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Recent results from the SAMPLE experiment

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Abstract. The SAMPLE experiment at MIT-Bates provides measurements of parity-violating electron scattering at backward angles and low momentum transfer. These measurements yield unique information on the contribution of strange quarks to the magnetic moment of the proton and also electroweak corrections such as the anapole moment. Recent results, some possible interpretations, and outstanding issues for the future are discussed.

PACS. 13.60.Fz Elastic and Compton scattering – 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

The role of strange quark-antiquark ($\bar{s}s$) pairs in the quark structure of the nucleon has been a subject of interest for many years. Constituent-quark models do successfully describe many properties of the nucleon by utilizing only up- and down-flavored quarks. However, there is no selection rule forbidding the creation of $\bar{s}s$ pairs by gluons and such quantum fluctuations should certainly be present at some level. Indeed, deep inelastic neutrino scattering experiments indicate that the s and $\bar{s}$ each carry about 2% of the nucleon momentum [1].

It is well known that the electric and magnetic form factors determined in elastic electron scattering provide precise and detailed information on the internal quark structure. Clearly, it is of interest to decompose these quantities into the contributions from the different flavors of quarks and antiquarks. By measuring the electric and magnetic form factors of both the proton and neutron, one has only two quantities of each type, insufficient to determine the contributions of the three relevant flavors (up, down, and strange) to these form factors. It was proposed by Kaplan and Manohar [2] that neutral weak vector form factors could provide the third quantity necessary to perform this flavor decomposition. It was subsequently realized [3,4] that these form factors could be experimentally determined through measurements of parity-violating electron scattering.

2 Theoretical background

2.1 Parity violation in electron scattering

The lowest-order contribution to the parity-violating e-N interaction is associated with the interference of Z-exchange with the dominant electromagnetic amplitude. The parity-violating helicity-dependent asymmetry for elastic electron-proton scattering can be written [5]

$$A = \left[\frac{-G_{\mathrm{F}} Q^2}{4\sqrt{2}\pi\alpha} \right] \cdot (A_E + A_M + A_A) , \qquad (1)$$

where the three terms $A_E \propto G_E^\gamma G_E^Z$, $A_M \propto G_M^\gamma G_M^Z$, and $A_A \propto (1-4\sin^2\theta_{\mathrm{W}}) G_M^\gamma G_A^e$ depend upon products of electromagnetic and weak neutral form factors. This asymmetry represents the fractional change in cross-section for left- *vs.* right-handed incident electrons. Due to the coefficient in square brackets, this asymmetry is generally quite small: $A \sim 10^{-4} Q^2$, where the squared momentum transfer Q^2 is expressed in units of $(\mathrm{GeV}/c)^2$. Thus, the experiments are quite challenging. For the SAMPLE experiment at backward angles, only the A_M and A_A terms are relevant.

The quantities G_E^γ, G_M^γ, G_E^Z, and G_M^Z are the vector form factors of the nucleon associated with γ- and Z-exchange. The neutral weak N-Z interaction also involves an axial vector coupling G_A^e in the third term of eq. (1). The lowest-order Z-exchange process is responsible for the $1 - 4\sin^2\theta_{\mathrm{W}}$ factor that appears in A_A and thus higher-order processes can contribute significantly to this term [6,7]. These processes include effects not present

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in neutrino scattering, such as anapole effects and other electroweak radiative corrections as discussed below. It is also useful to consider parity-violating quasielastic scattering from nuclear targets, particularly deuterium [8]. This provides additional useful information on the axial vector form factor contributions.

2.2 Strange form factors

The flavor structure of the electroweak couplings and isospin symmetry of the nucleon imply the relations

$$G^s_{E,M} = (1 - 4\sin^2\theta_{\mathrm{W}})G^{\gamma,p}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}\,. \quad (2)$$

Thus, measurement of the neutral weak form factors $G^{Z,p}_{E,M}$ can unambiguously determine the strange form factors $G^s_{E,M}$.

