Parity Violation with Electrons and Hadrons

E.J. Beise

Dept. of Physics, University of Maryland, College Park, MD, USA

A key question in understanding the structure of nucleons involves the role of sea quarks in their ground state electromagnetic properties such as charge and magnetism. Parity-violating electron scattering, when combined with determination of nucleon electromagnetic form factors from parity-conserving $e-N$ scattering, provides another degree of freedom to separately determine the up, down and strange quark contributions to nucleon electromagnetic structure. Strange quarks are unique in that they are exclusively in the nucleon’s sea. A program of experiments using parity violating electron scattering has been underway for approximately a decade, and results are beginning to emerge. This paper is a brief overview of the various experiments and their results to date along with a short-term outlook of what can be anticipated from experiments in the next few years.

1. Introduction

In 1988, Kaplan and Manohar [11] showed that information about the contribution of sea quarks to ground state nucleon properties, such as spin, charge and magnetic moments, could be learned using neutral weak probes of the nucleon such as neutrino-nucleon scattering. Soon after, McKeown [2] and Beck [3] outlined a possible program of experiments in parity-violating electron scattering that, when combined with existing measurements of nucleon electromagnetic form factors, would allow the identification of possible strange quark contributions to the proton’s charge and magnetism. Experiments were proposed at the MIT-Bates Laboratory, Jefferson Lab, and the Mainz Microtron to accomplish this goal. In the decade or so since, many theoretical models of the strange quark components of these neutral weak matrix elements, have appeared in the literature, and the first quantitative information from experiments is becoming available. Here I will provide a summary of the recent measurements, along with expected progress in the short term.

While the expectation is that strange quark contributions should be small, they occupy a special place in nucleon structure because their presence would be exclusively in the nucleon’s $\bar{q}q$ sea. Evidence to date suggests that they have a sizeable contribution to the nucleon’s unpolarized quark momentum distribution in the nucleon [11], as well as to the nucleon’s mass [5], although the latter has some degree of uncertainty due to both experimental and theoretical extrapolations required to obtain the result. A decade of precise spin-dependent deep-inelastic scattering experiments has led to the conclusion that strange quarks contribute significantly to the (small) fraction of the proton’s spin carried by quark spins [10], although again assumptions about SU(3) symmetry are required in
order to extract a result. Parity-violating electron scattering is primarily sensitive to the matrix element \( \overline{s}\gamma_\mu s \), which provides information about the \( s \) contributions to the nucleon’s charge and magnetization distributions. The neutral weak nucleon current as probed through PV e-N scattering is

\[
J^{NC}_\mu \equiv \langle N | \hat{j}^{NC}_\mu | N \rangle = U \left[ \gamma_\mu F_1^Z(Q^2) + i\sigma_\mu_\nu q^\nu \frac{F_2^Z(Q^2)}{2M} + \gamma_\mu \gamma_5 G_A^Z(Q^2) \right] U, \tag{1}
\]

where \( F_{1,2}^Z \) are the neutral weak equivalents of the nucleon’s Dirac and Pauli form factors \( F_{1,2} \). At low momentum transfer, \( F_1 \) and \( F_2 \) are more often expressed as the Sachs form factors \( G_E = F_1 + \frac{Q^2}{M^2} F_2 \) and \( G_M = F_1 + F_2 \), which can be directly related to the nucleon’s charge and magnetization distributions, respectively, and which have the normalizations \( G^p_E(0) = 1, G^p_M(0) = \mu_p, G^n_M(0) = \mu_n \). Corresponding definitions can be made for the vector weak form factors \( F_{1,2}^V \). Because the NW form factors are derived from the same matrix element \( \overline{s}\gamma_\mu q \) as their EM counterparts, they can be re-expressed in terms of the measured EM form factors, with an explicit remainder coming from strange quarks, assuming only that neutrons and protons differ by an interchange of \( u \) and \( d \) quarks.

