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The weak neutral current of the nucleon

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Abstract. Experiment and theory related to the neutral weak current of the nucleon is briefly reviewed. Completed measurements include those of the SAMPLE (MIT-Bates), HAPPEX (JLab) and PVA4 (Mainz) experiments. The future plans for the latter two experiments and those for the G0 experiment (JLab) are also discussed. The review includes discussion of the physics associated with the contributions of different quark flavors to the nucleon vector currents, as well as that associated with the axial vector currents.

PACS. 13.60.-r Photon and charged-lepton interactions with hadrons – 14.20.Dh Protons and neutrons – 25.30.-c Elastic electron scattering – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 12.15.Lk Electroweak radiative corrections

1 Introduction

The quark-gluon structure of hadrons, particularly at long distance scales, remains one of the key problems in modern physics. Over the past several years, understanding of the neutral weak currents of the nucleon, as determined through parity-violating electron scattering, has advanced significantly. These currents contribute to our picture of the quark sea (and hence the gluon sea) in the nucleon through their relation to strange quark vector currents, as well as to the weak interactions between quarks. Experimental results have begun to constrain these currents and a number of measurements are planned for the near future to complete the basic outlines. These are very difficult problems to approach theoretically, but calculations are also becoming more ambitious.

2 Electromagnetic and neutral weak currents

Because the electromagnetic and neutral weak currents are precisely related in the electroweak sector of the standard model, differing only in the couplings (charges) of the different quark flavors, comparison of these currents can yield information on the separate contributions of the quark flavors to the nucleon structure [1,2]. As an example, the electromagnetic and analogous neutral weak form factors of the proton may be written

$$G^{p,\gamma}_{E,M} = \frac{2}{3}G^u_{E,M} - \frac{1}{3}\left(G^d_{E,M} + G^s_{E,M}\right) \qquad (1)$$

$$G^{p,Z}_{E,M} = \left(1 - 4\,\frac{2}{3}sin^2(\theta_W)\right)G^u_{E,M} - \left(-1 + 4\,\frac{1}{3}sin^2(\theta_W)\right)\left(G^d_{E,M} + G^s_{E,M}\right), \qquad (2)$$

where the $G^i_{E,M}$ are the contributions of quark flavor i to the overall current. These expressions are exact to the extent that the quarks are point-like, Dirac particles (and neglecting the contributions of the higher mass quarks c, b and t). In order the determine the contributions of the three lightest flavors independently, a third combination is required; assuming charge symmetry [3] the electromagnetic form factors of the neutron may be written in terms of the contributions to the proton described above

$$G^{n,\gamma}_{E,M} = \frac{2}{3}G^d_{E,M} - \frac{1}{3}\left(G^u_{E,M} + G^s_{E,M}\right) \qquad (3)$$

The three linearly independent combinations $G^{p,\gamma}$, $G^{n,\gamma}$ and $G^{p,Z}$ can then be used to extract the three contributions G^u, G^d and G^s.

It is useful to recall the conditions that will lead to non-zero $G^s_{E,M}$. As the vector currents measure the algebraic sum of the quark and anti-quark contributions for a given flavor (notice that it is the charge of the *quark* that is factored out of the above expressions), in order for G^s_E to be non-zero, the strange quarks and anti-quarks would have to have different spatial distributions. This is not such an unusual picture; recall that the fluctuation of a proton to a neutron and π^+ results in a spatial "polarization" of the $d\bar{d}$ pair produced. This same difference in s and $\bar{s}$ spatial distributions must be present in order to generate a convection current contribution to G^s_M. The spin contribution to G^s_M is quite different, however. If the $s\bar{s}$ pair is produced in a spin singlet, the s and $\bar{s}$ magnetic moments will be parallel and thus contribute to G^s_M even if the spatial distributions of s and $\bar{s}$ are the same. A related question, whether the s and $\bar{s}$ momentum distributions are the same, has recently been re-addressed in connection with the NuTeV experiment [4].