One traditionally defines $\mu_s \equiv G^s_M(Q^2 = 0)$ as the strange magnetic moment of the nucleon. Since the nucleon has no net strangeness, we find $G^s_E(Q^2 = 0) = 0$. However, one can express the slope of G^s_E at $Q^2 = 0$ in the usual fashion in terms of a "strangeness radius" r_s, where $r^2_s \equiv -6\left[\mathrm{d}G^s_E/\mathrm{d}Q^2\right]_{Q^2=0}$.

As discussed in [5], a variety of theoretical methods have been employed in efforts to compute $G^s_{E,M}(Q^2)$ (or often just the quantities μ_s and r_s). Typically, one may consider the fluctuation of the nucleon into strange particles (*e.g.*, a K-meson and hyperon) or the fluctuation of the virtual boson (photon or Z) into a ϕ-meson. The physical separation of the s and $\bar{s}$ in such processes [9] or the production of an $s\bar{s}$ pair in a spin triplet leads to non-zero values of $G^s_{E,M}(Q^2)$. The numerical results of many theoretical treatments [5] vary considerably, but generally one obtains a value for $\mu_s \sim \pm 0.5$ (nuclear magnetons) and $r^2_s \sim \pm 0.2\ \mathrm{fm}^2$.

2.3 Neutral weak axial form factor

As noted above, the parity-violating interaction of electrons with nucleons also involves an axial vector coupling to the nucleon, G^e_A. The standard electroweak model relates the axial coupling, G_A, measured in charged current process (such as neutron beta-decay or (ν, l) reactions) to the neutral current process (of interest here).

For the case of elastic neutrino scattering, the interpretation of G^ν_A is simplified because the neutrino has no (to lowest order) electromagnetic interaction. However, due to the effect of $\bar{s}s$ pairs in generating the isoscalar neutral weak form factor, we have the relation

$$G^\nu_A = -G_A\tau_3 + G^s_A + R_\nu\,, \quad (3)$$

where R_ν represents radiative corrections of order α [10,6].

For parity-violating eN scattering, we have

$$G^e_A = G^Z_A + \eta F_A + R_e\,, \quad (4)$$

where $\eta = 8\pi\sqrt{2}\alpha/(1 - 4\sin^2\theta_{\mathrm{W}}) = 3.45$, $G^Z_A = -G_A\tau_3 + G^s_A$ (as in eq. (3)), F_A is the nucleon anapole form factor, and R_e are other electroweak radiative corrections. In fact, the anapole-type effects associated with the "γ-Z mixing" (fig. 1) amplitudes are the dominant correction [11,6,12]. It is conventional to estimate these effects using a dispersive treatment of $\sigma(e^+e^- \to \text{hadrons})$ data and flavor $SU(3)$ arguments. This approach may be appropriate for purely leptonic scattering, but it does not give a complete treatment for a proton target. For example, the impact of strong interactions between the virtual quarks in the Z-γ mixing loops and those in the target hadron is not included in the dispersion relation analysis. Some recent theoretical work has partially addressed these issues [13,14], but further work is needed. Also, for the Z-γ box contributions to R_e the intermediate hadronic state has been assumed to be a nucleon [11,15]. It is quite possible that there are significant contributions associated with intermediate Δ states and other nucleonic excitations.

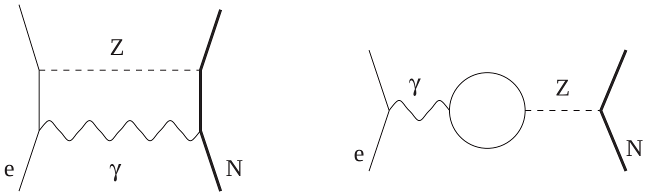

Fig. 1. Examples of amplitudes contributing to the electroweak radiative corrections R_e ("γ-Z box" on the left) and anapole corrections ("γ-Z mixing" on the right). Note that these do not contribute to neutrino scattering corrections R_ν.

