Experimental Status of Parity Violating Electron Scattering

E.J. Beise

for the SAMPLE collaboration

University of Maryland, College Park, MD, USA

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. A program of experiments is presently underway or planned at the MIT-Bates, Mainz and Jefferson Laboratories. The SAMPLE experiment at MIT-Bates will measure the strange magnetic form factor $G_M^s$ at low momentum transfer. Two data taking periods have recently been completed, representing about 15% of the desired data on hydrogen. A summary of recent progress on the SAMPLE experiment is presented, along with future plans at Jefferson Lab.

INTRODUCTION

Elastic electron scattering has been used as a probe of nucleon structure for many years. The electromagnetic properties of the proton are very well known, and recently there has been considerable progress in measuring the electric and magnetic form factors of the neutron [1,2]. Additional and complementary information on nucleon structure can be obtained through the use of neutral weak probes [3]. 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 $\langle N|s\Sigma|N\rangle$ can be obtained [4], and measurements of the nucleon’s spin-dependent structure functions in deep-inelastic lepton scattering [5], from which the axial current matrix element $\bar{s}\gamma_\mu\gamma_5s$ is extracted. In each case the $s$-quark contribution to the proton is about 10-15%, although both results are sensitive to theoretical interpretation.

With parity violating electron scattering it is possible to investigate the vector matrix element $\langle N|\bar{s}\gamma_\mu s|N\rangle$ through 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 [6]. 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 $G_{E,M}^{p,n}$. 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 strange quark contribution to the proton magnetic form factor $G_M^s$ can be calculated. The SAMPLE experiment at MIT-Bates will measure $G_M^s$ at low momentum transfer, with two data taking periods recently completed, representing about 15% of the desired data on hydrogen. A summary of recent progress on the SAMPLE experiment is presented, along with future plans at Jefferson Lab.
d quarks, the neutral weak vector form factors for the proton can be expressed in terms of the EM form factors in the following way:

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

(1)

The factors \( R_i^V \) are weak radiative corrections which must be applied to account for higher order processes. In addition the axial vector coupling leads to

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

(2)

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 turns out that it is not present at tree level, and an estimate of \( R_A^{T=0} \) [7] shows that it is 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 [8] Jefferson Lab (formerly CEBAF) [9] and Mainz [10]. These experiments represent the first generation attempt at determining the matrix element \( \sigma_{\gamma \mu s} \) in the proton, and many theoretical predictions have been put forth to estimate its size. Near \( Q^2=0 \), it can be characterized by two parameters: the “strange magnetic moment” \( \mu_s = G_M^s(0) \), and the Sachs “strangeness radius” \( r_s^2 = -\frac{1}{6} \frac{dG_M^s}{dQ^2} \). Predictions of various models are listed in table I. A notable point is that although several models have similar predictions for the magnitude of \( \mu_s \sim -0.3 \), the estimates of \( r_s^2 \) vary widely depending on the type of mechanism assumed.

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 proton, the asymmetry consists of three terms which reflect the interference between the NW and EM interactions:

\[ A_p \left[ \sigma_p \pi \alpha \sqrt{2} \right] \left[ \varepsilon G_E^p G_{Z,p} + \tau G_M^p G_{Z,n}^{\pi} - \frac{1}{2} \left( 1 - 4 \sin^2 \theta_W \right) \varepsilon' G_M^p G_{Z,A} \right], \]  

(3)

where \( \varepsilon = \left( 1 + 2(1+\tau) \tan^2 \frac{\theta}{2} \right)^{-1} \) and \( \varepsilon' = \sqrt{(1-\varepsilon^2) \tau (1+\tau)} \). The elementary unpolarized cross section is proportional to \( \sigma_p = \varepsilon \left( G_E^p \right)^2 + \tau \left( G_M^p \right)^2 \). 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 \( G_{Z,A} \) is suppressed by the factor \( (1-4 \sin^2 \theta_W) \).
Table 1: Theoretical predictions for $G_M^s(0)$ and the Sachs radius $r_s^2$, after Musolf et al., [7] with some recent additions.

| Type of Calculation (reference) | $\mu_s$         | $r_s^2$ (fm$^2$) |
|--------------------------------|-----------------|-----------------|
| Poles [11]                     | $-0.31 \pm 0.009$ | $0.14 \pm 0.07$ |
| Poles [12]                     | $-0.24 \pm 0.03$  | $0.21 \pm 0.03$  |
| Kaon Loops [13]                | $-0.40 \rightarrow -0.31$ | $-0.03 \pm 0.003$ |
| Kaon Loops [14]                | $-0.03$           | $0.01$           |
| “Loops and Poles” [15]         | $-0.28 \pm 0.04$  | $-0.03 \pm 0.01$  |
| SU(3) Skyrme [16]              | $-0.33 \rightarrow -0.13$ | $-0.11 \rightarrow -0.19$ |
| SU(3) chiral hyperbag [17]     | $0.42 \pm 0.30$   |                 |
| SU(3) chiral color dielectric [18] | $-0.40 \rightarrow -0.03$ | $-0.003 \pm 0.002$ |
| Chiral quark-soliton [19]      | $-0.45$           | $0.17$           |
| Constituent Quarks [20]        | $-0.13 \pm 0.01$  | $-0.002$         |
| “QCD Equalities” [21]          | $-0.73 \pm 0.30$  |                 |

