Eur Phys J A (2005) **24**, s2, 51–54
DOI: 10.1140/epjad/s2005-04-011-5

EPJ A direct
electronic only

Updated results from the SAMPLE experiment

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Received: 15 November 2004 / Published Online: 8 February 2005

Abstract. The SAMPLE collaboration has recently completed its measurements of the parity violating elastic electron scattering asymmetry from hydrogen and the quasielastic asymmetry from deuterium [1, 2,3,4,5]. Neutral weak form factors of the nucleon, both vector and axial, can be extracted from these data and used to determine the strange quark contribution to electromagnetic form factors. The results of the original measurements at a Q^2 of 0.1 (GeV/c)^2 [2,3] have recently been reanalyzed [4], incorporating improvements in simulation and new background data, and combined with a new measurement of the quasielastic deuteron asymmetry at a Q^2 of 0.038 (GeV/c)^2 [5]. Final results from this new analysis and data set will be presented.

PACS. 13.60.-r Photon and charged-lepton interactions with hadrons – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 13.40.Gp Electromagnetic form factors – 14.20.Dh Protons and neutrons

1 Introduction

In the simplest, nonrelativistic quark model protons and neutrons are composed of three heavy ($\approx$ 300 MeV/c^2), valence up (u) and down (d) quarks. In this model the various static properties of the nucleons such as mass and intrinsic spin are explained quite well in terms of the properties of the valence quarks. However, the full theory that describes the structure of nucleons and folds in the Standard Model and quantum chromodynamics (QCD) has the valence quarks as very light ($\approx$ 10 MeV/c^2) particles. Furthermore, the valence quarks are surrounded by a sea of gluons and quark-antiquark pairs. This quark sea can contain the heavier quarks such as the strange (s) as well as the lighter u and d. A full description of the properties of the nucleon must account for the presence of these quark-antiquark pairs.

A variety of experiments have detected nonzero strange quark contributions to static nucleon properties such as spin, mass, and momentum (see [6] for a recent review). Given that other low energy nucleon properties contain non-zero contributions from strange quarks it is natural to wonder how these quarks contribute to the electric and magnetic properties of the proton: the charge radius and the magnetic moment. These properties arise from the proton's vector strange matrix element $\langle p|\bar{s}\gamma^\mu s|p\rangle$, a quantity that can be determined by measuring the proton's neutral weak magnetic form factor G_M^Z [7]. A method for measuring G_M^Z using parity violating elastic electron scattering was proposed by Beck and McKeown [8,9]. This experimental technique has formed the basis for several past and present experiments trying to probe the strange quark contribution to the electric and magnetic properties of the nucleon. This paper discusses results from one of these experiments, SAMPLE, that was performed at the MIT/Bates Linear Accelerator Center in the late 1990s/early 2000s. For a recent review of this experiment see [6].

In the scattering of electrons from nucleons via the electromagnetic interaction (exchange of a virtual photon γ) the finite extant of the nucleon is parameterized by the electric and magnetic form factors G_E^γ and G_M^γ. These form factors are functions of the momentum transferred by the exchanged photon, or four-momentum transfer squared Q^2. An analogous pair of form factors, G_E^Z and G_M^Z, arise from the same scattering process when a neutral weak Z^0 boson is exchanged instead of a γ. The electromagnetic and neutral weak form factors for the proton (p) and the neutron (n) can be expressed in terms of contributions from the three lightest quarks u, d, and s [10]. If charge symmetry is assumed (see [11] for a discussion of the validity of this assumption), that is to say that the distribution of u quarks in the proton is the same as that of d quarks in the neutron, then the neutral weak form factors can be written in terms of the electromagnetic form factors and a strange quark contribution (to lowest order)

$$G_{E,M}^Z = \left(1 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^s. \quad (1)$$

The neutral weak interaction brings in a third form factor known as the axial form factor G_A^e; to lowest order it is written as follows

$$G_A^e = -\tau_3 G_A + \Delta s \quad (2)$$

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where $\tau_3 = 1(-1)$ for $p(n)$, $G_A(Q^2 = 0) = -(g_A/g_V) = 1.2670 \pm 0.0035$ as measured in β-decay experiments [12], and Δs is the strange quark contribution to the nucleon spin. Equations 1 and 2 both have higher order electroweak radiative corrections that are not considered here (see [10] for details).

