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Strange-quark vector currents and parity-violating electron scattering from the nucleon and from nuclei

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Measurements of the processes $p(\pi,\pi)$, $p(\nu,\nu)/p(\bar{\nu},\bar{\nu})$, and deep-inelastic $\vec{p}(\vec{\mu},\mu')$ can be interpreted in a manner which requires a significant strange-quark contribution to proton matrix elements. In this paper some implications of strange-quark contributions to proton vector currents and their manifestation in parity-violating electron-scattering experiments are examined. It is found that strange-quark currents of plausible magnitude significantly affect the parity-violating elastic electron scattering from the nucleon in certain kinematic regimes. It is also shown that, while the effects in on-going parity-violating experiments on ^{9}Be and ^{12}C are small, significant strange-quark contributions might be expected in experiments with nuclear targets at higher-momentum transfer.

I. INTRODUCTION

There has been much recent comment (for example, Refs. 1–3) on the measurement of polarized deep-inelastic muon scattering from the proton.[4] The interpretation by the experimental group implies that the spin carried by the quarks in the proton is a small fraction of the total and that the strange quarks carry a fraction comparable to that of the up and down quarks. The strange quarks are found, in fact, to be polarized in the direction opposite to the proton. These data are sensitive to the strange-quark axial-vector current in the proton $\langle p|\bar{s}\gamma^5\gamma^\mu s|p\rangle$. Kaplan and Manohar[5] have pointed out that two other measurements, νp elastic scattering and πp scattering, also suggest sizable values for strange-quark matrix elements in the proton. The first is again sensitive to the strange-quark axial-vector current and is consistent with the value determined from the deep-inelastic muon-scattering experiment. The second gives a value for $\Sigma_{\pi N}$ (see also Ref. 6), sensitive to the matrix element $\langle p|\bar{s}s|p\rangle$, which can be interpreted to imply that the proton mass would be only about 600 MeV if the strange quark were massless. It is therefore reasonable to ask whether the strange-quark *vector*-current matrix elements $\langle p|\bar{s}\gamma^\mu s|p\rangle$ contribute significantly to experiment since both weak and electromagnetic probes are sensitive to them.

In this paper some implications of the possibly sizable strange-quark vector currents in parity-violating (PV) electron-scattering experiments are addressed. Because the weak and electromagnetic currents couple to the light quarks differently, it may be possible to observe the effect of strange-quark currents in experiments with weak probes or where the weak and electromagnetic interactions interfere as they do in electron PV reactions.[7] Section II establishes the notation necessary to apply this idea to possible experiments. Section III presents a simple model for the nucleon form factors. Some examples of where these effects might be observed are discussed in Sec. IV. PV experiments on the proton are first considered; then the single-nucleon matrix elements are applied to PV experiments on nuclei including the experiments currently underway at Mainz[8] and MIT-Bates.[9] It is shown that the effects in the proton experiments can be large in the context of the possible determination of the neutron charge form factor or $\sin^2\theta_W$ from such measurements. The effects are small in the current nuclear experiments. The dominant contribution of the strange-quark currents to the Mainz ^{9}Be experiment is multiplied by $Z\mu_p+N\mu_n$ and hence is small. The MIT-Bates experiment is at very low momentum transfer and again results in a small strange-quark effect. The effects can, however, be substantial for nuclear targets at higher momentum transfers. The paper concludes with a summary.

II. NOTATION

To begin with, the definition of form factors for the quark currents $\langle N|\bar{q}\Gamma^\mu q|N\rangle$, where $\Gamma^\mu=\gamma^\mu$ or $\gamma^5\gamma^\mu$, is established. The electromagnetic and neutral weak currents for the nucleon may be written in terms of the currents of the quark fields[10]

$$J^\mu_{\rm em}=\left\langle N\left|\sum_{j=\text{quarks}}\bar{q}_jQ_j\gamma^\mu q_j\right|N\right\rangle , \tag{1}$$

$$J^\mu_{\rm wk}=\left\langle N\left|\sum_{j=\text{quarks}}\bar{q}_j\gamma^\mu[\tfrac{1}{2}T^3_j(1-\gamma^5)-Q_j\sin^2\theta_W]q_j\right|N\right\rangle , \tag{2}$$

where Q_j is the quark charge and T^3_j is the third component of the weak isospin of the quark ($T^3=\frac{1}{2}$ for left-handed u, c, and t quarks, $T^3=-\frac{1}{2}$ for left-handed d, s, and b quarks, and $T^3=0$ for all right-handed quarks). Writing the most general form (assuming gauge invariance and parity conservation) for the vector current of a spin-$\frac{1}{2}$ object as

