Abstract

Recently, there has been considerable theoretical interest in determining strange quark contributions to hadronic matrix elements. Such matrix elements can be accessed through the nucleon’s neutral weak form factors as determined in parity violating electron scattering. The SAMPLE experiment will measure the strange magnetic form factor $G_M^s$ at low momentum transfer. By combining measurements from hydrogen and deuterium the theoretical uncertainties in the measurement can be greatly reduced and the result will be limited by experimental errors only. A summary of recent progress on the SAMPLE experiment is presented.

INTRODUCTION AND BACKGROUND

Elastic electron scattering has successfully been used as a probe of nucleon structure for many years. The electromagnetic properties of the proton are now very well known \cite{1}, and recently there has been considerable progress in measuring the electric and magnetic form factors of the neutron \cite{2,3}. Additional and complementary information on nucleon structure can be obtained through the use of neutral weak probes. For example, there has been much recent theoretical interest in the possibility that sizeable strange quark contributions to nucleon matrix elements may exist. The two most cited pieces of experimental evidence are measurements of the $\pi$-nucleon $\Sigma$ term, from which the scalar matrix element $\langle N|\bar{s}s|N \rangle$ can be obtained \cite{4}, and measurements of the nucleon’s spin-dependent structure functions in deep-inelastic lepton scattering \cite{5}, from which the axial current $\bar{s}\gamma_\mu\gamma_5s$ is extracted. In
each case the $s$-quark contribution to the proton is about 10-15%, although both results are sensitive to theoretical interpretation.

Parity violating electron scattering provides the opportunity to investigate the vector matrix element $\langle N|\bar{s}\gamma^\mu s|N\rangle$. This matrix element can be determined directly from a measurement of the neutral weak form factor of the proton, i.e., the interaction between a proton and electron through the exchange of a $Z$ boson. The electromagnetic and weak form factors can be constructed as a sum of individual quark distribution functions multiplied by coupling constants given by the Standard Model for Electroweak Interactions. The lepton currents are completely determined, and the hadronic currents are the information to be extracted by experiment. The electromagnetic coupling gives the well known Sachs form factors $G_{E,M}^p, G_{E,M}^n$. Neglecting quarks heavier than the $s$-quark and making the assumption that the proton and neutron differ only by the interchange of $u$ and $d$ quarks, the neutral weak vector form factors can be expressed in terms of the EM form factors in the following way:

$$G_{E,M}^{Z,p} = \left(\frac{1}{4} - \sin^2 \theta_W\right) [1 + R^p_V] G_{E,M}^p - \frac{1}{4} [1 + R^p_V] G_{E,M}^n - \frac{1}{4} [1 + R^s_V] G_{E,M}^s$$

$$G_{E,M}^{Z,n} = \left(\frac{1}{4} - \sin^2 \theta_W\right) [1 + R^p_V] G_{E,M}^n - \frac{1}{4} [1 + R^p_V] G_{E,M}^p - \frac{1}{4} [1 + R^s_V] G_{E,M}^s$$

The factors $R^i_V$ are weak radiative corrections which must be applied to account for higher order processes. In addition there is an axial vector coupling which leads to

$$G_A^Z = -\frac{1}{2} [1 + R_A^{T=1}] g_A \tau_3 + \frac{\sqrt{3}}{2} R_A^{T=0} G_A^{(8)} + \frac{1}{4} [1 + R_A^s] G_A^s$$

where $\tau_3 = +1(-1)$ for the proton(neutron).

The term involving the SU(3) isoscalar form factor $G_A^{(8)}$ is generally ignored since it is not present at tree level, and an estimate of $R_A^{T=0}$ that it is in fact suppressed relative to the dominant first term. The isovector axial form factor $g_A(0)=1.26$ is determined from neutron beta decay. With the exception of $G_E^n$, the electromagnetic form factors are determined with good precision. The axial strange form factor $G_A^s$ is the same quantity extracted from polarized deep inelastic lepton scattering. The only undetermined quantities are the strange quark contributions $G_{E,M}^s$. At $Q^2=0$, $G_E^s=0$ because the proton has no net strangeness. The magnetic form factor $G_M^s(0)$ is not well constrained, and the $Q^2$ dependence of all three strange form factors is unknown. This has stimulated a program of parity violation experiments at Bates [7,8], CEBAF [9–11] and Mainz [12].

