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Status and plans for neutral weak form factors measurements

K.S. Kumar[a]

Department of Physics, University of Massachusetts, Amherst, MA 01002, USA

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Abstract. We report on a mature experimental program to measure the parity-violating asymmetry in the elastic scattering of longitudinally polarized electrons from unpolarized ^{1}H, ^{2}H and ^{4}He targets. The focus is the measurement of the nucleon neutral weak form factors at intermediate four-momentum transfer $(0.1 < Q^2 < 1)$ $(\mathrm{GeV}/c)^2$ which provide information about the impact of virtual strange quarks on the charge and current distributions inside nucleons. We report on recent technical progress in the design and scope of the experimental techniques. The physics implications of the published measurements are discussed and the current status and anticipated results from experiments under construction are summarized.

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1 Introduction

In analogy to the charge current weak interactions like beta decay mediated by W-bosons, there is a corresponding neutral current weak interaction mediated by the Z^0-boson. One way to measure the weak neutral current amplitude between electrons and quarks is to measure the extent of parity violation in electron-quark electroweak interactions. If one scattered longitudinally polarized electrons off unpolarized protons and flipped the sign of the beam polarization, the fractional difference in the cross-section would be [1]:

$$A_{\mathrm{LR}} \equiv \frac{\sigma_{\mathrm{R}} - \sigma_{\mathrm{L}}}{\sigma_{\mathrm{R}} + \sigma_{\mathrm{L}}} \simeq \frac{|A_Z|}{|A_\gamma|} \simeq \frac{4\pi\alpha}{Q^2} \simeq 10^{-4} Q^2 \,. \qquad (1)$$

Since the observation of parity violation in deep inelastic electron-nucleon scattering at SLAC [2], the experimental techniques employed to measure these tiny left-right asymmetries have been steadily refined such that statistical errors approaching 0.01 parts per million (ppm) and systematic errors of a few parts per billion (ppb) are possible [3]. This has spawned an important series of experiments that is the focus of the review.

2 Physics motivation

Over the past decade, several experimental programs have focused on probing for the manifestations of strangeness in nucleon properties, such as mass, spin, momentum , magnetic moment and charge radius. A clean measurement of the contribution of strange quarks to any of these properties would be a dramatic proof of non-trivial dynamics of sea quarks inside nucleons, providing a new window into non-perturbative QCD.

There are some indications that the strange quarks might contribute to the mass (via π-proton scattering measurements) and the spin (via spin-dependent deep inelastic scattering measurements). While these experiments are sensitive to the strange scalar and axial vector matrix elements, parity-violating elastic electron scattering can access vector strangeness matrix elements sensitive to the the contribution of strange quarks to nucleon charge and magnetic-moment distributions [4,5].

Elastic electron nucleon electromagnetic scattering is well described by the Dirac and Pauli (or, equivalently, the Sachs electric and magnetic) form factors. One can introduce equivalent neutral weak form factors that would be accessible in parity-violating elastic electron scattering. If one assumes the validity of the standard model (weak isospin symmetry) and charge symmetry and that only three flavors are active, then one needs three elastic electroweak electron nucleon amplitudes to achieve flavor separation [6]. Thus, for a given value of Q^2, if the proton and neutron electromagnetic form factors are well measured, the measurement of the neutral weak form factors at the same value of Q^2 allows the extraction of the strange form factors.

The exact calculation of the strange form factors from QCD is currently impossible since it involves non-perturbative dynamics of sea quarks. Various model approaches are used, such as chiral perturbation theory, quark models, lattice gauge theory, Skyrme models and dispersion relations [7,8]. Most models attempt to model

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[a] e-mail: `kkumar@physics.umass.edu`

Table 1. Strange form factor experiments.

Experiment	Target	θ_{electron}	Q^2	Status
SAMPLE	^{1}H	150°	0.1	published
HAPPEX	^{1}H	12.5°	0.47	published
SAMPLEII	^{2}H	150°	0.1	published
SAMPLEIII	^{2}H	150°	0.04	completed
A4	^{1}H	35°	0.23	2002
HAPPEX-H	^{1}H	6°	0.11	2003
HAPPEX-He	^{4}He	6°	0.11	2003
G0	^{1}H	10°	0.3–0.8	2003
A4	^{1}H	35°	0.1	2003
G0	^{1}H	110°	0.3–0.8	2004-7
G0	^{2}H	110°	0.3–0.8	2004-7
A4	^{1}H	145°	0.23	future
A4	^{1}H	145°	0.5	future

the low-Q^2 behaviour of the form factors:

$$\mu_s \equiv G_M^s(0); \qquad \rho_s \equiv \frac{\mathrm{d}G_E^s}{\mathrm{d}\tau}; \qquad \tau \equiv \frac{Q^2}{4M_p^2} \tag{2}$$

known as the strange magnetic moment and the strange radius.

