Contributions of Strange Quarks to Proton Structure

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Abstract. A number of measurements of elastic, parity-violating, electron-proton scattering have recently been completed and show some evidence for non-zero contributions of strange quarks to the ordinary charge and magnetization distributions of the nucleon. In this talk, I provide a brief review of the framework for, and description of, these experiments and discuss the results. The contribution of strange quarks to the magnetic form factor of the proton is determined to be -0.21 ± 0.11 n.m. at $Q^2 = 0.1$ GeV^2, and there is a hint that the radius of the strange quark distribution is larger than that of the anti-strange quarks. These findings suggest, therefore, that the strange quarks in the sea interact in a non-trivial way with the other fields making up the proton.

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INTRODUCTION

The detailed structure of hadrons continues to be an important puzzle in modern physics. The low-energy sector of QCD challenges our ability to construct an economical picture of its essential physics. One of the key issues is the role of the virtual quark and gluon fields. The contrast between the hydrogen atom and the proton as example systems is illustrative in this regard. Whereas the mass of the hydrogen atom is approximately that of its constituents, the mass of the proton greatly exceeds that of its constituent valence quarks. Indeed, the effect of the sea leptons in the hydrogen atom (via the Lamb shift) is of order 10^{-6} (α^3); the corresponding effects in the proton are largely unknown but likely to be much more significant. Measurements of strange quark effects in the proton provide a unique window on the low energy sea of QCD.

There have been a number of indications that the strange quark contributions to proton structure are non-zero. For example, the momentum carried by strange quarks is well established to be about 0.4 of that carried by u or d sea quarks [1]. The scalar matrix element $\langle \bar{s}s \rangle$, as determined from the πN sigma-term, has consistently been interpreted to be a significant fraction (perhaps 0.1 - 0.4) of the corresponding matrix elements of the u or d sea quarks [2]. Similarly, on the basis of spin-dependent deep-inelastic scattering, the fraction of the nucleon spin carried by strange quarks has most often been suggested to be slightly negative [3], although the semi-inclusive measurements from HERMES show no significant indication of a non-zero $\Delta s(x)$ [4]. Extraction of the latter two quantities (scalar and axial-vector matrix elements) is complicated by various aspects of non-perturbative QCD and therefore involves significant model dependence.

The vector matrix elements as determined in elastic electroweak scattering can also be used to determine the contributions of the individual quark flavors [5, 6, 7]. Contributions of the three lightest flavors can be separated using measurements of the electromagnetic form factors of the proton and neutron along with the corresponding neutral weak form factors of the proton. Each such measurement determines a linear combination of currents of the point-like quarks

$$G^i = \sum_{f=u,d,s} e^i_f \left\langle N \left| \bar{q}\gamma_\mu q \right| N \right\rangle \tag{1}$$

where $i = \gamma, Z$ denotes the current and e^i_f is the corresponding charge quark flavor f. An assumption is made that proton and neutron structure are related by exchanging u and d quarks as well as the corresponding anti-quarks [8], leading to the expressions for the contributions in the proton

$$G^{u,p}_{E,M} = \left(3 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{Z,p}_{E,M} \tag{2}$$

$$G^{d,p}_{E,M} = \left(2 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} + G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M} \tag{3}$$

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

One of the important qualitative aspects of the strange quark vector currents is associated with their charge weighting. Because the contributions of s and $\bar{s}$ to, e.g. G^s_E, are opposite in sign, if the s and $\bar{s}$ quarks have the same spatial distribution, G^s_E will be identically zero. Similarly, the convection current contribution to G^s_M will vanish. The magnetic moment of the spin triplet $(^3S_1)$ state vanishes as does that of the spin singlet $(^1P_1)$ state for $s\bar{s}$ pairs with gluon quantum numbers. Therefore, in order for either to be non-zero, the spatial s and $\bar{s}$ distributions must be different. In sum, for G^s_E or G^s_M to be non-zero, the $s\bar{s}$ pairs must "live long enough" to interact with their environment in the nucleon.

