we were able to perform these calibrations simultaneously with data taking. The helicity correlated position differences were less than 10 nm, and the corrections were negligible in the 1998 run.

In the 1999 run we have run with a strained GaAs crystal which produces higher polarization (typically 75%) but which has a higher analyzing power and produces larger asymmetries in the beam parameters. I will not present any results from 1999 because the data are still being taken. However, we can make the qualitative statement that the BPM differences in 1999 are typically larger than for the 1998 run which ran with unstrained GaAs.

Separate tests at lower beam energy where the scattered rate was higher were performed prior to the experiment to verify that fluctuations in the detected flux were dominated by counting statistics. Figure 2 shows the raw asymmetries measured in HAPPEX, and shows that the errors are statistical over 7 orders of magnitude; the width of the Gaussian is consistent with counting statistics.

Backgrounds were studied from the following tests: 1) The beam current was reduced so that the rates were a few hundred Hz, and the standard spectrometer tracking detector package was read out with events triggered on HAPPEX detector signals above a low threshold; 2) The spectrometer had been run in its standard configuration for several months prior to HAPPEX, during which time several e-P elastic calibration runs had been performed at various kinematics including nearby the HAPPEX kinematics. The result of tests 1 and 2 was that our main background comes from inelastically scattered electrons which rebound in the spectrometer and strike our detector. The correction to our asymmetry was 0.6 ± 1.7 %. 3) An e-P coincidence setup was used in which the proton spectrometer was used to tag where the electron went, and the proton spectrometer was moved to angles that select electrons which might hit the polarized iron in the dipole faces. The electron spectrometer detectors were read out in a bias-free way for each proton trigger. 4) Raytrace simulations were performed to study the rebounding of inelastics and the

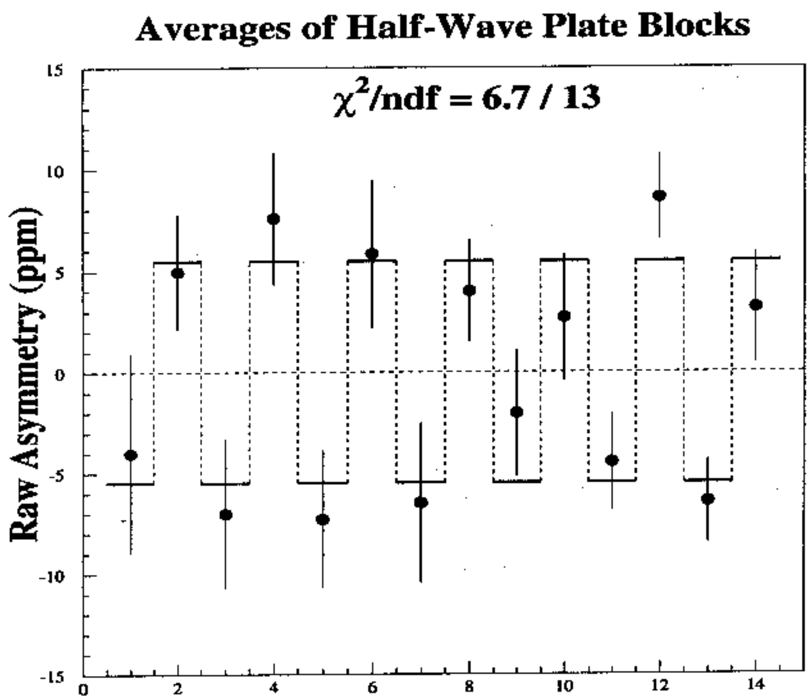

Figure 3: The parity violating asymmetry for different states of the half-waveplate.

a combination of a Mott scattering apparatus at the low energy end of the accelerator and a Møller apparatus in front of our target.

3 Results and Outlook

By dividing the raw asymmetry by the beam polarization, the resulting experimental asymmetry was $A = -14.5 \pm 2.0(\text{stat}) \pm 1.1(\text{syst})$ where the main systematic error came from the polarimetry. These results have been published in [5].

To extract the contribution of strange quarks, we compare our result with the theoretical expression using parameterizations of the electromagnetic form factors. The biggest uncertainty was in G_E^n for which we assumed a 50% experimental error corresponding to a 9.6% error in the asymmetry. For the other form factors, a dipole fit was used, and the uncertainty was about 4% in the asymmetry. Radiative corrections were applied. From our data we extract the following combination of strange form factors: $G_E^s + 0.39 G_M^s = 0.023 \pm 0.034(\mathrm{stat}) \pm 0.022(\mathrm{syst}) \pm 0.026(\delta G_E^n)$. We have listed the error due to G_E^n separately in anticipation of improvements in the accuracy of G_E^n.

This experiment rules out a large strangeness contribution but still allows for a few percent effect. While HAPPEX is sensitive mainly to the neutral weak *electric* form factor, the SAMPLE experiment at the MIT Bates Lab [6] was more sensitive to the neutral weak *magnetic* form factor. Together, the two experiments indicate that strange form factors are small at the moderate Q^2 where the experiments were performed. HAPPEX plans to reduce its error by a factor of 2 in 1999. Future parity experiments at Jefferson Lab will continue to probe the strange quark content of the proton. The Z^0 boson has additional uses which have been proposed for electron scattering, some examples being: 1) to measure the ratio of d to u quarks in deep inelastic scattering (see for example the discussion in [7]); and 2) to measure the neutron radius R_n in heavy nuclei [8]. Jefferson Lab, with its very stable beam conditions and excellent control of systematic errors, has a bright future for parity violation experiments.

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