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

The \( G_{E,M}^Z \) thus provide a third degree of freedom to disentangle the flavor structure of the proton’s charge and magnetism. The radiative corrections \( R_{V,p,n} \) represent contributions from higher order processes and have been computed \([7]\) to be \( R_V^p = -0.053 \pm 0.033 \) and \( R_V^n = -0.0143 \pm 0.0004 \).

The axial form factor \( G_A^Z \) is related to the same matrix element as that defining the nucleon’s spin, \( \overline{s}\gamma_\mu \gamma_5 s \), and its isoscalar component explicitly contains the \( s \)-quark contribution, \( A_s \). Its isovector \((T = 1)\) component, to which PV e-\( p \) scattering is primarily sensitive, can be expressed in terms of the neutron \( \beta \)-decay constant \((g_A/g_V) = -1.2670 \pm 0.0035\), but also contains higher order corrections that can come from, for example, an electromagnetic e-\( p \) interaction coupled with a weak exchange between quarks, or from \( \gamma-Z \) box diagrams. The effective axial form factor is

\[
G_A^p = -\tau_3 g_A(Q^2) + A_s + \eta F_A + R_e, \tag{3}
\]

where \( \tau_3 = +(-)1 \) for protons(neutrons), \( g_A(Q^2) = (g_A/g_V)/(1+Q^2/M_A^2)^2 \), and \( \eta F_A + R_e \) are due to the higher order terms.

Experimentally, parity-violating e-\( p \) scattering results in an asymmetry in the detected yield for a longitudinally polarized beam on an unpolarized target:

\[
A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\pi \alpha \sqrt{2}} \frac{A_E + A_M + A_A}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}, \tag{4}
\]

where

\[
A_E = \varepsilon G_E^Z G_E^\gamma, \quad A_M = \tau G_M^Z G_M^\gamma, \quad A_A = -\left( 1 - 4 \sin^2 \theta_W \right) \sqrt{\tau (1 + \tau) (1 - \varepsilon^2)} G_A^\gamma G_M^\gamma, \tag{5}
\]
and $\varepsilon$ are kinematic factors and the $\gamma$ index refers to nucleon EM form factors. A single measurement typically involves at least two of the above terms, so a complete separation of $G_E^Z$, $G_M^Z$ and $G_A^e$ involves at least three experiments. Quasielastic scattering from deuterium can be used to constrain $G_A^e(T = 1)$ since it carries similar sensitivity to the axial term but is relatively insensitive to the strange vector form factors. A program of experiments has been carried out at MIT-Bates and Jefferson Laboratories and new experiments are underway at JLab and also at the Mainz Microtron.

On the theoretical front, a wide variety of models have been used to estimate the magnitude of $G_s^e$ and $G_s^M$, including a few predictions for their behavior with $Q^2$. At $Q^2 = 0$, $G_E^s$ is constrained to be 0 since the proton has no net strangeness, but $G_M^s$ is not so constrained and is defined through the expression

$$\mu_p = \frac{2}{3}\mu_u - \frac{1}{3}\mu_d - \frac{1}{3}\mu_s.$$  \hspace{1cm} (6)

The low energy behavior of each is characterized by a radius parameter that can be written in a dimensionless form as $\rho = 4M_N^2 (dG/dQ^2)|_{Q^2=0}$. The wide variety of predictions precludes extensive discussion here, but reviews can be found in the literature \[10\]. Figure 1 shows a sampling of many of the models: a notable feature is that while many predict $\mu_s$ to be $\sim -0.3$, predictions for the electric strangeness $\rho_s$ vary widely and do not even agree on the sign.

It is of interest to note one recent calculation [11], where $G_M^s$ and $G^2_E$ were analyzed within the framework of chiral perturbation theory. It was first thought that the slope of $G_M^s$ could be determined analytically, and with constraints coming from the first results from SAMPLE and HAPPEX, limits on the $Q^2$ behavior could be predicted [12], which resulted in opposite signs for the two form factors. It was, however, recently shown in [13] that the slope of $G_M^s$ is sensitive to an unknown low energy constant that enters at $O(p^4)$ due cancellations at lower order, so both the magnitude and sign of $G_M^s$ at low $Q^2$ are still unconstrained by theory.