$$J^\mu_V=Q\bar{\mathcal{U}}\left[F_1\gamma^\mu+\frac{i\sigma^{\mu\nu}q^\nu}{2M_N}F_2\right]\mathcal{U} ,$$

introduces the standard Dirac and Pauli form factors, F_1 and F_2, respectively (and where $\overline{\mathcal{U}}$ and $\mathcal{U}$ are, for the moment, generic spinors). The conventional form factor for the axial-vector current, G_1 may also be introduced

$$J_A^\mu = Q_A \overline{\mathcal{U}} G_1 \gamma^\mu \gamma^5 \mathcal{U} .$$

Written in terms of individual quark-nucleon form factors the electromagnetic and weak currents are

$$J_{\rm em}^\mu = \overline{\mathcal{U}} \sum_{j=\rm quarks} Q_j \left[\gamma^\mu F_1^j + \frac{i\sigma^{\mu\nu} q^\nu}{2M_N} F_2^j \right] \mathcal{U} , \tag{3}$$

$$J_{\rm wk}^\mu = \overline{\mathcal{U}} \sum_{j=\rm quarks} \left[(\tfrac{1}{2} T_j^3 - Q_j \sin^2\theta_W) \left[\gamma^\mu F_1^j + \frac{i\sigma^{\mu\nu} q^\nu}{2M_N} F_2^j \right] - \tfrac{1}{2} T_j^3 \gamma^\mu \gamma^5 G_1^j \right] \mathcal{U} , \tag{4}$$

where $\overline{\mathcal{U}}$, $\mathcal{U}$ are now nucleon spinors. Equations (3) and (4) define the form factors for the quark currents of Eqs. (1) and (2). The ordinary nucleon electromagnetic (vector) form factors are then sums of the quark-nucleon form factors

$$F_{1,2}^\gamma = \sum_{j=\rm quarks} Q_j F_{1,2}^j \tag{5}$$

(in principle the quark-nucleon form factors of the proton and the neutron are not equivalent). Similarly one can define the neutral weak vector and axial-vector form factors

$$F_{1,2}^Z = \sum_{j=\rm quarks} (\tfrac{1}{2} T_j^3 - Q_j \sin^2\theta_W) F_{1,2}^j \tag{6}$$

and

$$G_1 = \sum_{j=\rm quarks} -\tfrac{1}{2} T_j^3 G_1^j . \tag{7}$$

Now consider the case where only u, d, and s quarks are important (from general arguments it can be argued that charm and heavier quarks contribute at a much smaller level[5]). To make contact with the notation of Kaplan and Manohar,[5] the quark-nucleon form factors are reparametrized with reference to the generators of SU(3) [although this does not imply that SU(3)-flavor symmetry is required]. The generators $\{\lambda^\alpha\}$, $\alpha = 1, \ldots, 8$, are normalized such that $\mathrm{Tr}\lambda^\alpha\lambda^\beta = \frac{1}{2}\delta^{\alpha\beta}$ and λ^0 is defined to be $\frac{1}{3}I$, where I is the identity matrix. The currents may then be rewritten in terms of new "SU(3) form factors" F^0, F^3, and F^8, corresponding to the identity matrix and the two diagonal SU(3) generators

$$J_{\rm em}^\mu = \left\langle N \left| \sum_{\alpha=0,3,8} \sum_{j=1,2,3} \bar{q}_j a^\alpha \lambda_{jj}^\alpha \gamma^\mu q_j \right| N \right\rangle \tag{8}$$

$$= \overline{\mathcal{U}} \sum_{\alpha=0,3,8} a^\alpha \left[\gamma^\mu F_1^\alpha + \frac{i\sigma^{\mu\nu} q^\nu}{2M_N} F_2^\alpha \right] \mathcal{U} \tag{9}$$

and

$$J_{\rm wk}^\mu = \left\langle N \left| \sum_{\alpha=0,3,8} \sum_{j=1,2,3} \bar{q}_j \gamma^\mu [b^\alpha (1-\gamma^5) - a^\alpha \sin^2\theta_W] \lambda_{jj}^\alpha q_j \right| N \right\rangle \tag{10}$$

$$= \overline{\mathcal{U}} \sum_{\alpha=0,3,8} \left[(b^\alpha - a^\alpha \sin^2\theta_W) \left[\gamma^\mu F_1^\alpha + \frac{i\sigma^{\mu\nu} q^\nu}{2M_N} F_2^\alpha \right] - b^\alpha \gamma^\mu \gamma^5 G_1^\alpha \right] \mathcal{U} . \tag{11}$$