THE SAMPLE EXPERIMENT at MIT-BATES

SAMPLE [8] 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 is sensitive to $G_M^s(0) = \mu_s$ and, if $\mu_s = 0$, is $-7.6 \times 10^{-6}$ (-7.6 ppm). The goal of the experiment is to achieve an absolute experimental error of $\delta \mu_s \sim 0.22$, which requires $\sim$150 Coulombs of polarized beam on a 40 cm 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, as shown in figure 1. The average beam current 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 by closing shutters in front of the phototubes and with empty target runs. It is also necessary to determine the contribution to the light yield which does not come from Čerenkov light, which is performed in two ways. First, runs are taken with the mirrors covered leaving the phototube shutters open. Additionally, data is taken with nine out of ten pulses from the accelerator reduced by several orders of magnitude so that individually scattered electrons can be detected in coincidence with photons incident on the phototube. The tenth pulse is used as a “tracer bullet” to directly compare the ordinary detector signal to the “pulse-counting” signal.

The two most dominant sources of light-producing background are (a) scintillation light generated in the air from particles producing EM showers in the target.
and (b) Cerenkov light arising from Michel positrons due to $\pi^+$ photoproduction in the target. (Due to the low beam energy, inelastically scattered electrons are a negligible contribution.) The former source is assumed to have zero asymmetry because they are low-momentum transfer EM processes. The asymmetry of the latter source has been estimated to be very small ($\sim 1 \times 10^{-7}$) [22]. At present it appears that elastic scattering comprises at least 50% of the light yield. A detailed breakdown of these contributions will result from further simulations and data analysis which are currently in progress. Additional shielding should remove the Michel positrons and thus increase the relative contribution of elastic events to the light yield in future runs.

Circularly polarized laser light from a Titanium-sapphire laser is incident upon a bulk GaAs crystal, from which an electron beam of approximately 35% 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. The beam helicity is chosen randomly on a pulse-by-pulse basis, except that pulse pairs 1/60 sec apart have opposite 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. In addition, a $\lambda/2$ plate can be manually rotated upstream of the Pockels cell to manually reverse the polarization of the beam independent of all electronic signals.

The electron beam deposits approximately 550 watts of power into the liquid hydrogen 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, and in this observable no change in density was seen at the level of much better than 1% [23].

If helicity correlations are present in the beam properties they will cause false asymmetry contributions to the data. The raw measured asymmetry $A_{raw}$ must be corrected for these effects. The corrected asymmetry $A_c$ can be expressed as

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

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, as well as a feedback loop between the beam charge asymmetry in the accelerator and the Pockels cell voltage. With this, the helicity correlations due to the beam intensity are reduced from 100-200 ppm to $\sim$1ppm or less. The corrections to the asymmetry are then made with measured helicity correlations in the beam and the measured detector sensitivity to beam properties as determined from the natural long term drifts in the beam. Other properties such as helicity correlated differences in beam size are studied with dedicated runs in between data taking and appear to be negligible.

Two running periods have now been completed for SAMPLE, one in fall 1995 and the other in spring 1996, totalling about 21 Coulombs of good data. (requiring any individual correction to the data be less than 1 ppm). Figure 2 shows the asymmetry in (a) beam current, (b) horizontal beam position for all good data. The open symbols ("NORMAL") are runs with the normal orientation of the $\lambda/2$ plate and the closed points ("REVERSE") are with the helicity manually reversed. In Panel (c) is the raw detector asymmetry, and in (d) the asymmetry after corrections due to helicity correlations in the beam are applied.

The SAMPLE beam line is at an angle with respect to the accelerator, which will cause the electron spin to precess by 16.7° from longitudinal. The beam spin can be made longitudinal at the SAMPLE target by preparing the spin off-axis at the injector with a Wien filter. Nonetheless, any remaining small transverse component in the beam will result in a parity conserving Mott asymmetry if the detector is not perfectly azimuthally symmetric. The Mott asymmetry was measured by preparing the electron beam in its two possible transverse states ($\phi=0°$ and $\phi=90°$). The Mott contribution to the full detector physics asymmetry was determined to be consistent with 0 at the level of 0.5 ppm.

Analysis of the 1996 data set is presently underway. Combining all of the good
Figure 2: Measured asymmetries in (a) beam intensity and (b) horizontal beam position, and the detector asymmetry (c) before and (d) after corrections due to helicity correlated beam properties are applied.

data from 1995 and 1996, each shown in figure 3, results in a physics asymmetry that is approximately of the same magnitude as the expected PV asymmetry of about -6 ppm. At present the statistical error on the data results in an error on $\mu_s$ of ±0.4.