These models agree on neither the signs or magnitude of the strange form factors. Nevertheless, some guidance can be obtained from the size of the magnetic moment of the Λ-baryon ($0.6\mu_N$) and the charge radius of the neutron ($\rho_n \sim 3$).

2.1 The experimental program

Experiments must therefore achieve a sensitivity significantly smaller than these values for the corresponding leading moments of the strange form factors. The full exploration further requires measurements over the range $0.1 < Q^2 < 1$ (GeV/c)^2, as well as forward- and backward-angle measurements off ^{1}H, ^{2}H and ^{4}He targets. In table 1, the past, current and future experiments measuring strange form factors are summarized in roughly chronological order.

3 Published measurements

3.1 SAMPLE

The SAMPLE experiment was carried out at the MIT-Bates Linear Accelerator, with the principal goal of measuring μ_s. This was accomplished by measuring the parity-violating amplitude in elastic electron proton scattering at backward angles at $Q^2 \sim 0.1$ (GeV/c)^2. The neutral current amplitude has two primary contributions, one from G_M^s and one from the axial form factor G_A. In order to separate these contributions, three separate physics runs were carried out: 200 MeV on a hydrogen target and 200 MeV and 125 MeV on a deuterium target.

Elastic events at backward angles were detected by the Čerenkov light produced as they pass through air. This detection technique can provide a very large solid angle on very thick targets. At 200 MeV, scattered electrons at backward angles from inelastic scattering did not have very high efficiency for producing Čerenkov light, thus avoiding spurious asymmetry contributions from unknown inelastic amplitudes. The Čerenkov light was collected into 10 shielded phototubes via concave mirrors from a total solid angle of 0.7 steradian.

Polarized electrons were produced by a Ti-Sapphire laser shining on a bulk GaAs crystal. The polarization of the beam was about 36%. The accelerator provided 25 μs long pulses at 600 Hz for a duty cycle of 1.5%. The electrons impinged on a 40 cm long liquid-hydrogen target with an average beam current ranging from 40 μA and 60 μA.

False asymmetries due to helicity correlations in the electron beam parameters were minimized using a linear regression technique. This was tested on the response of a luminosity monitor, which detected charge particles at 12°. These data showed that the cumulative asymmetry in the luminosity monitor was less than 0.2 ppm.

For the hydrogen target, at an incident beam energy of 200 MeV, the measured asymmetry is [9]

$$A_p = -4.92 \pm 0.61 \pm 0.73\,\text{ppm}, \tag{3}$$

while for the deuterium target with the same beam energy, the measured asymmetry is

$$A_d = -6.79 \pm 0.64 \pm 0.55\,\text{ppm}, \tag{4}$$

from which the following parameters are extracted at $Q^2 = 0.1$ (GeV/c)^2 [10]:

$$G_M^s = 0.14 \pm 0.29 \pm 0.31; G_A^e(T=1) = 0.22 \pm 0.45 \pm 0.39. \tag{5}$$

In order to improve the accuracy of the G_A result, SAMPLE has recently completed a third physics measurement, this time with a 125 MeV beam on a deuterium target. The contribution from G_A is further enhanced at this lower Q^2 and the result is expected to be released soon.

3.2 HAPPEX

The HAPPEX experiment was carried out in Hall A at JLab, where the emphasis was on the measurement of the electron-proton weak neutral current amplitude at forward angles, where both electric and magnetic form factors contribute. A CW beam of 3.3 GeV struck a 15 cm liquid-hydrogen target. Scattered electrons at $\theta_{\text{lab}} \sim 12.5°$ were detected by a pair of 5.5 msr precision spectrometers, whose optics provides a mass focus that spatially separate the elastic events from all inelastic events. This allowed the use of integrating flux counters, thus making high rates possible.

The integrating detector in each spectrometer consisted of a sandwich of five lead and lucite layers viewed by a single phototube. Separate low-rate runs which tracked individual particles established that the backgrounds in the integrated signal were negligible. The polarized beam at JLab is exceptionally quiet, ideal for parity violation experiments. The beam jitter in intensity, position, angle and energy are small enough so that the impact of false asymmetries due to helicity-correlated beam motion can be studied to a sensitivity of 10 parts per billion within a few hours.