As discussed above, the strange quark vector currents can be isolated by supplementing the existing electromagnetic form factor measurements with the corresponding measurement of the neutral weak current. It can be measured in elastic neutrino scattering [9] or in parity-violating electron scattering [10]. In the case of parity-violating scattering, the interference of the electromagnetic and much smaller neutral weak amplitudes is measured by virtue of its parity-violating property. The elastic scattering asymmetry for right- and left-handed electrons may be written

$$A = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\varepsilon G^\gamma_E G^Z_E + \tau G^\gamma_M G^Z_M - (1 - 4\sin^2\theta_W)\varepsilon' G^\gamma_M G^e_A}{\mathscr{D}} \tag{5}$$

where

$$\tau = \frac{Q^2}{4M_p^2},\ \varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1},$$

$$\mathscr{D} = \varepsilon(G^\gamma_E)^2 + \tau(G^\gamma_M)^2,\ \text{and}\ \varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}.$$

From these measurements the neutral weak analogs of the electric and magnetic form factors can be determined by measuring at forward and backward electron scattering angles; the axial vector form factor can be determined from quasi-elastic scattering from deuterium at backward scattering angles [11]. The scale of the asymmetries is 10 ppm for momentum transfers of about 0.5 GeV^2.

EXPERIMENTS

A number of parity-violating electron scattering experiments have been undertaken over the past ten years. Of particular interest here are those with hydrogen and deuterium targets. This program began with the SAMPLE experiment at MIT-Bates and has continued at Mainz and at Jefferson Lab.

The experiments have a number of common features which all derive from the small size of the asymmetry at the momentum transfers of interest ($0.1 \leq Q^2 \leq 1$ GeV^2). The luminosity generally exceeds 10^{38} cm^{-2} s^{-1} to ensure a high counting rate ($\Delta A = 1/\sqrt{N}$ where N is the total number of counts). The detectors are configured to accept as large a fraction of the azimuthal range as possible.

Systematic effects must be controlled at the same level as the statistical uncertainty. This is generally accomplished through careful control of the electron beam. The remarkable precision of these experiments is due primarily to the ability to control the position, intensity and polarization of the laser beam used to produce the electron beam (via the photoelectric effect). Whereas, e.g., the average position of the beam may change throughout the experiment, the average beam position *difference* for the right- and left-handed beams is the critical quantity. Typically, averaged over the entire experiment, the beam intensity asymmetry is controlled at the ppm level, that of the energy at the 0.01 ppm level and the beam position differences (and associated angular differences) at the 10 nm level.

Subsequent to the first measurement in this series – $Q^2 \cong 0.1$ GeV^2 scattering at backward angles from hydrogen and deuterium targets in the SAMPLE experiment [12] – the emphasis has shifted to forward angle scattering. Six measurements have been reported. In Hall A at Jefferson Lab, the HAPPEx collaboration has used the high resolution spectrometers to measure scattering at very forward angles. A first measurement [13] at $Q^2 = 0.48$ GeV^2 was made several years ago and more recently the first results from measurements on hydrogen [14] and helium[1] [15] targets at $Q^2 \cong 0.1$ GeV^2 have been reported. A new HAPPEx measurement at $Q^2 = 0.63$ GeV^2 and with uncertainties approximately 3 times smaller than those of their original measurement has recently been approved. In Mainz, a large, dedicated array of PbF_2 crystals and a corresponding set of custom electronics has been used by the A4 collaboration to measure forward asymmetries at $Q^2 \cong 0.1, 0.23$ GeV^2 [16, 17]. This apparatus has now been turned around to measure backward asymmetries on hydrogen and deuterium targets. In Hall C at Jefferson Lab, the G0 experiment utilizes a dedicated superconducting spectrometer to measure both forward asymmetries from a hydrogen target [18] and backward asymmetries from both hydrogen and deuterium. The large acceptance of the G0 spectrometer allowed a range of forward asymmetries $0.1 \leq Q^2 \leq 1$ GeV^2 to be measured

[1] Helium is a spin zero target and therefore sensitive to only G_E^s.