The coefficients a^α and b^α are determined by Eqs. (3) and (9), (4) and (11):

$$a^0 = 0 , \quad b^0 = -\tfrac{1}{4} ,$$
$$a^3 = 1 , \quad b^3 = \tfrac{1}{2} ,$$
$$a^8 = 1/\sqrt{3} , \quad b^8 = 1/2\sqrt{3} .$$

In this notation the electromagnetic and weak form factors are defined to be

$$F_{1,2}^\gamma = \sum_{\alpha=0,3,8} a^\alpha F_{1,2}^\alpha , \tag{12}$$

$$F_{1,2}^Z = \sum_{\alpha=0,3,8} (b^\alpha - a^\alpha \sin^2\theta_W) F_{1,2}^\alpha , \tag{13}$$

and

$$G_1 = \sum_{\alpha=0,3,8} -b^\alpha G_1^\alpha . \tag{14}$$

Therefore the electromagnetic form factors depend only on $F_{1,2}^3$ and $F_{1,2}^8$—a convenient result of this parametrization. Finally, in terms of the quark-nucleon form factors, the SU(3) form factors are

$$F_{1,2}^0 = \tfrac{1}{3}(F_{1,2}^u + F_{1,2}^d + F_{1,2}^s) , \tag{15}$$

$$F_{1,2}^3 = \tfrac{1}{2}(F_{1,2}^u - F_{1,2}^d) , \tag{16}$$

and

$$F^8_{1,2} = \frac{1}{2\sqrt{3}}(F^u_{1,2} + F^d_{1,2} - 2F^s_{1,2}) . \quad (17)$$

The forms of the axial-vector form factors G^α_1 in terms of G^u_1, G^d_1, and G^s_1 follow Eqs. (15)–(17) exactly.

III. NUCLEON-FORM-FACTOR MODEL

The form factors defined above are constrained by both electromagnetic and weak scattering data. It is generally believed that the proton and neutron are, to a very good approximation, a strong isospin doublet. A simple realization of strong isospin symmetry is implemented here. It is assumed that the u and d form factors are symmetric in the proton and neutron (i.e., $F^{u,p} = F^{d,n}$, etc.) and that the s form factors are equivalent. This implies that the form of F^3 is that of a strong isovector; hence, it is rewritten as

$$F^3_{1,2} \to F^3_{1,2}\langle \tau^3 \rangle ,$$

where τ^3 is the third component of strong isospin with eigenvalues $+1$ and -1 for the proton and neutron, respectively. For this choice, then, the $F^\alpha_{1,2}$ are the same for the proton and the neutron. These relations are also taken to hold for the G^α_1 form factors.

Some of the normalizations of the remaining nine form factors for the proton and neutron are fixed. The familiar electromagnetic-form-factor normalizations are

$$F^3_1(Q^2=0) = \tfrac{1}{2} , \quad F^3_2(Q^2=0) = \tfrac{1}{2}(\kappa_p - \kappa_n) ,$$

$$F^8_1(Q^2=0) = \frac{\sqrt{3}}{2} , \quad F^8_2(Q^2=0) = \frac{\sqrt{3}}{2}(\kappa_p + \kappa_n) .$$

In addition, the normalization of one of the SU(3)-singlet form factors F^0_1 is known since it is just the baryon number: $F^0_1(Q^2=0) = 1$. The normalizations of the axial-vector form factors may be determined from weak charged-current interactions and from hyperon β decay [in this one case SU(3)-flavor symmetry is assumed]:

$$G^3_1(Q^2=0) = F + D ,$$

$$G^8_1(Q^2=0) = \frac{1}{\sqrt{3}}(3F - D) ,$$

where F and D are the SU(3) hyperon-β-decay constants taken from Ref. 5 to be $D = 0.80 \pm 0.02$, and $F = 0.45 \pm 0.02$. This leaves two form-factor normalizations undetermined—F^0_2 and G^0_1. From the ν, $\bar{\nu}p$ elastic experiment,[11] Kaplan and Manohar determine a value for G^0_1 of 0.06 ± 0.16, and from the polarized deep-inelastic sum rule they determine the consistent value 0.1 ± 0.2. It is believed that $F^0_2(Q^2=0)$ is essentially unconstrained by experiment; this has led to the suggestion that it be measured in an elastic ep parity-violation experiment.[7]