The beam polarization was 39% during the first half of data taking, while a strained GaAs photocathode provided 70% polarization during the second half of the experiment. The beam polarization was measured both with a conventional Moller polarimeter as well as a newly commissioned Compton polarimeter, which provided a non-invasive, continuous monitor of the beam polarization. The final combined result of all the data taking runs is [11]

$$A_{\mathrm{LR}} = -14.60 \pm 0.94(\mathrm{stat}) \pm 0.54(\mathrm{syst})\ \ \mathrm{ppm}. \tag{6}$$

Combining the above result with data on nucleon electromagnetic form factors allows the extraction of a linear combination of electric and magnetic strange form factors:

$$(G_E^s + 0.392 G_M^s)/(G_M^{p\gamma}/\mu_p) = 0.091 \pm 0.054 \pm 0.039. \tag{7}$$

The result is shown normalized to the proton magnetic form factor to underscore the sensitivity of the measurement. It implies that the linear combination of strange form factors that was probed is less than 10% of the proton electromagnetic form factor.

4 Experiments in progress

4.1 A4

The A4 experiment is taking place at MAMI, the Mainz Microtron and is measuring the weak neutral current amplitude in the elastic electron proton scattering at a scattering angle of $\theta_{\mathrm{lab}} \sim 35 \pm 5°$. Their first measurement is with an incident energy of 855 MeV, giving a Q^2 of 0.23 $(\mathrm{GeV}/c)^2$. The unique feature of the experiment is a large-acceptance lead fluoride (PbF_2) calorimeter.

A 20 μA 70% longitudinally polarized beam scatters off a 20 cm liquid-hydrogen target. Data are obtained in 20 ms time windows locked to the 50 Hz power line frequency. A water Čerenkov luminosity monitor detects charged particles between 4 and 11 degrees and is used to normalize the data and study the effects of spurious asymmetries. The beam polarization is measured by a Compton backscattered laser polarimeter.

The calorimeter is designed to detect elastic electrons at a rate of 10^7/s amongst a background rate of 10^8/s made up of inelastic electrons, soft pions and photons. The calorimeter is made up of an array of 15 radiation length long PbF_2 crystals with a front surface of 25 × 25 mm. Light from showers in the crystal array are summed, integrated over 20 ns, digitized and histogrammed in real time by custom-built fast electronics. The system was carefully monitored to ensure that there was minimal dead time and/or non-linearity.

The experiment has accumulated more than 600 hours of data in 2001 and 2002. They measure an asymmetry of $A_{\mathrm{phy}} = -7.90 \pm 1.10 \pm 0.85$ (ppm), while the standard model expectation is -5.7 ppm. This result is preliminary and more work on systematic corrections, estimation of the neutron electromagnetic form factors as well as standard model radiative corrections are required before any information on strange form form factors can be extracted.

The A4 Collaboration plans to double their accumulated statistics at this kinematic point and then measure the neutral current amplitude at $Q^2 \sim 0.1\ (\mathrm{GeV}/c)^2$, which is achieved in the same detector configuration with a reduced incident beam energy. They then plan to turn the calorimeter apparatus around by 180° to look at electrons scattered at backward angles. They plan to measure the asymmetry at $Q^2 \sim 0.23$ and 0.5 $(\mathrm{GeV}/c)^2$, which would complement the forward-angle measurements made by A4 and HAPPEX.

5 Experiments under construction

5.1 G0

The G0 experiment at JLab plans to make a complete set of forward- and backward-angle asymmetry measurements on hydrogen and deuterium in the range $0.16 < Q^2 < 0.95\ (\mathrm{GeV}/c)^2$. It is based on a novel toroidal spectrometer which detects scattered events in the range $62° < \theta < 78°$. When the spectrometer is oriented in the forward direction, recoil protons are detected in this range, which corresponds to electrons scattering in the range $15° < \theta < 5°$. The entire range of Q^2 is thus obtained simultaneously, with an incident beam energy of 3 GeV.

The spectrometer would then be rotated by 180° and backward angle electrons will be detected. In this configuration, data would be taken at three different beam energies with both hydrogen and deuterium targets. In this way, the electric and magnetic strange form factors as well as the axial form factor would be each independently obtained at $Q^2 \sim 0.3, 0.5, 0.8\ (\mathrm{GeV}/c)^2$.

The spectrometer is made up of eight superconducting coils in a common cryostat, with a diameter of 4 m and an operating current of 5 kA. The geometry provides line-of-sight sheilding of the detectors from the target. The total solid angle of 0.9 sr is accepted. Recoil protons and electrons are momentum-analyzed and detected by plastic scintillators that are placed on the focal surface to accept specific Q^2 values from the entire 20 cm target length.

For forward-angle events, time of flight is used to reject backgrounds. The high degree of segmentation keeps instantaneous rates below 1 MHz. The beam microstructure is reduced from 497 MHz by a factor of 16 to provide ∼ 32 ns timing windows. For backward-angle measurements, additional detectors are added at the entrance of the spectrometer to separate electrons from pions and protons.

Custom electronics have been developed to count particles at very high rates in each beam helicity window while rejecting backgrounds, with minimal dead time. Data are recorded by shift registers feeding scalers and by time-to-digital converters. Kinematics corresponding to elastic scattering as well as the N-Δ transition will be employed.