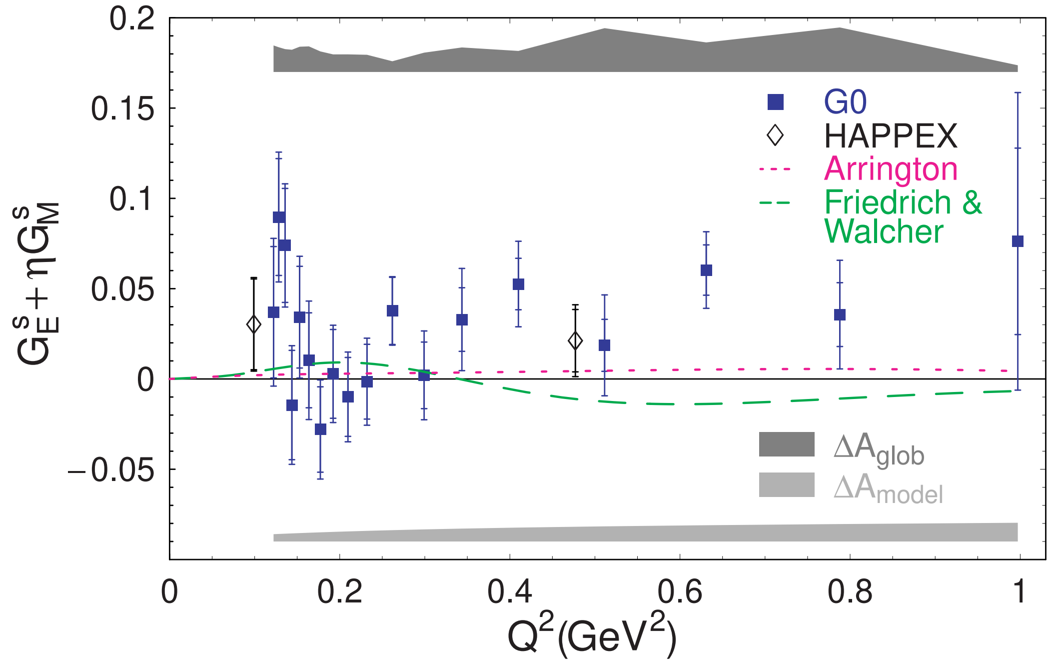

FIGURE 1. Linear combination of strange quark contributions to the charge and magnetic form factors of the proton as measured in the G0 experiment [18]. The inner error bars are statistical; the outer error bars are the sum in quadrature of the statistical and point-to-point systematic uncertainties. The upper error band shows the correlated systematic uncertainty; the lower band the uncertainties in the electroweak form factors including those in G_A^e. The results from the first [13] and second [14] HAPPEx hydrogen measurements, made with essentially identical kinematics, show the good agreement between the experiments. The dashed curves show the effect of different parameterizations of the electromagnetic nucleon form factors [20, 21] (see text for details). The admixture of G_M^s is $\eta \sim Q^2$ for the G0 kinematics.

simultaneously. The G0 apparatus has also been turned around and will begin measuring backward asymmetries from hydrogen and deuterium starting in spring 2006.

RESULTS

The experiments described above in general measure a linear combination of G_E^s and G_M^s

$$G_E^s + \eta G_M^s = \frac{4\sqrt{2}\pi\alpha}{G_F Q^2} \frac{\mathscr{D}}{\varepsilon G_E^\gamma} \left(A_{phys} - A_{NVS}\right), \tag{6}$$

where $\eta\left(Q^2, E_i\right) = \tau G_M^p / \varepsilon G_E^p$ and A_{NVS} is the "no vector strange asymmetry" calculated from Eqn. 5 with $G_E^s = G_M^s = 0$ for all Q^2. Fig. 1 shows the results of the forward angle measurement from the G0 experiment [18] (using the parameterization of the electromagnetic form factors of Kelly [19]). Results of the HAPPEx experiments are also plotted in Fig. 1 because they measure essentially the same linear combination as G0 at their two kinematic points. The dashed curves show the effect of different parameterizations of the electromagnetic nucleon form factors. For example, the value