The momentum-transfer dependence of these form factors is also well known for the most part. For simplicity, the dipole approximation is chosen for all form factors. In the case of the electromagnetic form factors it is the "Sachs form factors"[12] which are reasonably represented by the dipole form. Using the definitions of the Sachs form factors

$$G_E = F^\gamma_1 - \tau F^\gamma_2 , \quad (18)$$

$$G_M = F^\gamma_1 + F^\gamma_2 , \quad (19)$$

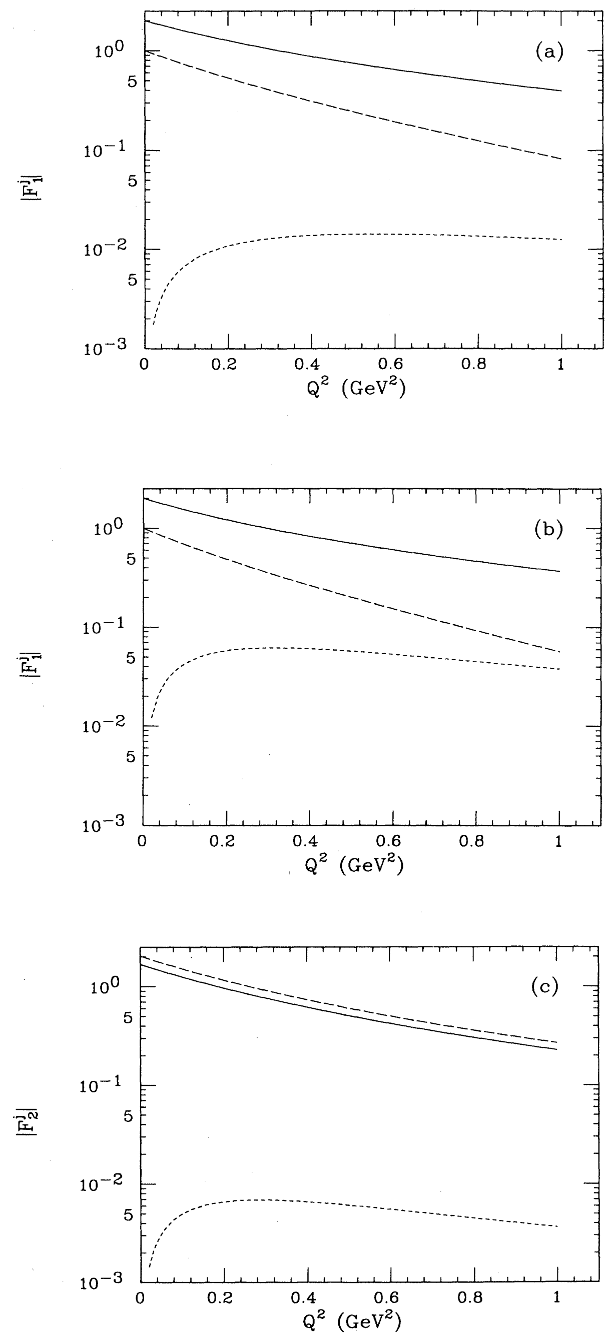

FIG. 1. (a) Magnitudes of the quark form factors for the case $M^0_V = M_V$ and $F^0_2(0) = -0.45$ (Skyrme model): solid, F^u_1; long dash, F^d_1; and short dash, F^s_1. (b) Magnitudes of quark form factors for the case $M^0_V = 0.9M_V$, $F^0_2(0) = -0.12$ [$F^s_2(0) = 0$]: curve designations as in (a). (c) As in (b) except for the form factors F^j_2.

where $\tau = Q^2/(2M_N)^2$, the "dipole model" expressions can be written for the F_1^α and F_2^α:

$$F_2^\alpha(Q^2) = \frac{F_2^\alpha(0)}{(1+\tau)[1+Q^2/(M_V^\alpha)^2]^2} \tag{20}$$

and

$$F_1^\alpha(Q^2) = \frac{F_1^\alpha(0)}{[1+Q^2/(M_V^\alpha)^2]^2} + \tau F_2^\alpha(Q^2) \; . \tag{21}$$

The axial-vector form factors G_1^α are also assumed to have a dipole form

$$G_1^\alpha = \frac{G_1^\alpha(0)}{[1+Q^2/(M_A^\alpha)^2]^2} \; , \tag{22}$$

where the value $M_A^0 = M_A^3 = M_A^8 = 1.03 \pm 0.04$ GeV is used.[5]

Several comments are in order with regard to this parametrization of the nucleon form factors.

(1) Whereas the Q^2 dependence of F^3 and F^8 is fixed by the electromagnetic form factors, the Q^2 dependence of the singlet form factors F_1^0 and F_2^0 is not known. In the examples to follow, the dipole parametrization is assumed for the singlet form factors as well.

(2) In principle, the Q^2 variation of F_1^0 and F_2^0 may be different. They are assumed to be the same in the examples of Sec. IV.