The interference between the electromagnetic and neutral weak currents is isolated in the parity-violating asymmetry in electron-nucleon scattering, which may be written

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{A_E + A_M + A_A}{D} \tag{4}$$

where

$$\begin{aligned}
A_E &= \epsilon(\theta) G_E^\gamma G_E^Z, \\
A_M &= \tau G_M^\gamma G_M^Z, \\
A_A &= -\left(1 - 4\sin^2\theta_W\right)\sqrt{\tau(1+\tau)(1-\epsilon(\theta)^2)} G_M^\gamma G_A^Z, \\
D &= \epsilon(\theta)\left(G_E^\gamma\right)^2 + \tau\left(G_M^\gamma\right)^2, \text{ and} \\
\epsilon(\theta) &= \left[1 + 2(1+\tau)\tan^2\theta/2\right]^{-1}
\end{aligned}$$

and is typically of order -10 ppm at a momentum transfer of $Q^2 \sim 0.5$ GeV^2. The three parts of the asymmetry, involving the unknown form factors G_E^Z, G_M^Z and G_A^e, may be separated by measuring at different electron scattering angles (for the first two) and by measuring quasi-elastic scattering in deuterium (mostly sensitive to the axial term G_A^e) [1].

The axial vector contribution is of significant interest in these measurements because of its relation to the weak interaction between quarks in the target. The lowest order process is identical to that in elastic neutrino scattering from the nucleon; however, because the electron is charged there are significant corrections due to effective weak interactions of photons. As photons fluctuate to fermion pairs (leptons and quarks), the subsequent annihilations can involve weak interactions, e.g. production of a Z boson which then interacts with the quarks in the target. The key point here is that the only contributions of this sort that the experiment is sensitive to are those that violated parity, hence the requirement for a weak interaction in the overall amplitude. This *effective* weak interaction of the photon with a composite target was called the anapole moment by Zel'dovich [5]. The size of these effects has been estimated to be about 30% [6] in agreement with the results from the SAMPLE experiment [7] (see Section 3). They may be considered in the context of a picture in which the photon "measures" the degree to which quarks in the nucleon have a longitudinal spin component (i.e. a spin component parallel to their momenta); an analog of the explanation for the anapole moment of the Cs nucleus [8] by Bouchiat and Piketty [9].

3 Experiments

Parity-violating electron scattering experiments have recently been performed at the MIT-Bates, Mainz MAMI and Jefferson Lab accelerators. They have in common high current, high polarization electron beams and long cryogenic targets; the detection schemes differ and are discussed below. Because the parity-violating asymmetries are so small, helicity-correlated beam parameters must also be carefully controlled to reduce false asymmetries. Such controls, involving, for example, very careful optical treatment of the laser beam used to generate the electrons and feedback to reduce helicity-correlated beam current variations, are now routine, and the overall effects in the most recent measurements have become a small contribution to the overall uncertainties.

The SAMPLE experiment (at MIT-Bates) has recently reported final results for its program of measurements [10,7]. In this experiment, an air Cherenkov detector was used to detect the scattered electrons from a 40 cm LH$_2$ target over a large backward angle acceptance (1.5 sr) by integrating photomultiplier tube signals. It is the last of the electron-parity violation experiments to use bulk GaAs photocathodes ($P_e \sim 35\%$) in the polarized electron source. Three measurements were made: hydrogen and deuterium targets with 200 MeV incident energy electrons ($Q^2 = 0.1$ GeV^2), and a deuterium target at 125 MeV incident energy ($Q^2 = 0.04$ GeV^2). The 200 MeV results have changed relative to the preliminary report. Three corrections (connected with ordinary radiative corrections, background asymmetries and pion production backgrounds) of order 4% each, and all in the same direction, increased the magnitude of the asymmetries. The deuterium measurements are in agreement with the theoretical calculation of G_A^e in [6]; combining the theoretical value with the hydrogen measurement yields the value

$$G_M^s(Q^2 = 0.1\text{GeV}^2) = +0.37 \pm 0.20 \pm 0.26 \pm 0.07 \tag{5}$$

where the uncertainties are statistical, systematic and the overall uncertainty radiative corrections, respectively. These results are presented in Fig. 1. Note that these results are mostly sensitive to the isovector contribution to G_A^e; the small isoscalar contribution is taken from theory. The uncertainties in the SAMPLE experiment are dominated by background and helicity-correlated beam parameter correction contributions.

The HAPPEX experiment (at Jefferson Lab) has reported final results from its first measurement [11,12]. This experiment was performed by integrating the signals from lead acrylic shower counters placed in the focal regions of each of the high resolution spectrometers in Jefferson Lab Hall A. The measurement utilized a 15 cm LH$_2$ target with an incident energy of 3.2 GeV and an average scattering angle of 12.3° giving an average $Q^2 = 0.477$ GeV^2. High polarization ($\sim 70\%$) "strained cathode" electron sources were used for these measurements. This is a notable step forward for these measurements as the final uncertainty is $\propto 1/P_e$.