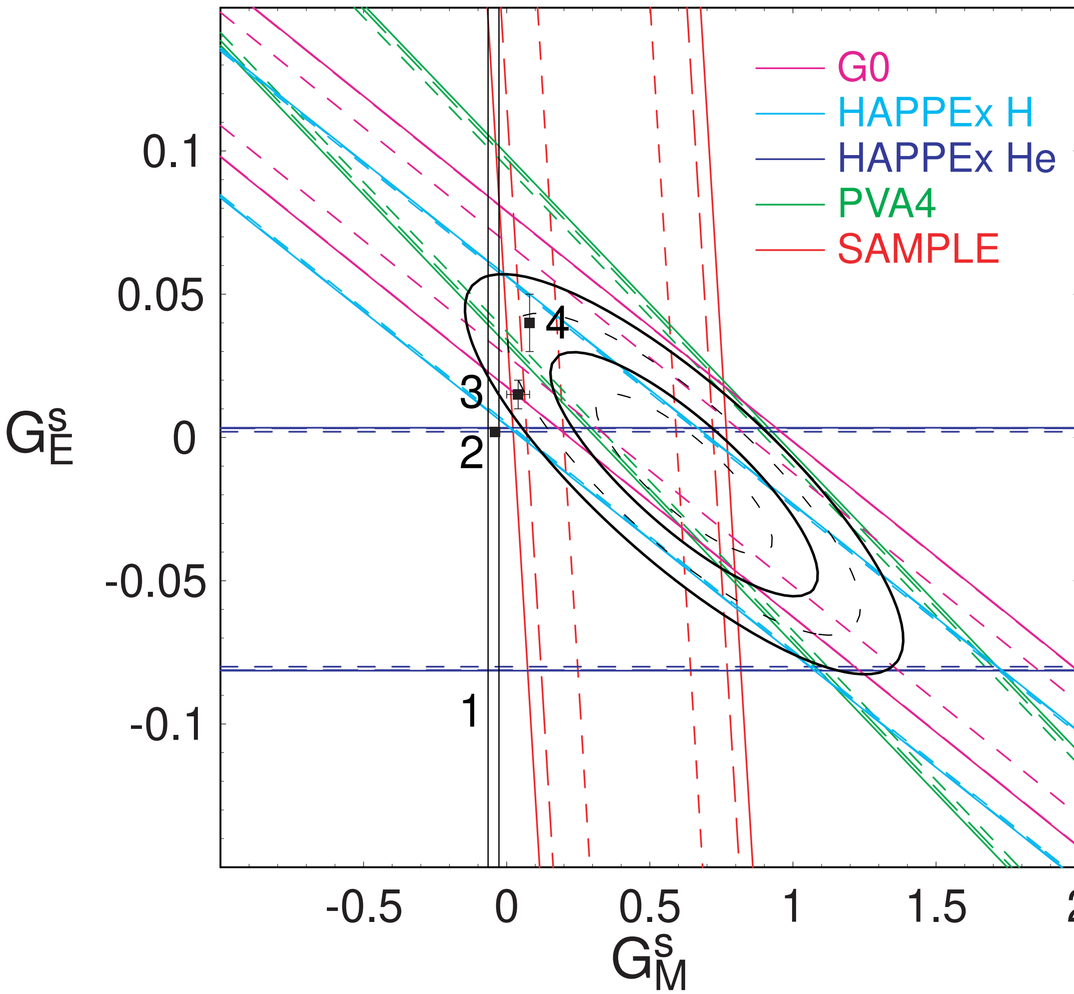

FIGURE 2. Results from the SAMPLE [12], PVA4 [17], HAPPEx hydrogen [14], HAPPEx helium [15] and G0 [18] experiments. The dashed, etc. bands for each experiment indicate, successively, statistical, and the quadrature sums of statistical + systematic, and statistical + systematic + model uncertainties. The solid ellipses indicate the 68 and 96% confidence regions; the corresponding dashed ellipses indicate 1σ and 2σ intervals for each of G_E^s and G_M^s assuming no restriction on the other parameter. A selection of relatively recent calculations are also shown – 1: Leinweber, et al. [22], 2: Lyubovitskij, et al. [23], 3: Lewis, et al. [24], and 4: Silva, et al. [25].

of $G_E^s + \eta G_M^s$ at $Q^2 = 0.63$ GeV^2 increases from 0.059 to 0.072 for parameterization of Ref. [20]. We note that both G_E^s itself and the linear combination $G_E^s + \eta G_M^s$ are zero at $Q^2 = 0$; the leading dependence of the combination in Fig. 1 is linear in Q^2.

We have the largest amount of information near $Q^2 = 0.1$ GeV^2 – five measurements – and it can be combined in a plot of G_E^s vs. G_M^s as shown in Fig. 2. The agreement among the experiments is excellent; the combined results are

$$\begin{aligned} G_E^s &= -0.013 \pm 0.028 \\ G_M^s &= 0.62 \pm 0.31. \end{aligned}$$

Both HAPPEx experiments shown in Fig. 2 (with hydrogen and helium targets) have taken significantly more data than is shown; the expectation is that the statistical uncertainties for these two measurements will shrink by a factor of two or three[2]. From these data one can also determine contributions of the three lightest flavors to the proton and neutron magnetic form factors at $Q^2 = 0.1$ GeV^2

$$G_M^p = 2.12 \ \{u: 2.28 \pm 0.21,\ d: 0.03 \pm 0.11,\ s: -0.21 \pm 0.11\} \tag{7}$$