(3) If the Q^2 dependence of F_1^3 and F_1^8 is taken to be the same (i.e., $M_V^3 = M_V^8 \equiv M_V$), the neutron charge form factor is zero. This assumption will be discussed in considering PV elastic scattering from the proton in Sec. IV A. The value $M_V = 0.843$ GeV is used.

(4) The manner in which the strange-quark nucleon form factors enter should be noted. In Sec. IV essentially two types of parameter variations are considered in the examples: setting $M_V^0 = M_V$ and varying $F_2^0(0)$, and fixing $F_2^0(0) = -0.12$ [$F_2^s(0) = 0$] and varying M_V^0. In the case of $M_V^0 = M_V$, variations of $F_2^0(0)$ generate contributions to F_1^s and F_2^s in a straightforward way [cf. Eqs. (20), (21), and (15)–(17)]. For this case F_1^s is normalized to zero (as it must be since the net strangeness of the nucleon is zero) and F_2^s is, by definition, nonzero for $Q^2=0$. To set the scale of these form factors it is useful to compare them to, for example, the F^u. Figure 1(a) shows F_1^u and F_1^s for the range of Q^2 considered in this paper and for $M_V^0 = M_V$ and $F_2^0(0) = -0.45$ (Skyrme model).[5] It can be seen that at most $|F_1^s/F_1^u|$ is about 0.03. For this set of assumptions $|F_2^s/F_2^u| = 0.25$ independent of Q^2. For the other type of variation in which $F_2^0(0)$ is fixed at -0.12, changes in M_V^0 generate contributions to F_1^s and F_2^s in a somewhat different way. Both are zero at $Q^2=0$. The largest values of the ratios $|F_1^s/F_1^u|$ and $|F_2^s/F_2^u|$ are about 0.10 and 0.02, respectively, as is shown in Figs. 1(b) and 1(c) (where $M_V^0 = 0.9M_V$).

(5) The axial-vector form factors G_1^α are not as well known as the electromagnetic vector form factors. In particular, the assumption of a dipole form implies uncertainties beyond those quoted for the parameters. Variations of the G_1^α are not considered in the examples below, but of course they must be in more detailed discussions.

Lastly, it is perhaps useful to note that the F^s are "net" form factors, i.e., the strange and antistrange quarks come in with opposite signs. These form factors are, in a sense, analogs of the neutron charge form factor which represents the charge distribution of a neutral object; the F^s represent the strangeness distribution of a zero strangeness object.

IV. EXAMPLES

A. Elastic PV electron-proton scattering

The asymmetry for the scattering of longitudinally polarized electrons from unpolarized protons may be written[7]

$$\mathcal{A} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{GQ^2}{\pi\alpha\sqrt{2}} \left[F_1^\gamma F_1^Z + \tau F_2^\gamma F_2^Z + \tan^2\theta/2 \left[2\tau(F_1^\gamma + F_2^\gamma)(F_1^Z + F_2^Z) - \frac{E+E'}{2M_N}(1-4\sin^2\theta_W) G_1 (F_1^\gamma + F_2^\gamma) \right] \right]$$
$$\times [(F_1^\gamma)^2 + \tau(F_2^\gamma)^2 + 2\tau \tan^2\theta/2 (F_1^\gamma + F_2^\gamma)^2]^{-1} \; , \tag{23}$$

where E, E' are the incident and scattered electron energies, θ is the electron scattering angle, and θ_W is the weak mixing angle. Four examples of interesting kinematics are presented in this section to serve as a "sketch" of the territory. The first two are aimed at determining M_V^0 and $F_2^0(0)$. The possibility of extracting the elastic charge form factor of the neutron, G_E^n, from such a measurement is discussed in the third example. In the fourth, a higher Q^2 measurement is considered as regards the determination of the weak mixing angle θ_W.

A first look at the singlet form factors $F_{1,2}^0$ might consist of two measurements—one which is sensitive to $F_2^0(0)$ and one which is sensitive to the singlet mass parameter M_V^0. Figure 2 shows the asymmetry as a function of $F_2^0(0)$ for scattering at backward angles ($Q^2 = 0.25$ GeV^2) for three values of M_V^0. These kinematics, proposed in Ref. 7, ensure a large contribution from F_2^Z. Figure 3 shows the asymmetry as a function of M_V^0 for forward angle scattering ($Q^2 = 0.25$ GeV^2) for three values of $F_2^0(0)$. The asymmetry is sensitive to F_1^Z for these kinematics. It should be noted that $F_2^0(0) = -0.12$ corresponds to $F_2^s = 0$ and that estimates from a Skyrme model and those based on a baryon chiral Lagrangian[5] give $F_2^0(0) = -0.45$ and $\sim +0.1$, respectively. It is also important to note that the asymmetries are on the order of 10^{-5} and therefore comparable to or larger than those being measured currently.[8,9] These experiments would be feasible at an intermediate-energy electron accelerator