### 2. SAMPLE at MIT-BATES

In the SAMPLE experiment [8, 9], PV electron scattering was measured in the backward direction, from both hydrogen and deuterium targets, in order to determine $G_M^s$ and $G_A^e(T = 1)$ at $Q^2 = 0.1 \,(\text{GeV}/c)^2$. A 200 MeV, 40 $\mu\text{A}$ polarized beam was scattered from a 40 cm liquid hydrogen target. Cerenkov light from scattered electrons was detected in an array of ten mirror-phototube pairs arranged symmetrically about the beam axis covering angles between 130° and 170°. The scattered electron rate was integrated over the 25 $\mu\text{sec}$ beam pulse and sorted by beam helicity state, which was flipped pseudo-randomly at 600 Hz. Results from the 200 MeV running were published in [8] and [9], where the latter included data from quasielastic scattering from deuterium. It was found that while $G_M^s$ is likely small, there was an approximately 1.5$\sigma$ discrepancy between the extracted value of $G_A^e(T = 1)$ and that expected assuming a value for the weak radiative corrections as computed by Zhu et al. [14]. This led to theoretical investigations of the nuclear contributions in the deuterium data as well as a more detailed look at the extraction of $G_A^e(T = 1)$ from the data.
Figure 1. Graphical summary of the various types model predictions for $\mu_s$ and the electric strangeness radius parameter $\rho_s$. The horizontal axis refers to a particular calculation: see [10] for a recent summary. For scale, the equivalent radius parameter for the neutron’s charge form factor is also shown.

In a simple static approximation, the PV asymmetry in deuterium is an incoherent sum of that of the neutron and proton, and the contributions from $G_A^s(T = 1)$ largely cancel, and the sensitivity to $G_A^e(T = 1)$ is approximately the same as for a proton target. Nuclear corrections can potentially modify the asymmetry, both through parity-conserving [15], and parity-violating [16, 17] two-body effects. At the SAMPLE kinematics the PC terms modify the asymmetry by 1-3%, and the PV terms are negligible. The SAMPLE apparatus also has contributions from threshold breakup and elastic $e-d$ scattering which modify the asymmetry by a few percent.

An improved analysis of the SAMPLE deuterium data now brings the extracted value of $G_A^e(T = 1)$ into reasonable agreement with [14], as shown in Figure 2 but has a relatively small impact on $G_A^s$. The new results include a complete GEANT model of the detector, a revision to the electromagnetic radiative corrections and a dilution correction for coherent $\pi^0$ production in the experimental yield which was previously neglected. Furthermore, the calculation of [17] was used to model the physics asymmetry. These combined theoretical and experimental efforts lead to better confidence that the higher order contributions to $G_A^e$ are now under control. Results from the third SAMPLE measurement, at lower momentum transfer, also agree with expectations from theory [18]. The hydrogen results were also revised [19], resulting an experimental asymmetry of, after all dilution corrections, $A_{exp} = -5.61 \pm 0.68 \pm 0.88$ ppm. Combining this result with the theoretical value of $G_A^e$ results [20] results in the more upright ellipse in Figure 2. While this result is consistent with little or no strange quark effects, it suggests a positive
Figure 2. Updated results from the 200 MeV SAMPLE data, which resulted in better agreement with the theoretical expectation \cite{14} for the axial form factor.

value for $G_M^s$ whereas most calculations predict a $Q^2 = 0$ value near $\mu_s \sim -0.3$.