At the SAMPLE kinematics the contribution from the axial vector form factor term $G_A^Z$ is about 20%. The weak radiative correction to this term $R_T^{A=1}$ has been estimated to be $-0.34 \pm 0.34$ [24]. This leads to a theoretical limit on the ultimate uncertainty in the experimental result corresponding to $\delta G_M^s \sim \pm 0.18$. A direct measure of this radiative correction would therefore be useful. This can be achieved by measuring the asymmetry in quasielastic scattering from deuterium at the same kinematics, and taking the ratio $A_p/A_d$ would as a result reduce the theoretical error to $\delta G_M^s \sim \pm 0.02$. Running with deuterium is planned in the future.

JEFFERSON LAB EXPERIMENTAL PROGRAM

At higher beam energies and forward angles one has the possibility of obtaining information on the $Q^2$ dependence of the strange form factors, although an explicit extraction of $G_E^s(Q^2)$ from $e-p$ scattering also requires good knowledge of neutron electromagnetic properties. Measurements of PV $e-p$ scattering are planned for Jefferson Lab and Mainz. (For a description of the latter, see the contribution by F. Maas to these proceedings.)
Figure 3: Preliminary results for the parity violating asymmetry from the 1995 and 1996 SAMPLE running periods. The error bars include an estimate of the systematic uncertainty due to background processes.

Experiment E91-010 at Jefferson Lab will measure $A_{PV}$ in the proton at $Q^2 = 0.5 \text{(GeV/c)}^2$ using the two high resolution spectrometers in Hall A. The standard detector package of the Hall A spectrometers will be replaced with a shower counter, with integrating electronics in order to allow for the very high expected rates into the spectrometer. This measurement alone would not allow separation of $G_E^s$ and $G_M^s$, but it would determine if strange quarks play a significant role in the structure of the proton, modulo the uncertainty in $G_E^n$. If large effects are seen, a more extended program of measurements at lower $Q^2$ on proton and $^4\text{He}$ targets is anticipated.

The “G0” experiment, E91-017, will consist of a superconducting toroidal spectrometer and an array of scintillators along the focal plane to determine the PV asymmetry at both forward and backward electron angles. At forward electron kinematics the detector will be sensitive to recoil protons corresponding to momentum transfers of $0.1 < Q^2 < 1.0 \text{ GeV}^2$. A second set of measurements in which the orientation of the spectrometer is reversed will allow the detection of electrons at $108^\circ$. Additional measurements on deuterium will constrain the uncertainty associated with $G_A^Z$. $G_E^s$ and $G_M^s$ can then be separated over a range of momentum transfer.

Another approach to determining strange quark effects in a hadronic system is to use parity-violating elastic scattering from a $J = 0$, $T = 0$ nucleus. Elastic electron scattering from a spinless nucleus occurs only through charge scattering. For $T = 0$ nuclei, only isoscalar terms remain and the asymmetry reduces to

$$A = \frac{G_F Q^2}{\pi \alpha \sqrt{2}} \left[ \sin^2 \theta_W + \frac{1}{4} \frac{F_s}{F_c} \right]. \quad (5)$$
$F_c$ is the electromagnetic charge response function of the nucleus and $F_s$ is the equivalent strange quark response function.

Multinucleon effects which could complicate the extraction of $G_E^s$ from a nuclear target have been calculated [25] and appear to be small. Musolf and Donnelly have also argued [26] that two measurements on a $(0^+0)$ nucleus, at low and moderate $Q^2$ might ultimately constrain $G_E^s$ to a higher level of precision than that achievable with a measurement on a proton target, since uncertainties associated with $G_M^s$, $G_E^m$ and $G_A^Z$ are no longer present.

Experiment 91-004 will measure $^4\text{He}(e,e')$ at $Q^2 = 0.6$ GeV$^2$, again using the Hall A spectrometers. At the highest TJNAF design luminosity ($\mathcal{L} \sim 3.2 \times 10^{38}$), the counting rate into each spectrometer is sufficiently low to track individual particles through the spectrometer. The asymmetry with no strange quarks is relatively large, ($\sim 50$ ppm), but because of the low counting rates the experiment is expected to be statistics limited. However, even a modest measurement of the asymmetry will be able to determine if strange quark contributions to hadronic properties are large.

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 [27]. Currently very little information is known. Considerable progress on the SAMPLE experiment has been made and a long data-taking run is anticipated in 1997. Future running with a deuterium target is also planned. The first experiments using polarized beam at Jefferson Laboratory are planned for 1997, establishing the groundwork for a broad program of PV experiments in the future.

Work on the SAMPLE experiment is supported by the National Science Foundation and by the Department of Energy.

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