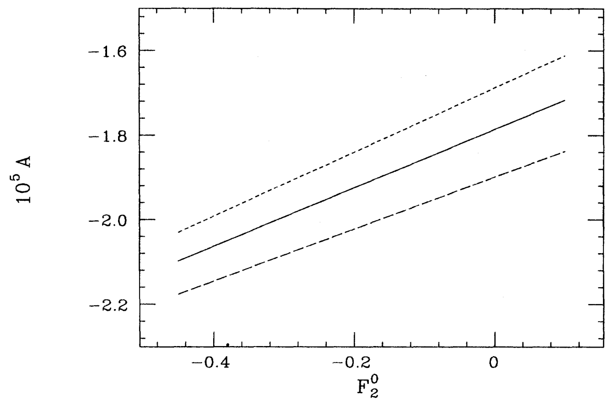

FIG. 2. Variation of the $p(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of $F_2^0(0)$ for three values of M_V^0: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2. Kinematics are $E=350$ MeV, $\theta=130°$, and $Q^2=0.25$ GeV^2.

such as MIT-Bates.

An interesting proposal was made recently[13] to determine the elastic charge form factor of the neutron, G_E^n, by measuring the PV elastic scattering from the proton and using isospin invariance to infer G_E^n from a combination of the electromagnetic and neutral weak form factors. A simple procedure was used in this paper to test the reliability of this idea in light of possibly significant effects from the strange quarks. An asymmetry was generated using the parametrizations described in Sec. III (i.e., with $G_E^n=0$) for each of the kinematic sets considered in Ref. 13. G_E^n was then extracted from these asymmetries *using the assumptions of Ref. 13,* i.e., that $F_1^s(Q^2)=F_2^s(Q^2)=0$. In Figs. 4(a) and 4(b) the value of G_E^n so extracted from the "experiment" is plotted as a function of M_V^0. The deviation of the curves from zero is due to the presence of the strange-quark-nucleon form factors. One can see that if the singlet form factors have the same dipole mass as the "3" and "8" form factors, one is able to extract G_E^n correctly. This is accidental in the sense that it only holds for the case in which the other Sachs form factors are dipoles. For reference, a common parametrization[14] of G_E^n gives $G_E^n=0.054$ and 0.036 for the kinematics of Figs. 4(a) and 4(b), respectively. Therefore, in the context of the model described in Sec. III, relatively small differences between the singlet mass and the standard vector mass can cause a significant error in the extraction of G_E^n.

The final example of elastic electron-proton scattering is related to the proposal to determine the weak mixing angle θ_W in the regime of a strongly interacting system.[15] Figures 5(a) and 5(b) show the asymmetry as a function of $\sin^2\theta_W$ for the kinematics suggested in Ref. 15. The ranges of the parameters $F_2^0(0)$ and M_V^0 are chosen as they are in Figs. 2–4. Again there are large uncertainties