The result for the asymmetry is

$$A(Q^2 = 0.477\text{GeV}^2) = -15.05 \pm 0.98 \pm 0.56\text{ppm}. \tag{6}$$

The experimental precision is clearly limited by statistics; the largest sources of systematic uncertainty are from the beam polarization measurement ($\Delta P_e/P_e = 3.2\%$) and the determination of Q^2 ($\Delta Q^2/Q^2 = 1.8\%$). Because the experiment involved forward electron scattering the asymmetry (see (4)), only a linear combination of G_E^s and G_M^s can be determined, in this case

$$G_E^s + 0.392 G_M^s = 0.014 \pm 0.020 \pm 0.010 \tag{7}$$

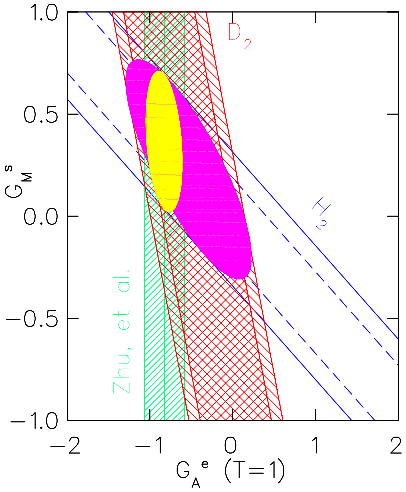

Fig. 1. Combined results from SAMPLE 200 MeV measurements with hydrogen and deuterium targets [10,7]. The *inside error bands* represent the statistical uncertainty, the *outer bands* the statistical and systematic uncertainties combined in quadrature. The *smaller ellipse* corresponds to a combination of the theoretical result of Zhu et al. [6] and the hydrogen measurement

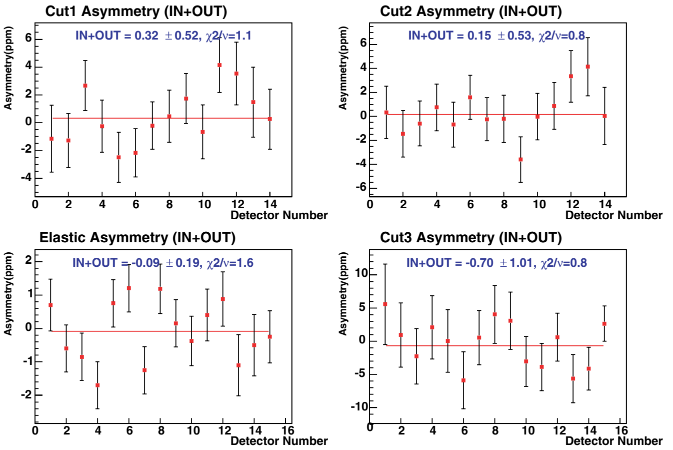

Fig. 2. False asymmetries measured in the forward angle G0 measurement for 4 regions of the proton time-of-flight spectrum. These asymmetries are computed by adding the asymmetries obtained in the two different "half-wave plate" states (a $\lambda/2$ plate is inserted in the polarized source laser line, reversing the sign beam polarization by non-electronic means). Cuts 1 and 2 correspond to protons of higher momentum, cut 3 to protons of lower momentum than the elastic protons

consistent with zero. In this case the first uncertainty corresponds to total experimental value (statistical and systematic added in quadrature); the second to the uncertainty due to the various electromagnetic nucleon form factors (dominated by the uncertainty in G_M^n). The program in Hall A is continuing with measurements on hydrogen and ^{4}He targets at a momentum transfer of $Q^2 = 0.11$ GeV^2. These experiments acquired a significant fraction of their data in Summer 04 and will continue next year.

The PVA4 experiment (at Mainz) has reported a result from its first measurement [13]. In this experiment, individual electrons were detected in a large solid angle array of PbF$_2$ crystals ($\Delta\Omega = 0.62$ sr with 1/2 the eventual set of 1022 crystals), using a fast trigger to separate elastic and inelastic scattering. This is the first parity-violating electron scattering experiment to count particles rather than integrating signals. The measurement was made at angles between 20 and 30 degrees using a beam of 854 MeV electrons incident on a 10 cm LH$_2$ target. The average momentum transfer for this measurement is $Q^2 = 0.23$ GeV^2; it measures a combination of G_E^s and G_M^s.