Installation of the apparatus is nearing completion and the commissioning will take place in fall 2002. It is anticipated that the first physics run will begin in late 2003. Backward-angle measurements will take place between 2005-7.

5.2 HAPPEX-II

The HAPPEX Collaboration in Hall A at JLab is preparing for two new experiments, scheduled to begin in summer 2003. These experiments will detect scattered electrons at $\theta_{\mathrm{lab}} \sim 6^\circ$, which is achieved by the HRS high-resolution spectrometers in conjunction with septum magnets. One experiment will measure the weak neutral current amplitude off hydrogen, while the other will make the measurement of ^{4}He, both employing an incident beam energy of 3.2 GeV.

For the hydrogen measurement, the physics asymmetry is 1.7 ppm and the goal is to measure it with a statistical error of 5% and a systematic error of 3%. The total rate into the two spectrometers is 125 MHz. The combination of small statistical error and high rate requires significant improvements in the monitoring and control of electron beam fluctuations, as well as an improved detector technology capable of handling a high radiation dose.

For the helium measurements, a dense gas target capable of holding 10 atmospheres of helium at a temperature of 20 K is being constructed. The spectrometer system in Hall A easily separates elastic events from the inelastic events that have lost more than 20 MeV. The physics asymmetry is about 15 ppm and will be measured to an accuracy of 3%. Significant improvement in reducing normalization errors from those of the HAPPEX measurement is required, most notably in the beam polarization measurement.

The hydrogen and helium measurements combine to form a powerful constraint on the leading moments of the strange form factors ρ_s and μ_s. One measures the combination $\rho_s + \mu_p \mu_s$ to an accuracy of ± 0.31, while the other measures ρ_s to an accuracy of ± 0.5. The helium measurement has the advantage that it only depends on the nucleon electric form factors.

6 Other applications

6.1 SLAC E158

The E158 experiment is taking place at the Stanford Linear Accelerator Center (SLAC), using the longitudinally polarized 50 GeV electron beam incident on a 1.5 m long liquid-hydrogen target. The goal of the experiment is to measure the weak neutral current amplitude for electron-electron (Moller) scattering to a precision of about 8%, from which the most precise determination of the weak mixing angle $\sin\theta_{\mathrm{W}}$ can be extracted at $Q^2 \ll M_Z^2$. The raw asymmetry is small, of the order of 130 ppb and the goal is to measure it to an accuracy of 10 ppb.

The electron beam is produced by a novel gradient-doped GaAs photocathode that produced a charge 6×10^{11} electrons per pulse, at a pulse length of 200 ns, repetition rate of 120 Hz and 80% polarization. The experiment requires unprecedented control and monitoring of the electron beam parameters. During recent data taking, the charge asymmetry was kept well below 1 part per million (ppm) and was verified by independent devices to within 5 ppb. The electron beam position was controlled to be within 20 nm on target and was verified to within 2 nm by redundant measurements.

The experiment has completed two data taking runs, each accumulating about one-quarter of the total approved statistics, for a cumulative error on the asymmetry of the order of 15 parts per billion. The expected error on the weak mixing angle $\sin^2\theta_{\mathrm{W}} \sim 0.0017$. It is anticipated that the remaining statistics will be collected in a final run in late 2003.

6.2 Qweak

A new experiment has been approved at JLab to measure the asymmetry in elastic scattering from hydrogen with an incident energy of 1.2 GeV and a Q^2 of 0.03 $(\mathrm{GeV}/c)^2$. At these kinematics, the contribution of strange form factors is small and the asymmetry measures the weak charge of the proton, thus probing for physics beyond the standard model in a manner similar to SLAC E158. The experiment is in the early stages of design and aims at being ready to run in 2007

6.3 ^{208}Pb

Another approved experiment at JLab is the measurement of the asymmetry in elastic scattering from ^{208}Pb. The basic idea is that from electromagnetic scattering, the photon couples to the proton, whereas the Z couples predominantly to the neutron. While a detailed map of the ground-state neutron distribution is possible in principle, only one or two Q^2 points are practical in parity violation experiments. Nevertheless, a judicious choice of the kinematical point, it is possible to establish the difference between the proton and neutron average radius (the so-called neutron skin) at the 1% level.

The experiment will scatter 850 MeV electrons at 6°. The asymmetry is estimated to be about 0.7 ppm and the goal is to measure it to a relative accuracy of 3%.

7 Conclusion

The technique of parity-violating electron scattering has made giant strides over the past two decades. The HAPPEX experiment has set important limits on the size of strange form factors and the SAMPLE experiment has suggested that the proton axial current may be important.

New experiments that are about to come on line will clarify the picture. If axial current effects turn out to be small, the new measurements should set stringent limits on the size of the strange form factors or better still, establish their existence.

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