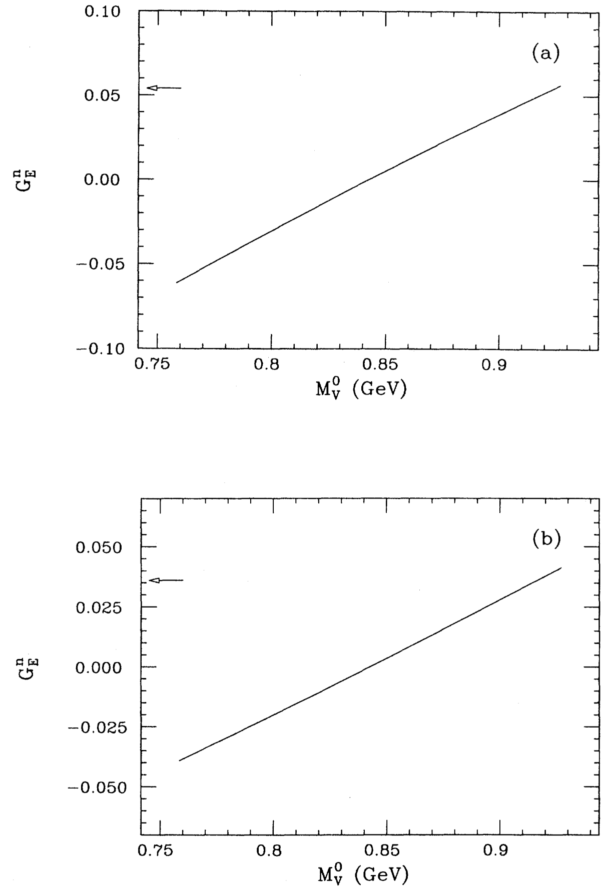

FIG. 4. Extracted value of G_E^n as a function of M_V^0 using the assumptions of Ref. 13 [i.e., that $F_1^s(Q^2)=F_2^s(Q^2)=0$]. The input value of G_E^n is zero (resulting from the dipole approximation of Sec. III). The value of G_E^n for the Galster *et al.* (Ref. 14) parametrization is denoted by the arrow. Kinematics are $E=4.0$ GeV, $\theta=9.3°$, and $Q^2=0.4$ GeV^2. (b) As in (a) except kinematics are $E=4.0$ GeV, $\theta=15.4°$, and $Q^2=1.0$ GeV^2.

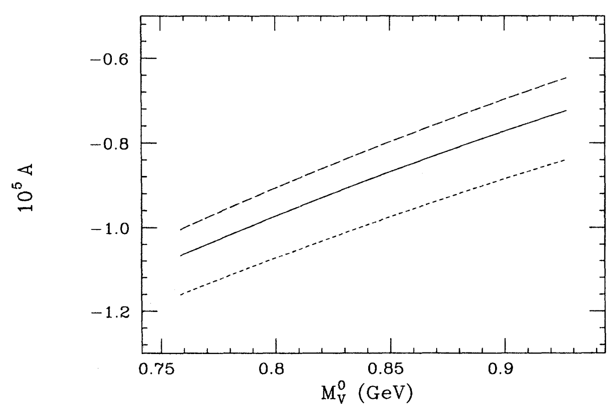

FIG. 3. Variation of the $p(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of M_V^0 for three values of $F_2^0(0)$: solid, $F_2^0(0)=-0.12$; long dash, $F_2^0(0)=0.1$; short dash, $F_2^0(0)=-0.45$. Kinematics are $E=950$ MeV, $\theta=33°$, and $Q^2=0.25$ GeV^2.

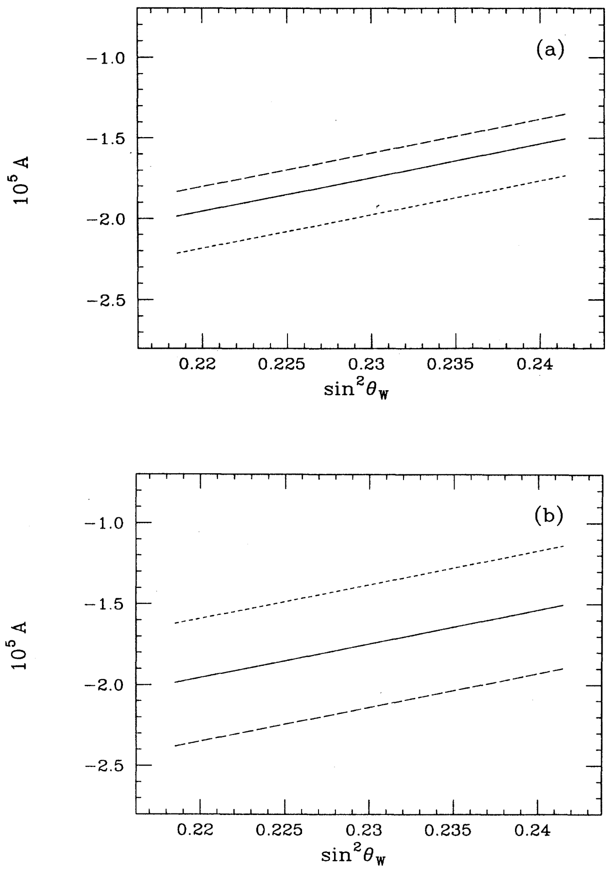

FIG. 5. (a) Variation of the $p(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of $\sin^2\theta_W$ with $M_V^0=\sqrt{0.71}$ GeV^2: solid, $F_0^2(0)=-0.12$; long dash, $F_0^2(0)=0.1$; short dash, $F_0^2(0)=-0.45$. Kinematics are $E=2.0$ GeV, $\theta=20°$, and $Q^2=0.43$ GeV^2. (b) As in (a) except $F_2^0(0)$ is fixed to be -0.12: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2.

resulting, in particular, from relatively small variations in M_V^0.