$$G_M^n = -1.42 \ \{u: -0.07 \pm 0.11,\ d: -1.14 \pm 0.21,\ s: -0.21 \pm 0.11\} \tag{8}$$

Model calculations of G_E^s and particularly of G_M^s have varied considerably; a representative recent sample is shown. Generally, the models tend to favor negative G_M^s, with $G_M^s(Q^2 = 0) \sim -(0.2 - 0.3)$, and positive G_E^s.

SPECULATION

In an effort to better understand all the data, we return to the G0 data (Fig. 1) and consider the significant Q^2 dependence at low and moderate values. As noted earlier, the quantity $G_E^s + \eta G_M^s$ is normalized to zero[3] and increases linearly with Q^2. If we assume a simple dipole shape for G_M^s with a low Q^2 value fixed by the combination of experiments at $Q^2 = 0.1$ GeV^2, the quantity ηG_M^s rises slowly and reaches a maximum at $Q^2 = \Lambda^2$ before falling like $1/Q^4$ at larger momentum transfers as is shown in Fig. 3. The difference between this curve and the data is G_E^s – apparently a negative quantity that has a maximum magnitude near $Q^2 = 0.25$ GeV^2. The G_E^s suggested here is very similar in magnitude and shape to G_E^n albeit with the opposite sign. That G_E^s should turn out to have this shape is, perhaps, not surprising. Just as G_E^n describes the charge distribution of an overall charge neutral object, G_E^s describes the strangeness distribution of an overall zero strangeness object. There is some modest additional support for this picture from the combination of the original PVA4 measurement at $Q^2 = 0.23$ GeV^2 [16] and the G0 data which overlap in a broad region centered around $G_E^s \cong -0.1$ and $G_M^s \cong +0.5$. This momentum transfer will be the focus of backward angle measurements (hydrogen and deuterium) in the PVA4 and G0 experiments.