It would be extremely difficult to measure $G^Z_{E,M}$ with a straight cross-section measurement due to the difference in coupling strengths between EM and neutral weak interactions. However, the parity violating nature of the weak interaction can be exploited to make the measurement feasible. If a beam of longitudinally polarized electrons is scattered from a target of unpolarized electrons and the helicity (product of the electron spin and momentum directions) of the electrons is changed, then the cross section asymmetry A_{PV} is sensitive to the neutral weak interaction at leading order

$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{A_E + A_M + A_A}{\left[\epsilon \left(G^\gamma_E\right)^2 + \tau \left(G^\gamma_M\right)^2\right]} \tag{3}$$

where G_F is the Fermi coupling constant and α is the fine structure constant. The other terms in 3 are defined as follows

$$A_E = \epsilon G^Z_E(Q^2) G^\gamma_E(Q^2) \tag{4}$$

$$A_M = \tau G^Z_M(Q^2) G^\gamma_M(Q^2) \tag{5}$$

$$A_A = -\left(1 - 4\sin^2\theta_W\right)\sqrt{\tau(1+\tau)(1-\epsilon^2)} \times G^e_A(Q^2) G^\gamma_M(Q^2) \tag{6}$$

$$\tau = \frac{Q^2}{4M_N^2} \tag{7}$$

$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2\frac{\theta}{2}} \tag{8}$$

where M_N is the mass of the nucleon.

At backward scattering angles the A_E term in 3 is negligible relative to the other two terms so a measurement of A_{PV} on the proton A_p is sensitive to G^s_M and G^e_A. The isovector piece of G^e_A is not well-constrained by theory or experiment, necessitating an additional measurement to extract it. This additional measurement comes from measuring A_{PV} for the deuteron A_d. If one assumes the static approximation is true for the deuteron, i.e. it is essentially a free proton and neutron, then one can write A_d in terms of A_p and A_n

$$A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_p + \sigma_n} \tag{9}$$

where $\sigma_{p(n)}$ is the cross-section for elastic $e - p(n)$ scattering. The deuteron asymmetry is sensitive to G^s_M and $G^e_A(T=1)$ (the isovector piece of G^e_A) as well, therefore, a measurement of A_p and A_d at backward scattering angles and a fixed Q^2 should allow G^s_M to be uniquely determined.

2 Experiment

The SAMPLE experiment was performed at the MIT/Bates Linear Accelerator Center in Middleton, MA; the target and detector apparatus were installed in the North Hall. The proton asymmetry was measured at a beam energy of 200 MeV during the summer of 1998 [2]. The deuteron asymmetry was measured at two different beam energies: 200 MeV during the summer of 1999 [3] and 125 MeV during the fall of 2001 and spring of 2002 [5]. The original proton and deuteron results at 200 MeV were updated after the completion of the 125 MeV data-taking [4,5].

Longitudinally polarized electrons were generated in the polarized source by photoemission from a bulk gallium arsenide (GaAs) crystal; a Ti:Sapphire laser provided the circularly polarized photons used to emit the electrons. The helicity Pockels cell (HPC) was used to reverse the laser and electron polarizations 600 times a second. A correction Pockels cell (CPC), set to function as an intensity adjuster, was also placed in the laser line to reduce the helicity correlated charge asymmetry measured in the experimental hall. A position feedback system consisting of a piece of optical glass on a piezoelectric mount was used to reduce the helicity correlated position differences measured in the hall by adjusting the position of the laser spot on the cathode in a helicity-correlated way [13]. The electron spins were precessed away from the longitudinal in a Wien filter prior to injection into the main accelerator to compensate for the 36.5° bend the electrons went through as they entered the experimental hall.