Since these experiments were proposed several years ago, many theoretical predictions have been put forth to estimate the size of the $s$-quark contributions. The vector contributions are characterized by two parameters: the “strange magnetic moment” $\mu_s = G_M^s(0)$, and the “strangeness radius” $r_s^2 = -\frac{1}{6} \frac{dF_s}{dQ^2}$. Predictions of the various models, which range from vector-meson dominance-like mechanisms to Skyrme calculations to those involving
TABLE I. Theoretical predictions for $G_M^s(0)$ and $r_s^2$, after Musolf et al. [1] with recent additions.

| Type of Calculation (reference) | $\mu_s$ | $r_s^2$ (fm$^2$) |
|----------------------------------|---------|------------------|
| Poles [14]                      | $-0.31 \pm 0.009$ | $0.14 \pm 0.07$ |
| Poles [15]                      | $-0.24 \pm 0.03$  | $0.21 \pm 0.03$  |
| Kaon Loops [16]                 | $-0.40 \rightarrow -0.31$ | $-0.03 \pm 0.003$ |
| Kaon Loops [17]                 | $-0.03$  | $-0.01$ |
| “Loops and Poles” [18]          | $-0.28 \pm 0.04$ | $-0.03 \pm 0.01$ |
| SU(3) Skyrme [19]               | $-0.33 \rightarrow -0.13$ | $-0.11 \rightarrow -0.19$ |
| SU(3) chiral hyperbag [20]      | $0.42 \pm 0.30$  |                 |
| SU(3) chiral color dielectric [21] | $-0.40 \rightarrow -0.03$ | $-0.003 \pm 0.002$ |
| Chiral quark-soliton [22]       | $-0.45$  | $-0.17$ |
| Constituent Quark [23]          | $-0.13 \pm 0.01$ | $-0.002$ |
| “QCD Equalities” [24]           | $-0.73 \pm 0.30$ | |

kaon loop diagrams, were described in detail in references [6] and [13] and an updated list is shown in Table I. A notable point is that although different models have similar predictions for the magnitude of $\mu_s$, (with a few exceptions) the estimates of $r_s^2$ vary widely depending on the type of mechanism assumed.

**PARITY-VIOLATING ELECTRON SCATTERING AT MIT-BATES**

Parity violating electron scattering is evaluated in terms of the asymmetry in the cross section for the scattering of right- and left-helicity electrons from an unpolarized target. For elastic scattering from a free nucleon, the asymmetry can be written as a sum of three terms which reflect the interference between the NW and EM interactions:

$$A_p = \left[ \frac{G_F Q^2}{\sigma_p \pi \alpha \sqrt{2}} \right] \left[ \varepsilon G_E^p G_E^p \tau G_M^p G_M^p - \frac{1}{2} \left( 1 - 4 \sin^2 \theta_W \right) \varepsilon' G_M^p G_A^p \right], \quad (4)$$

$$A_n = \left[ \frac{G_F Q^2}{\sigma_n \pi \alpha \sqrt{2}} \right] \left[ \varepsilon G_E^n G_E^n + \tau G_M^n G_M^n - \frac{1}{2} \left( 1 - 4 \sin^2 \theta_W \right) \varepsilon' G_M^n G_A^n \right], \quad (5)$$

where $\tau = Q^2 / 4 M_p^2$, $\varepsilon = \left( 1 + 2(1 + \tau) \tan^2 \frac{\theta_W}{2} \right)^{-1}$ and $\varepsilon' = \sqrt{(1 - \varepsilon^2) \tau (1 + \tau)}$. The terms $\sigma_{p,n} = \varepsilon (G_E^{p,n})^2 + \tau (G_M^{p,n})^2$ are proportional to the elementary unpolarized cross sections. The kinematic factors result in the first two terms of the asymmetry dominating at forward angles and the latter two terms contributing at backward angles, although the term containing the axial vector form factor $G_A^p$ is suppressed by the factor $(1 - 4 \sin^2 \theta_W)$. 


The SAMPLE experiment at Bates [7] is a measurement of $A_p$ at backward angles ($130^\circ < \theta < 170^\circ$) and $E_{lab} = 200$ MeV, resulting in $Q^2 = 0.1$ (GeV/c)$^2$. At these kinematics the parity violating asymmetry for a proton target is $-7.3 \times 10^{-6}$, assuming no contribution from $s$-quarks, and is dominated by the middle term and thus is sensitive to $G_M^s(0)$. The SAMPLE goal is to achieve a statistical error of approximately 7%. The dominant experimental systematic error is expected to come from knowledge of the beam polarization. Recently, Garvey et al. reanalyzed quasielastic $\nu(\tau)-p$ scattering data from BNL experiment E734 [25], and extracted a value of $G_M^s(0) = -0.4 \pm 0.7$ with some model dependence, extrapolating the result from $Q^2 \sim 0.75$ (GeV/c)$^2$. The SAMPLE experiment would improve this result by a factor of 3, to an absolute error of $\delta G_M^s = 0.22$.