CONCLUSIONS

Four new forward angle measurements of parity-violating electron scattering from the proton have been released in 2005. These measurements are self-consistent and suggest the following picture of the physics. Together with the older SAMPLE results, G_M^s is determined by these new measurements to be $+0.62 \pm 0.31$ at $Q^2 = 0.1$ GeV^2. There is a hint in the data, particularly from the Q^2 dependence of the G0 measurements, that

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[2] A final combined determination for this momentum transfer also awaits detailed assessment of the effects of the large acceptances in the experiments; a minor impact on the results presented here is expected.

[3] $G_E^s(Q^2 = 0)$ counts the number of strange quarks in the proton and $\eta \propto Q^2$.

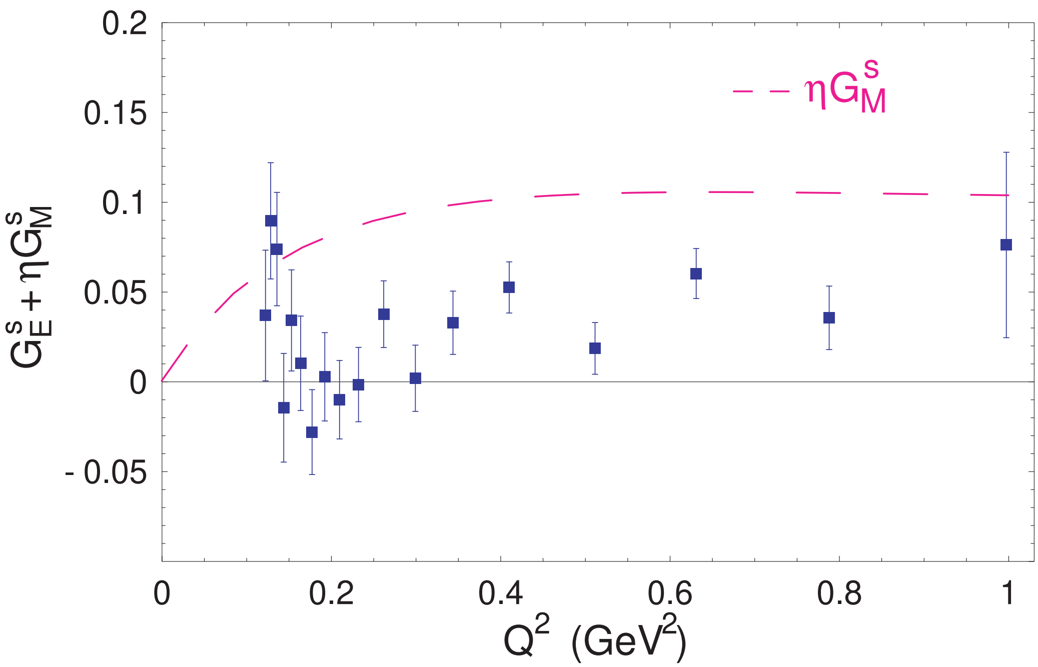

FIGURE 3. G0 forward angle data with a representative dipole form factor for G_M^s using the value at $Q^2 = 0.1$ GeV^2 from Fig. 2. The difference between ηG_M^s and the data is representative of a possible contribution from G_E^s.

G_E^s is negative and approximately the size and shape of G_E^n. If this picture proves to be correct, the quantity $G_E^s + \eta G_M^s$ at forward angles involves a significant cancellation of the two form factors. Most theoretical models predict the opposite signs for each of these form factors.

In order to determine better G_E^s and G_M^s separately, backward angle measurements will be undertaken in the PVA4 and G0 experiments (starting in late 2005). These measurements will be supplemented by completion of the low Q^2 HAPPEx program (providing a more precise separation at $Q^2 = 0.1$ GeV^2) as well as a new, more precise, forward angle measurement at $Q^2 = 0.63$ GeV^2 to complement a G0 backward angle measurement. The latter measurements will provide better information on the possible partial cancellation of the effects of G_E^s and G_M^s in the forward angle data at higher momentum transfers.

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