3. HAPPEX at JLab

The first measurements of parity-violating electron scattering at Jefferson Laboratory \cite{21} were carried out by the HAPPEX collaboration, who used a 3.3 GeV polarized beam on a 15 cm hydrogen target and detected the scattered electrons using the pair of high resolution spectrometers (HRS) in Hall A at 12.5°. The measured asymmetry, at $Q^2=0.48$ (GeV/c)$^2$, is sensitive to the combination $G_E^s + 0.39G_M^s$. The counting rate of approximately 1 MHz per spectrometer required the use of integrating techniques, and a set of Pb-scintillator total absorption counters was used instead of the standard tracking detector package. The HAPPEX experiment was the first to use a strained GaAs crystal in the polarized electron source, which produces beam polarization in excess of 70%. Such sources can have an analyzing power for linear polarization in the incident laser light that could potentially result in significant helicity correlated position differences of the beam on the experimental target. Such effects were, however, kept to a negligible level by insertion of a rotatable half-wave plate in the laser beam and with a feedback system nulling any helicity-correlated intensity asymmetry.

The experimentally determined asymmetry from the HAPPEX experiment is $A_{exp} = -15.05 \pm 0.98 \pm 0.56$ ppm, corresponding to $G_E^s + 0.39G_M^s = 0.025 \pm 0.020 \pm 0.014$ where the latter uncertainty is due to knowledge of the nucleon EM form factors. HAPPEX thus for the most part precludes the parameter space in which $G_E^s$ and $G_M^s$ have the same sign.
The future program for HAPPEX includes a forward angle measurement at $Q^2=0.1$ (GeV/c)$^2$ on hydrogen [22], as well as the first measurement of the PV asymmetry in elastic electron scattering from helium [23]. Due to the fact that $^4$He is a spin-0, isospin-0, target, only a single weak form factor exists and it can be directly related to $G_E^s$ with a good model of the $^4$He nucleus. Theoretical expectations are that contributions to the asymmetry from many-body effects in the helium are negligible [24] at low momentum transfer. The combined measurements, or the new hydrogen measurement combined with the SAMPLE result, will result in a determination of $G_E^s$.

4. PVA4 at Mainz

The PVA4 collaboration at Mainz has taken a different experimental approach, with a detector with sufficient segmentation and specialized electronics that counting the scattered particles is feasible despite high rates. A 20 $\mu$A beam of polarized electrons was incident on a 10 cm target. Scattered electrons are detected at 35° with a PbF$_2$ Čerenkov shower calorimeter. The detector design includes 1022 PbF$_2$ crystals arranged in 7 rings, and processed in 3x3 modules with self-triggering and histogramming electronics: for the first two measurements approximately half of the detector was instrumented. The energy resolution of the detectors must be sufficient to separate the 10 MHz of elastically scattered electrons from the 90 MHz of inelastic electrons coming from threshold pion and resonance production. The achieved energy resolution was 4%/\sqrt{E} [25].

The first PVA4 measurement was at a beam energy of 855 MeV, corresponding to $Q^2=0.23$ (GeV/c)$^2$ and a sensitivity to the combination $G_E^s + 0.22 G_M^s$. The experimental asymmetry after all dilution corrections is $A_{exp} = -5.6 \pm 0.6 \pm 0.2$ ppm, corresponding to an approximately 1σ deviation of the asymmetry from that expected with no strange quarks, but again hinting that $G_E^s$ and $G_M^s$ are either both small or have opposite sign. Additional data have already been taken, the run concluding in June 2003, at 570 MeV beam energy, corresponding to $Q^2=0.1$ (GeV/c)$^2$. Again by combining these data with the results from SAMPLE will allow the first experimental limits on $G_E^s$. Future plans involve reversing the detector for backward angle measurements at $Q^2=0.23$ and 0.48 (GeV/c)$^2$ to combine with the existing HAPPEX and PVA4 data.

Although the kinematic sensitivities of each of the experiments is somewhat different, the results from each of the three above $e$-$p$ measurements can be shown, as in Figure 4, as a deviation from the asymmetry expected with no strange quarks. While any single measurement is consistent with little or no strange quark contribution, the trend in all three experiments suggests an $s$-quark contribution that is slightly positive.