In the accelerator the electrons were accelerated to the final beam energy of 125 or 200 MeV. At the end of the accelerator was an energy feedback system that reduced the fluctuations in the electron beam energy [14]. Dipole magnets bent the electrons through 36.5° onto the North Hall beam line. Prior to entering the experimental hall the electrons passed through a region containing a Møller polarimeter that could be used to measure the beam polarization in dedicated, low-current runs. Upon entering the hall the electron beam passed through a series of toroids and RF cavities used to measure the beam current and position of each beam pulse. A set of Čerenkov detectors (lucite coupled to photomultiplier tubes) were placed symmetrically about the beamline upstream of the target to monitor the halo about the electron beam and another set were placed downstream to measure the luminosity.

The experimental apparatus, shown in Fig. 1 consisted of a high-power cryogenic target encased in a lead-lined scattering chamber [15]. The scattering chamber was enclosed in a large, light-tight box that also contained the detector package. The detector package consisted of an array of ten, large ellipsoidal mirrors symmetrically placed about the scattering chamber at backward angles. The mirrors focused Čerenkov light from back-scattered particles onto a corresponding array of 8 inch photomultiplier tubes (PMT) encased in lead shielding. Each PMT was read out by a channel of integrating electronics; the current from each PMT anode was sent to a current-to-voltage converter before being integrated and digitized.

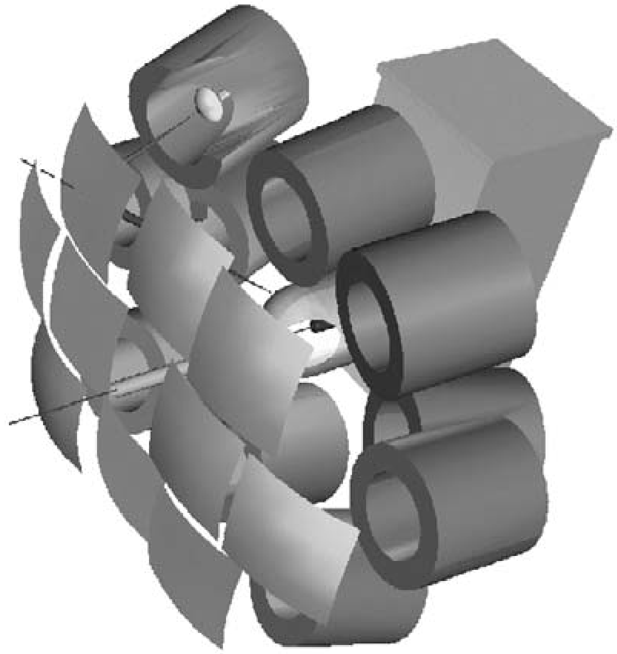

Fig. 1. This is a schematic of the SAMPLE target and main detector apparatus. The electron beam enters from the *left* and strikes the target which is shown inside the scattering chamber in a cutaway view

In this mode of operation there was no way to separate the background events from the signal. Dedicated runs of various types were used to measure the background contribution.

3 Analysis

The first step in the data analysis was to calculate the raw detector asymmetry for beam pulses of positive and negative helicity. Simultaneously, the sensitivity of the detectors to changes in the various beam parameters were calculated. In the next step of the analysis this information on detector sensitivity was used to remove any beam parameter dependence from the measured asymmetry.

After this correction had been performed, corrections for various background processes were applied as given by the following expression

$$A_{exp} = \frac{R_C}{P_B f_l f_e (1 - f_\pi)} \left[A_O - (1 - f_l) A_C \right] \qquad (10)$$

where R_C is an electromagnetic radiative correction, P_B is the measured beam polarization, f_l is the fraction of the yield due to light on the PMTs, f_e is the fraction of the light signal due to Čerenkov events, and f_π is the fraction of the Čerenkov light due to pion production. The quantity A_O is the beam parameter corrected asymmetry measured under normal running conditions; A_C is the same asymmetry measured with shutters drawn over the PMTs to block out the light signal. The final quantity A_{exp}, where exp is p or d depending on whether the target is full of hydrogen or deuterium, was combined with the theoretical asymmetry in order to extract G_M^s and $G_A^e(T=1)$.