The result for the asymmetry is

$$A(Q^2 = 0.230\text{GeV}^2) = -5.44 \pm 0.54 \pm 0.26\text{ppm} \tag{8}$$

to be compared with the "no-strange-quarks" value of

$$A_{ns}(Q^2 = 0.230\text{GeV}^2) = -6.30 \pm 0.43\text{ppm}. \tag{9}$$

Again, this experimental result is limited by statistics; the systematic uncertainties are also dominated by the beam polarization measurement ($\Delta P_e/P_e = 3.2\%$). The extracted value for the linear combination of form factors is

$$G_E^s + 0.225 G_M^s = 0.039 \pm 0.034, \tag{10}$$

this time about 1σ away from zero. The uncertainty here is just that of the experiment. A new measurement at the same scattering angle and a momentum transfer of about $Q^2 = 0.1$ GeV^2 has recently been completed. It also yields an asymmetry which is significantly smaller in magnitude than the no-strange value [14]. The PVA4 measurements will continue at backward angle starting in 2005.

The G0 experiment (at Jefferson Lab) will measure asymmetries at both very forward and backward electron scattering angles. In order to do this, recoil protons are detected for the forward angle asymmetry; electrons are detected for the backward angle asymmetry. These particles are measured in a superconducting magnetic spectrometer with a maximum momentum of about 800 MeV; in one orientation, the recoil protons are detected at a scattering angle of about 70°, in the other, electrons are detected at the complementary angle of 110°. With these capabilities, the spectrometer allows for measurements of asymmetries in the range $0.1 < Q^2 < 1.0$ GeV^2 for both the forward and backward cases. The physics goal of the experiment is to measure the separated strange quark contributions (G_E^s and G_M^s) at the level of a few percent of the electromagnetic form factors, and G_A^e with a precision of roughly ± 0.2 (compare to $G_A \sim -1.25$) over the range of momentum transfers above.

The forward angle G0 measurement was completed in May 2004 and the data are being analyzed. The false asymmetries are again expected to be small in this experiment. An indication of the quality of the data is shown in Fig. 2. The uncertainties in this experiment are expected to be dominated by contributions from background corrections particularly at higher momentum transfer. The beam polarization is measured with 1-2% uncertainty in Hall C and is therefore a less pronounced contributor than in the HAPPEX and PVA4 experiments.

4 Discussion

There have been many calculations of the strange quark contributions to nucleon form factors (see [2] for a recent summary). A new calculation by the Adelaide group [15] sets a very high standard of precision and provides a sense of where such calculations are at the moment. Based on charge symmetry applied to groups of baryons and assuming, for example, that the contributions of the sea u and d quarks in the proton are the same, quenched lattice calculations (with chiral extrapolations to physical pion masses) are used to calculate ratios connecting the groups and arrive at the contribution of strange quarks to the magnetic moment of the proton. Their result is $\mu_s = -0.051 \pm 0.021$, certainly a challenge for experiment.

In more general terms, our picture of nucleon sea now has some interesting components. The E866 experiment at Fermilab and the Gottfried sum before it has shown that at certain small scales at least, the u and d quarks in the proton sea live long enough to interact with the "medium" (since they have different momentum distributions and carry different fractions of the total momentum). The sea therefore appears not to be inert (which it could have been). At these and longer distance scales an important question is whether these quarks, as a result of interactions, tend to group themselves into objects which resemble the asymptotic meson and baryon states, e.g. in the case of the proton into a neutron and π^+. In certain contexts, this picture of a hadronic expansion has served very well; in the end, there is little or no direct evidence of its correctness. Strange quarks, probed in parity-violating electron scattering experiments, provide a unique window on the sea of the nucleon at large distance scales. If they "live long enough" to interact with the medium, they could help answer the questions posed above regarding the u and d sea quarks. At this stage of our understanding, it is not clear what the effect of their higher mass ($\sim \Lambda_{QCD}$) will be. If the experimental results indicate contributions to the nucleon form factors smaller than a few %, as perhaps suggested by the HAPPEX results, we will have learned that they don't interact, thrusting the question about the mass dependence of interactions to the forefront. Non-zero signals, perhaps hinted at by the PVA4 results, will continue to challenge us to find the most efficient low energy theory and effective degrees of freedom that incorporate the characteristics of the sea.

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