Parity Violation in Forward Angle Elastic Electron Proton Scattering

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HAPPEX is a new experiment to probe the strange structure of the nucleon with parity violating electron scattering. We describe the physics motivation, provide an experimental overview and report on the results from the first data run. The asymmetry for the elastic scattering of 3.3 GeV electrons off target protons at a scattering angle of 12.5 degrees was measured to a precision of 15% of itself. The contribution from strange quark form factors was found to be zero within the experimental and theoretical uncertainties.

1. Physics Motivation

There has been considerable theoretical interest in the possibility that strange quark matrix elements among nucleon states are sizeable [1]. These speculations have been triggered by experimental measurements of the π-nucleon Σ term and measurements of nucleon spin dependent structure functions. One interpretation of these measurements are that strange quark scalar and axial vector matrix elements contribute to nucleon properties at the level of 10-15%.

A particularly clean experimental technique [2] for isolating the effects of strange quarks in the nucleon is measuring parity-violation amplitudes in the elastic scattering of polarized electrons from protons [3]. The theoretical asymmetry is given in the Standard Model by [4]

$$A_{\rm LR} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \times \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1-4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} G_A^{pZ}}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2} \tag{1}$$

where $G_E^{p\gamma}(G_M^{p\gamma})$ is the electric(magnetic) Sachs form factor for photon exchange, $G_{E,M}^{pZ}$ is the corresponding quantity for Z^0 exchange and θ_W is the electroweak mixing angle. All form factors are functions of Q^2 and ε, τ, and ε' are kinematic quantities [5].

To interpret the measurement of the asymmetry, $G_{E,M}^{p,Z}$ can be expressed in terms of proton, neutron, and strange form factors if the up(down) quarks in the proton have the same properties as the down(up) quarks in the neutron (assumption of isospin symmetry). If the electromagnetic form factors are sufficiently well known from experiment, the only unknown quantities involve strange form factors.

The HAPPEX experiment at the Thomas Jefferson National Accelerator Facility (Jlab) ran in April '98 with an incident electron energy of 3.356 GeV and a nominal scattering angle of 12.3°. For these kinematics, $\tau \sim 0.136$, $\varepsilon \sim .97$, $\varepsilon' \ll 1$ and the term involving

G_A^{pZ} contributes only a few percent relative to the other terms. The predicted asymmetry is on the order of 10 parts per million (ppm). The goal of the experiment is to determine if indeed the strange quark form factors are large enough to be an important part of any detailed description of the proton.

2. Description of the experiment

An overview of the HAPPEX apparatus in given in Figure 1. A $\sim 100\mu$A continuous-wave beam of electrons was scattered from a 15 cm long liquid hydrogen target. The polarized electron source, accelerator, instrumented beam line, target, spectrometers, and detectors are all central parts of the experiments that must be controlled to eliminate systematic errors that would overwhelm the $\sim$ 10 ppm measured asymmetry.

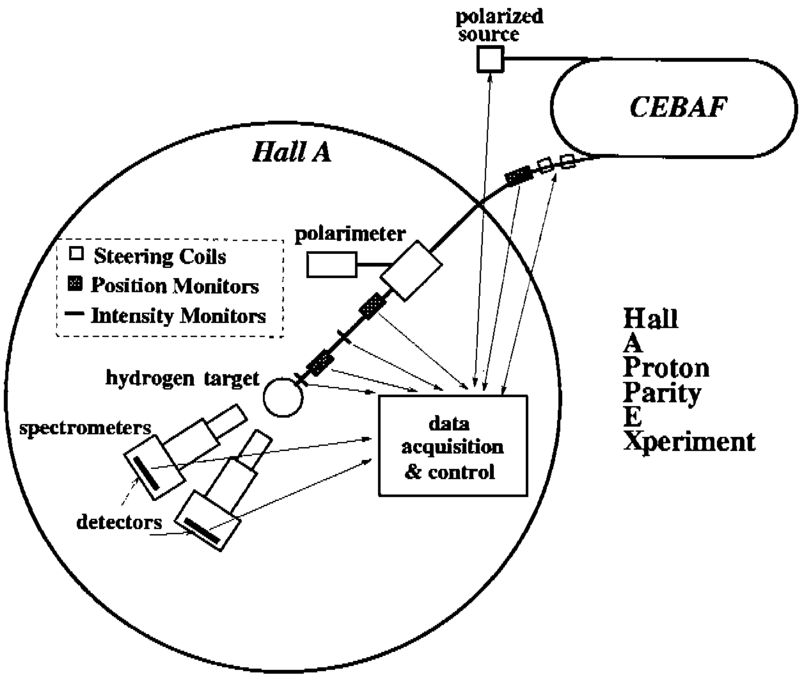

Figure 1. Overview of the HAPPEX experiment

The electrons which were scattered elastically at $\langle\theta_{lab}\rangle \sim \pm 12.3°$ were focussed by two identical high resolution 5.5 msr spectrometers onto a total-absorption detector made up of a lead-lucite sandwich. The spectrometers, which deflect the electrons by 45° out of the scattering plane, focus inelastic trajectories well away from our detectors. The signals form the Cerenkov detectors were integrated without introducing background.