A variety of improvements were made to the data analysis and theoretical calculations between the publication of the original results [2,3] and the final results [4, 5]. In both the hydrogen and deuterium 200 MeV data sets an improved Monte Carlo code was used, based on GEANT [16], that incorporated the geometry of the target and detectors. This code was used to calculate the electromagnetic radiative corrections R_C due to internal and external bremsstrahlung processes as well as the theoretical asymmetry used for the form factor extraction [17]. The pion dilution factor was a new addition to the analysis; it was not present in the original publications. New calculations by Schiavilla were incorporated into the theoretical deuteron asymmetry to account for both quasielastic scattering and threshold breakup. Finally, the treatment of a ϕ dependent background process in the hydrogen measurement was altered (see [6] for details). The effect was to increase the experimental asymmetry in each data set by about 10-15% and reduce the theoretical asymmetry by 3-5%.

The third set of SAMPLE data, on deuterium at a beam energy of 125 MeV, were taken to serve as a cross-check on the original 200 MeV deuteron result. The original deuteron measurement [3] resulted in a value for $G_A^e(T=1)$ that deviated significantly from the theoretical value [18].

4 Results

Updated results for the measured asymmetries on the proton and deuteron are listed below. The results are taken from [5] and [4] (all Q^2 are in units of $(\mathrm{GeV/c})^2$)

$$A_p(Q^2 = 0.1) = (-5.61 \pm 0.67 \pm 0.88) \quad \mathrm{ppm} \qquad (11)$$

$$A_d(Q^2 = 0.091) = (-7.77 \pm 0.73 \pm 0.72) \quad \mathrm{ppm} \qquad (12)$$

$$A_d(Q^2 = 0.038) = (-3.51 \pm 0.57 \pm 0.58) \quad \mathrm{ppm} \qquad (13)$$

where the first error is statistical and the second is systematic. The updated theoretical asymmetries, taking into account the detector geometry, are

$$A_p(Q^2 = 0.1) = -5.56 + 3.37 G_M^s + 1.54 G_A^{e(T=1)} \qquad (14)$$

$$A_d(Q^2 = 0.091) = -7.06 + 0.72 G_M^s + 1.66 G_A^{e(T=1)} \qquad (15)$$

$$A_d(Q^2 = 0.038) = -2.14 + 0.27 G_M^s + 0.76 G_A^{e(T=1)} \qquad (16)$$

from [5] and [4].

Figure 2 shows the deuteron asymmetry measured at 125 and 200 MeV as a function of Q^2. The result of theoretical calculations for A_d based on [18] are shown as well. The good agreement between theory and experiment shown in this plot from [5] motivated the use of the theoretical calculation for $G_A^e(T=1)$ in the final result for G_M^s quoted in [4]. Figure 3 is taken from [4] and shows the region allowed by the measurement of A_p on hydrogen at