It should be noted that, in addition to the parity-violation results, both the PVA4 and SAMPLE experiments have measured a “beam spin asymmetry” resulting from scattering from a purely transversely polarized beam [26, 27]. To lowest order, the asymmetry, which results in a variation of the cross section in azimuthal angle with respect to the beam axis, is to lowest order the result of two-photon processes. Such processes have recently become of interest because they may help explain the discrepancy in the determination of the proton charge form factor at high momentum transfer from polarization and cross section data [28], and they are related to the Virtual Compton Scattering process which provide information about nucleon polarizabilities [29].
Figure 3. Summary of existing measurements of the PV asymmetry in elastic $e-p$ scattering, shown as the fractional deviation of the measurement from the asymmetry expected if $G_M^s=G_E^s=0$ at all momentum transfers. Overlaid are the expected uncertainties coming from the first phase of the G0 experiment, scheduled to run in early 2004.

5. G0 at JLab

The G0 experiment at JLab is a dedicated to determining $G_E^s$, $G_M^s$ and $G_A^e$ from a single experimental apparatus over a broad $Q^2$ range. The detector consists of a superconducting toroidal spectrometer with an array of scintillators along the focal plane to determine the PV asymmetry at both forward and backward scattered electron angles. Polarized electrons are scattered from a 20 cm liquid hydrogen target. In the forward configuration, the recoil protons are detected and sorted by $Q^2$ covering the range $0.1 < Q^2 < 1.0$ (GeV/c)$^2$. In the backward configuration the apparatus is reversed and electrons scattered at 108° will be detected with three dedicated magnet settings corresponding to $Q^2 = 0.25$, 0.5 and 0.8 (GeV/c)$^2$. In the forward mode, the protons are identified and separated from pions via time-of-flight from the target to detector, which is about 20 ns. In the backward mode the detector package requires an augmentation with another array of scintillators (Cryostat Exit Detectors) and aerogel Čerenkov counters to eliminate negative pions from the trigger. Data will also be acquired with a deuterium target to experimentally determine the $Q^2$-dependence of $G_A^e$.

The first engineering run of the experiment, in its forward mode, was carried out in late 2002 during which a few days of asymmetry data were collected. While the statistical uncertainties are too large to draw physics conclusions from these data, the measured asymmetry of approximately 5 ppm is consistent with expectation, has a reasonable $Q^2$ behavior, and reverses appropriately with manual reversal of the sign of the beam polar-
ization. After a second engineering run, the G0 collaboration will carry out its forward mode physics measurement. While a definitive determination of the relative signs and/or magnitude of $G_M^s$ and $G_E^s$ will require the backward angle measurements as well, this first set of data will both extend the kinematic reach and improve the precision of the data shown in Figure 4. Additional details of the G0 experiment can be found in [30] and [31].

Improvements in polarized beam technology in the last decade have made precise measurements of parity-violating electron scattering possible, and the next generation of experiments, which move beyond studies of hadron structure to other physics are now being considered. One direction is to use parity-violating electron scattering as a precise probe of neutron distributions in heavy nuclei [32], which may have relevance in understanding the structure of neutron stars. Another direction is to carry out precision tests of the standard model at relatively low momentum transfer where sensitivity to additional Z-bosons, for example, is greatly enhanced. The latter is of particular interest in light of the recent results from the NuTeV collaboration in which a 3σ deviation from expectation in $\sin^2 \theta_W$ was measured [33]. The latter direction is being pursued by the QWEAK collaboration at JLab, and further details can be found in [30] in these proceedings.

6. Summary

Since the earliest measurements of parity-violating electron scattering at SLAC [34] in which the weak mixing angle was first measured, the basic techniques of parity-violating electron scattering have remained more or less the same. But the achievable precision has greatly improved as a result of new high intensity electron beams, advances in polarized beam technology, and technical advances in the feedback and laser systems that are needed for polarized beam delivery. New physics directions also emerged and the results are beginning to become available from the first experiments to use PV electron scattering as a probe of hadron structure. We can look forward to more new results in the near future with the next phases of HAPPEX and PVA4 and the first results from the G0 experiment, all of which should further our understanding of the role of sea quarks in the nucleon’s ground state structure.

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