The polarized electron beam originated from a bulk GaAs photocathode excited by circularly polarized laser light. The helicity of the beam was set every 33.3 ms locked to the 60 Hz frequency of the AC power in the lab. The helicity was structured as pairs helicity of the first window in each pair was determined by a pseudo-random number generator. All signals were integrated over a 32 ms gate which began ~ 1 ms after the start of each window. The output of the integrators was digitized by 16-bit customized analog to digital converters designed to minimize noise and crosstalk.

3. Physics Run

In April '98, the experiment ran for a total of 30 calendar days. The accelerator produced a stable beam of $\sim 40\%$ polarized electrons at an average current of $\sim 95\mu$A. The recorded data constituted a total of 78 C of electrons incident on the hydrogen target. In the following, we describe the salient features of the results. A paper describing these results has recently been published [6].

The data were taken is sets typically of 1-2 days duration. A $\lambda/2$ plate was inserted in the path of the laser beam for the odd sets. The $\lambda/2$ plate reverses the sign of the parity-violating signal while leaving many other systematic effects unchanged. The averages of the sets is plotted in Figure 2. There is a striking correlation between the sign of the signal and the presence of the $\lambda/2$ plate, a convincing signal of parity violation. No corrections have been applied to this data. The raw asymmetry A_{raw} is -5.64 ± 0.75 ppm.

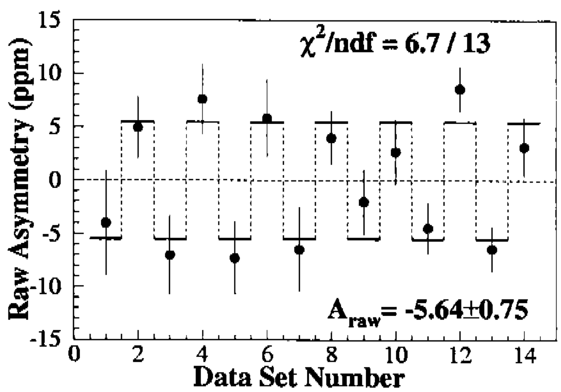

Figure 2. Raw asymmetry as a function of set number. ($\lambda/2$ plate inserted for odd sets.)

We took great pains to establish that the raw asymmetry is entirely due to parity violation and not due to correlations between the helicity of the beam and any other properties of the beam, such as intensity, energy, position, or angle. At JLab, the only quantity for which we found a non-zero helicity-correlated difference was beam intensity, which was measured with two independent RF cavities. The helicity correlation was reduced to less than 1 ppm by using a slow feedback system.

The position of the beam was measured at five locations with RF stripline monitors.

the accelerated beam made it easy to set stringent limits on any helicity-correlated beam parameters. Averaged over the entire run, limits on the position differences were typically on the order of a few nm. One of the position monitors was located at a point of high dispersion in the transport line and set a limit on the average helicity-correlated fractional energy difference at the 10^{-8} level. The effects of the helicity correlations on the measured asymmetry was evaluated by modulating seven different coils in the beam line and also modulating the beam energy. This was done simultaneously with production data taking.

The Q^2 of the data, averaged over the acceptance of the detector, was determined by the drift chambers to be 0.479 ± 0.003 $(\mathrm{GeV/c})^2$ by separate low-current runs that used tracking drift chambers in front of our detectors to study individual events. We tested the fact that the backgrounds from pole-tip scattering, etc., were low by also taking individual events at low beam current and using drift chambers.

The measured asymmetry is given by $A_{exp} = A_{raw}/P_e$, where P_e is the beam polarization. The beam polarization was measured in two ways. The first is Moller scattering with a spectrometer just upstream of our target. The second is Mott scattering at the 5 MeV point of the accelerator.

The Mott polarimeter was periodically used to measure the beam polarization during the entire duration of the run. The average value was 0.403. The overall fractional error is estimated to be 7%. The average polarization from the Moller polarimeter is 0.373. The Moller polarimeter was also used to verify that the electron polarization vector was parallel to the beam. For the final value of the polarization we use $P_e = 0.388 \pm 0.027$. This is the simple average of the two polarimeters with a 7% systematic error.