Update on the SAMPLE Experiment

In the SAMPLE experiment, polarized electrons are incident on a 40 cm long liquid hydrogen target. Elastically scattered electrons are detected in the backward direction by a large solid angle air Čerenkov detector consisting of ten mirrors which image the target onto ten 8 inch photomultiplier tubes. The average current of the beam is typically 40 $\mu$A, delivered with a 1% duty cycle at 600 Hz. The counting rate in each photomultiplier tube is very high, so individually scattered electrons are not detected but the signal is integrated over the 15 $\mu$sec beam pulse and normalized to the charge in each burst. Background is measured independently with empty target runs and by closing shutters in front of the phototubes. In figure 1 is shown a typical normalized yield distribution and a bar plot representing the contributions of the light yield from hydrogen (dots), the background from hydrogen (vertical lines), and background from the target cell (slanted lines), and the beam line (solid).

In September 1995 the first substantial data taking with polarized beam was carried out. Approximately 76 hours of high quality asymmetry data were acquired, corresponding to a statistical error of 0.5 ppm. Analysis of the data is in progress to understand and minimize the most important systematic errors before beginning a long experimental run in spring 1996. Some features of the data are discussed below.

The polarized beam is delivered to the SAMPLE apparatus at a maximum repetition rate of 600 Hz. Circularly polarized laser light from a Titanium-sapphire laser is incident upon a crystal made of bulk GaAs, from which an electron beam of approximately 40% polarization is extracted. The circularly polarized light is generated by a linear polarizer followed by a Pockels cell which acts as a quarter wave plate when the appropriate voltage is applied. The helicity of the electron beam is flipped by reversing the polarity of the voltage on the Pockels cell. In addition, a linear polarizer plate can be manually rotated in the laser beam to reverse the polarity independently of the Pockels cell. The beam control and data acquisition are based upon the system used in previous parity violation measurements at Bates [26], where a systematic error $2 \times 10^{-8}$ was reported. The beam helicity is chosen randomly on a pulse-by-pulse basis, except that pulse pairs 1/60 sec apart have opposite
FIG. 1. (a) Representative histogram showing normalized yield in one phototube. (b) Bar plot showing contributions from various sources to normalized yield. The different contributions are: light yield from hydrogen (dots), background from hydrogen (vertical lines), background from the target cell (slanted lines), and from the beam line (solid).

helicity. “Pulse-pair” asymmetries are formed every 1/30 sec, greatly reducing sensitivity to 60 Hz electronic noise and to drifts in beam properties such as current, energy, position and angle, which generally occur on time scales much longer than 1/30 sec. In each 1/30 sec measurement period, there are ten calculated asymmetries (in each of the ten “time-slots” of the 600 Hz beam for each of the ten mirror signals, so that a half-hour run contributes $5 \times 10^6$ separate measurements of a pulse-pair asymmetry. Shown in figure 2(a) is a typical distribution of asymmetries measurements for one mirror in a half-hour run. The width is about 1%, consistent with the expected counting statistics per beam pulse.

The electron beam deposits approximately 550 watts of power into the target. Density fluctuations are minimized by subcooling the liquid below its boiling point by a few degrees and by rapidly circulating the fluid in a closed loop such that a packet of hydrogen is in the path of the beam for only a short time. No density reduction was seen in the normalized yield at the level of a few percent as the beam current was varied between 4 to 40 µA. Fluctuations in the normalized yield due to variations in beam properties limit the accuracy with which this observable can be used to determine density changes. A more sensitive determination is to monitor the width of the pulse-pair asymmetry. In this observable no change in density was seen at the level of 1% or better.

Helicity correlations in the beam properties can cause parity-conserving asymmetry contributions to the data. The raw measured asymmetry $A_{\text{raw}}$ must be corrected for these
effects. The corrected asymmetry $A_c$ can be expressed as

$$A_c = A_{raw} - \frac{1}{S} \sum_i \frac{\partial S}{\partial \alpha_i} \delta \alpha_i^{LR},$$

(6)

where $S$ is the normalized detector yield, $\alpha_i$ is one of five beam parameters (position and angle in $x$ and $y$, and energy), and $\delta \alpha_i^{LR} = \alpha_i^R - \alpha_i^L$ is the helicity correlated difference in the beam parameter. To first order, the experiment is designed to be as insensitive as possible to fluctuations in beam properties. This includes feedback loops to stabilize the beam energy and position on target. The corrections are then made with measured helicity correlations in the beam and the measured detector sensitivity to beam properties. The latter is performed by systematically changing the position and angle of the beam on target with a system to rapidly control two sets of steering coils and by changing the energy of the beam rapidly with an RF phase-shifting apparatus. The sensitivity of the asymmetry to beam position differences was typically 1% per mm. The coil-pulsing system also allows us to minimize the background in the detector as a function of beam location. In the experiment of reference [26] it was determined that the largest source of beam fluctuations originated in the transport of the laser beam. A feedback loop between beam charge asymmetry and Pockels cell voltage minimizes helicity correlations due to the laser beam. Figure 2(b) shows the beam charge asymmetry at the exit of the accelerator.