3 SAMPLE experiment

The SAMPLE experiment at MIT-Bates measures the asymmetry at backward angles from both the proton and deuteron at low $Q^2 = 0.1\ (\mathrm{GeV}/c)^2$. Those measurements are sensitive to the strange magnetic form factor G^s_M and the isovector axial form factor $G^e_A(T = 1)$, and the results [16] are shown in fig. 2. The measurements indicate that the magnetic strangeness is small

$$G^s_M(Q^2 = 0.1) = 0.14 \pm 0.29 \pm 0.31 \quad (5)$$

and consistent with an absence of strange quarks. We can correct this value for the calculated Q^2-dependence of G^s_M to leading order in $SU(3)$ chiral perturbation theory [17] to obtain a result for the strange magnetic moment:

$$\mu_s = 0.01 \pm 0.29 \pm 0.31 \pm 0.07\,, \quad (6)$$

where the third uncertainty accounts for the additional uncertainty associated with the theoretical extrapolation to $Q^2 = 0$. An interesting theoretical question is whether $SU(3)$ chiral perturbation theory is suitable for the Q^2-dependence since an unknown counterterm appears to dominate when one extends to next-to-leading order [18]. Future measurements [19] performed at other values of momentum transfer should provide an answer.

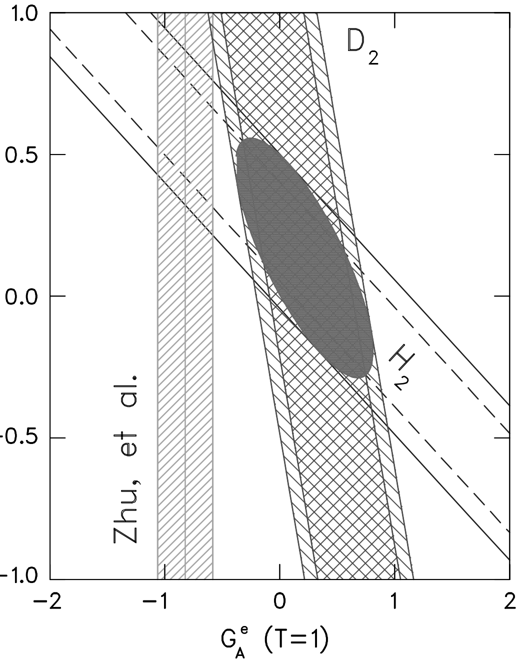

Fig. 2. Combined analysis [16] of the data from the two SAMPLE measurements. The two error bands from the hydrogen experiment [20] and the deuterium experiment [16] are indicated. The inner hatched region includes the statistical error and the outer represents the systematic uncertainty added in quadrature. Also plotted is the calculated isovector axial e-N form factor $G^e_A(T=1)$ obtained by using the anapole form factor and radiative corrections by Zhu *et al.* [13]. The typical theoretical prediction that $G^s_M \sim -0.3$ [5] coupled with the calculation of $G^e_A(T=1)$ is substantially ruled out by the experimental data.

In addition, the SAMPLE experimental result indicates that the substantial modifications of G^e_A predicted in [6] are present, but probably with an even larger magnitude than quoted in that work. It therefore appears that the neutral axial form factor determined in electron scattering is substantially modified from the tree-level Z-exchange amplitude (as determined in elastic ν-p scattering). Assuming the calculated small isoscalar axial corrections are not grossly inaccurate, the isovector axial form factor can be determined from the SAMPLE results

$$G^e_A(T=1) = +0.22 \pm 0.45 \pm 0.39 \tag{7}$$

in contrast with the calculated value [13] $G^e_A(T=1) = -0.83 \pm 0.26$. This may be an indication that the anapole and other radiative correction effects in the nucleon are somewhat larger (by a factor of 2-3) than expected based on these calculations. New measurements on the deuteron at lower Q^2 were completed earlier this year and should help clarify the picture.

4 Conclusion and outlook

One should note that the calculations of $G^e_A(T=1)$ combined with the typical theoretical predictions $G^s_M \simeq -0.3$ are substantially at variance with the experimental result. In addition, the results for μ_s indicate that $\bar{s}s$ pairs contribute less than 6% of the proton's magnetic moment [16]. Thus the SAMPLE experiment provides important new information on the electroweak and flavor structure of the nucleon. Future theoretical work related to the anapole effect, intermediate states in the "box" diagrams, and exchange current effects in the deuteron experiment are necessary to fully interpret these results. In addition, the $G0$ experiment at Jefferson Lab promises to provide definitive new information on all the weak form factors and their associated Q^2-dependence.

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