4. Implications and Outlook

With our value of P_e, we obtain the experimental asymmetry:

$$A_{exp} = 14.5 \pm 2.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})(ppm).$$

In order to obtain information about strange quarks from this data, we must use values for the known form factors in the theoretical formula for A_{th} [4]. Any difference may be attributed to the presence of strange form factors. We use the function due to Galster [7] for G_E^n. The difference between the real value and the Galster value is indicated by δG_E^n with error ΔG_E^n. ΔG_E^n is estimated to be about 50% of the Galster function, contributing a 9.6% error to A_{th}. We will leave this as a separate error since it is significant and since experiments in progress should improve the value of δG_E^n.

The dipole parameterization is taken as a reasonable approximation at our Q^2 for the other form factors: $G_E^p = G_D$, $G_M^p = \mu_p G_D$, and $G_M^n = \mu_n G_D$ [4], where $G_D = (1 + 4.97\tau)^{-2}$. This introduces an uncertainty in the predicted asymmetry of about 4% of itself. Radiative corrections [4] are known and only on the order of a few percent of the asymmetry. The G_A^Z term has a large radiative correction, $\sim$ 50% of itself, but for our kinematics, this term contributes only a few percent. The theoretical prediction with these assumptions and no strange quarks is

$$A_{th} = -15.8 \pm 0.7 \pm 1.5(\delta G_E^n)\mathrm{ppm}.$$

Table 1
Summary of contributions to the errors for A_{raw}, A_{exp}, and A_{th}.

A	Source of error	$\Delta A/A(\%)$
A_{raw}	Statistics	13.4
	Others	<0.3
A_{exp}	Beam Polarization	7
	Q^2 Determination	1
	Backgrounds	2
A_{th}	Nucleon Form Factors (excluding G_E^n)	4.0
	Radiative Corrections	1.4
	G_E^n	9.6

The breakdown of the various sources of errors to the experimental asymmetry and the theoretical prediction are tabulated in Table 1. The significance of our experiment can be evaluated in terms of representative model calculations for $\delta A = (A_{exp} - A_{th})/A_{th}$. This is done in Fig. 3. Our data point is plotted under the assumption that δG_E^n is negligible. The largest of the predictions are excluded by our data. Previous data sensitive to different combinations of the form factors and at different Q^2 values are also consistent with the absence of strange quarks, but at a somewhat less sensitive level [5,8]. We can extract the combination of strange form factors at $Q^2 = 0.48$: $G_E^s + 0.39G_M^s = 0.023 \pm 0.034$ (stat) ± 0.022 (syst) ± 0.026 (δG_E^n).

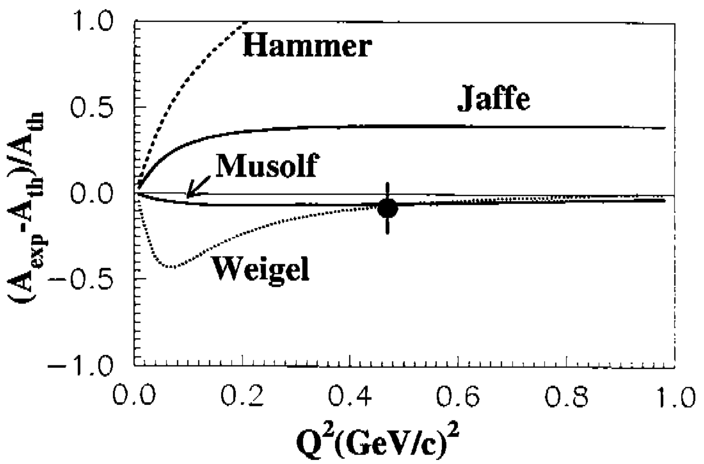

Figure 3. Experimental $\delta A/A$ assuming $\delta G_E^n = 0$, together with several representative calculations. For papers that did not include the Q^2 dependence, a dipole form is assumed [4]

We plan to improve our precision by a factor of 2 in 1999. Improvements in G_E^n will be important for us to extract useful information. Although we have ruled out some of the more generous predictions, it is important to pursue the subject further. Expanding the Q^2 range is important, as well as separating G_E^s from G_M^s, by varying the kinematics, by using an isoscalar target such as ^{4}He and by measuring the asymmetry in quasi-elastic scattering off ^{2}H.

Acknowledgments

The high quality of the beams provided by this new facility is invaluable for the performance of precision experiments. We wish to thank the entire staff of Jlab and the Hall A collaboration for their tireless work in preparing the electron beam and the experimental apparatus. We also wish to thank the organizers of INPC98 for a very stimulating and enjoyable meeting.

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