![Graph 1](image1.png)

![Graph 2](image2.png)

**FIG. 2.** (a) Representative histogram of pulse-pair asymmetries in one mirror for one 1/2 hour run. (b) Beam charge asymmetry at the end of the Bates accelerator for the duration of the fall 1995 run.

Analysis of the data is presently underway. Asymmetries on the order of 100 ppm or larger in the beam charge were seen and found to be due to problems with the laser feedback
system, which were repaired part way through the run. These data have been removed from figure 2(b). Helicity correlated shifts in the beam position at the target of 200 nm (vertical) and 200-600 nm (horizontal) were also found throughout the run and are under investigation. The feedback loop on beam position on target was commissioned, and an additional feedback loop on beam energy was developed and will be tested in the upcoming run.

Deuterium

At the SAMPLE kinematics the contribution from the axial vector term \( G_M G_A^Z \) is about 20%. The weak radiative correction to this term \( R_T^{A=1} \) has been estimated to be \(-0.34 \pm 0.28\) [27]. This leads to a theoretical limit on the ultimate uncertainty in the experimental result corresponding to \( \delta G_M^s \sim \pm 0.12 \). A direct measure of this radiative correction would therefore be useful. In quasielastic scattering from deuterium at the same kinematics, the axial term contributes approximately the same amount to the asymmetry as in the proton, but the contribution from the term proportional the \( G_s M \) is greatly reduced because the proton and neutron contributions add incoherently and nearly cancel. Taking the ratio \( A_p/A_d \) would as a result reduce the theoretical error to \( \delta G_M^s \sim \pm 0.01 \). The ratio \( A_p/A_d \) would be insensitive to systematic errors in the measured beam polarization. At the SAMPLE kinematics the expected value of the deuteron asymmetry is \( A_d = -9.6 \times 10^{-6} \) and the counting rate is about twice that for the proton. The only required modification to the SAMPLE apparatus is a recovery system for the costly deuterium. In 1994 an additional 1000 hours of beam time was approved for a deuteron measurement [3].

In the “static” approximation, the deuteron asymmetry can be written as an incoherent sum of contributions from the proton and neutron weighted by the unpolarized cross sections:

\[
A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_d}.
\]  

Hadjimichael, Poulis and Donnelly investigated the dependence of \( A_d \) on the structure of the deuteron [28] and found that is insensitive to corrections to the static model at the level of 1-2%.

Because the SAMPLE detector has no energy resolution, the measured deuteron asymmetry includes contributions from elastic \( e-d \) scattering and from electrodisintegration. The elastic asymmetry \( A_{el} \) at backward angles was estimated by Pollock [29] to be very sensitive to \( G_M^s \). The electrodisintegration asymmetry \( A_{ted} \), as well as other small contributions from elastic scattering, was calculated by Musolf and Donnelly [30]. Fortunately, all of these contributions are small because the scattering is greatly dominated by the quasielastic cross section. The resulting contribution to the measured asymmetry can be summarized as:

\[
A_{tot} = \frac{1}{\sigma_{tot}} [A_{QE} \sigma_{QE} + A_{el} \sigma_{el} + A_{ted} \sigma_{ted}]
\]

\[
= (-9.6) \left( \frac{47}{52} \right) + (10.3) \left( \frac{1}{52} \right) + (-12.8) \left( \frac{4}{52} \right)
\]

\[
= -9.5 \text{ ppm}.
\]
The degree to which the deuteron measurement will improve the determination of $G_s^M(0)$ can be summarized in figure 3. The solid lines in the left-hand graph show the constraints on $G_s^M(0)$ that would result from the $A_p$ alone. The result is clearly correlated with $R_A^{T=1}$. The dashed lines represent the calculation of $R_A^{T=1}$ by Musolf and Holstein along with the estimated uncertainty. In the right panel is shown the sensitivity of a measurement of $A_d$ (solid lines) which is nearly independent of $G_s^M$, and the ratio $A_p/A_d$ (dashed lines), which is nearly independent of $R_A^{T=1}$. The ellipse represents the resulting constraints.

**FIG. 3.** Left Panel: expected $1\sigma$ limits on $G_s^M$ from hydrogen measurement alone. Right Panel: $\sigma$ limits on $R_A^{T=1}$ and $G_s^M$ from a combined measurement of hydrogen and deuterium.

**CONCLUSIONS**

Theoretical interest in understanding the role of strange quarks in the nucleon has stimulated a new generation of experiments in parity-violating electron scattering and also in neutrino scattering [31]. Currently very little information is known. Considerable progress was made in 1995 on the SAMPLE experiment at Bates, and a long data-taking run on the proton is expected to occur in 1996. Additional running with a deuterium target has also been approved.

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