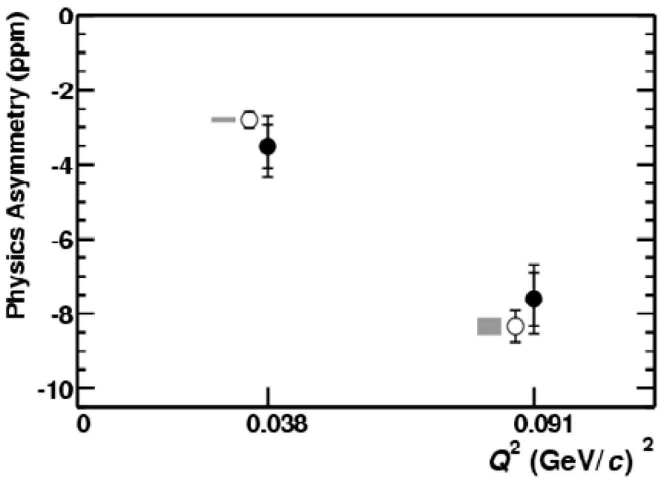

Fig. 2. This is a plot of the deuteron asymmetry A_d as a function of Q^2. The *filled circles* are the data from the 125 and 200 MeV SAMPLE runs (statistical and systematic error bars are shown). The *empty circles* are the theoretical prediction for A_d using [18] for the multi-quark radiative corrections and a value of 0.15 for G_M^s. The *grey bands* show the change in A_d as G_M^s is changed by ± 0.3 n.m. The figure is from [5]

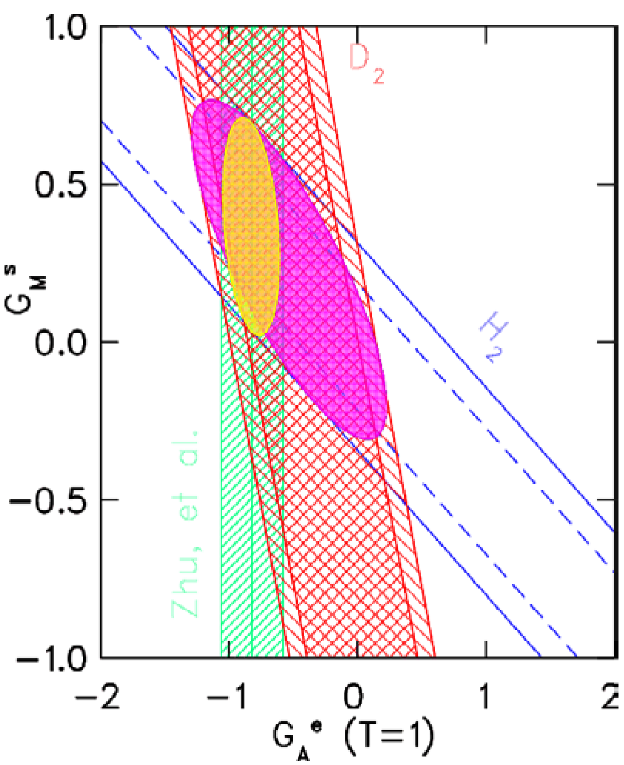

Fig. 3. This is a plot of G_M^s versus $G_A^e(T=1)$ and shows the region allowed by the various SAMPLE measurements. The *open* and *cross-hatched bands* are the regions allowed at the one sigma level by the 200 MeV hydrogen and deuterium measurements, respectively. The *vertical, hatched band* is the theoretical calculation of $G_A^e(T=1)$ based on [18]. The *small oval* is the final result reported in [4]

200 MeV and the theoretical calculation of $G_A^e(T=1)$. Using the theoretical value of -0.83 ± 0.26 for $G_A^e(T=1)$ results in

$$G_M^s(Q^2 = 0.1) = 0.37 \pm 0.20 \pm 0.26 \pm 0.07 \qquad (17)$$

where the errors are due to statistics, systematics, and the uncertainty on the electroweak radiative corrections [4]. This is lower than, but consistent with, the earlier result quoted in [3].

5 Conclusion

The SAMPLE collaboration has performed an important series of measurements of the parity violating electron scattering asymmetries from the proton and the deuteron. These measurements have made it possible to extract, for the first time, the strange quark contribution to the magnetic form factor of the nucleon; a quantity that is directly related to the magnetic moment of the proton and the neutron. This strange quark contribution was found to be slightly positive. The measurements of the deuteron asymmetry can also be used to place constraints on the quantities C_{2u} and C_{2d} which represent electron-quark axial couplings in the Standard Model [6]. The SAMPLE collaboration has also performed the first ever measurement of a single spin asymmetry for scattering of transversely polarized electrons from an unpolarized proton target [19]. These measurements are sensitive to two-photon exchange diagrams in $e - N$ scattering.

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