B. Quasielastic PV electron-nucleon scattering

A simple calculation of the strange-quark contributions to the Mainz experiment measuring quasielastic PV electron scattering from ^{9}Be can be made by assuming that the electrons are being scattered from free nucleons. The above expression for the nucleon asymmetry [Eq. (23)] may then be used to calculate the overall asymmetry

$$\mathcal{A}=\frac{Z\mathcal{A}^p\sigma_0^p+N\mathcal{A}^n\sigma_0^n}{Z\sigma_0^p+N\sigma_0^n}\,, \tag{24}$$

where $\mathcal{A}^p$ and $\mathcal{A}^n$ are the proton and neutron asymmetries and σ_0^p and σ_0^n are the unpolarized proton and neutron cross sections, respectively. For the Mainz kinematics ($E=300$ MeV, $\theta_{\min}=115°$) the cross-section difference [numerator of Eq. (23)] is dominated by the term proportional to

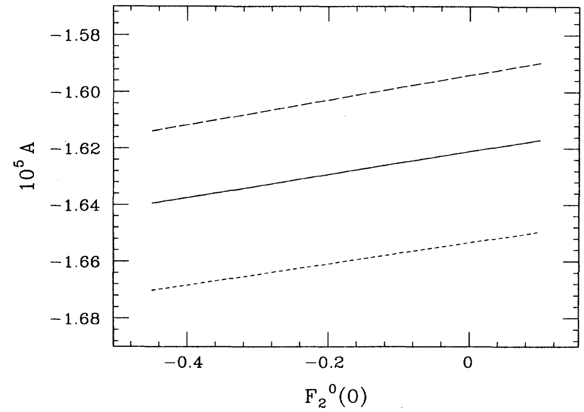

FIG. 6. Variation of ^{9}Be$(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of $F_2^0(0)$: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2. Kinematics are $E=300$ MeV, $\theta=115°$, and $Q^2=0.24$ GeV^2 matching the experiment currently running at Mainz (Ref. 8).

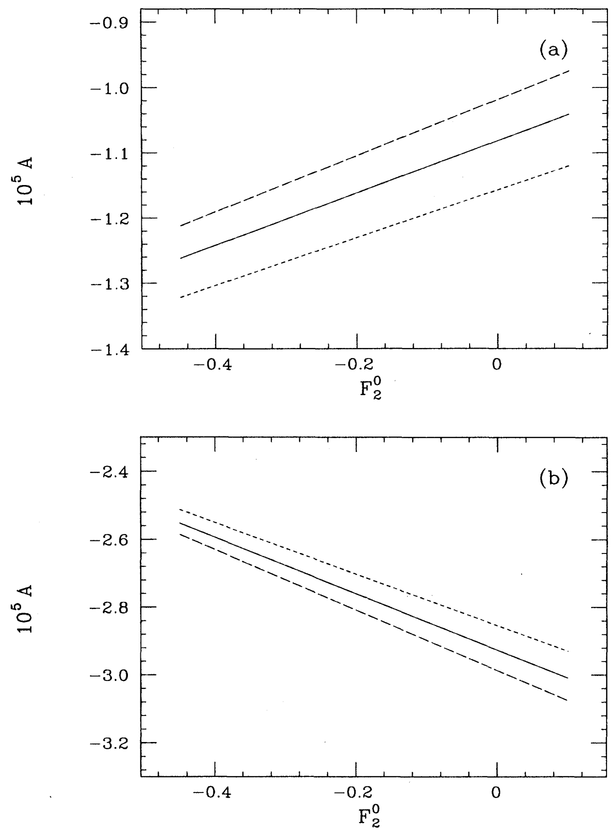

FIG. 7. Variation of (a) the elastic $p(\vec{e},e')$ and (b) the elastic $n(\vec{e},e')$ symmetries $\mathcal{A}$ for the Mainz kinematics of Fig. 6 as a function of $F_2^0(0)$: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2. Note the effect of the strange-quark currents on the individual asymmetries is larger than for the combined asymmetry in quasielastic scattering from ^{9}Be.

$$[Z(F_1^{p\gamma}+F_2^{p\gamma})+N(F_1^{n\gamma}+F_2^{n\gamma})](F_1^s+F_2^s) =(ZG_M^p+NG_M^n)(F_1^s+F_2^s) \quad (25)$$

hence the effects of F^s nearly cancel as is shown in Fig. 6. Figures 7(a) and 7(b) show that the effects on the individual proton and neutron asymmetries for the same kinematics are significantly larger. The preliminary result from this experiment is approximately consistent with the standard-model prediction with $\sim 25\%$ uncertainty.[8]

C. Elastic PV electron-nucleus scattering

The PV asymmetry for scattering from $J=0$, $T=0$ nuclei is considered in this section. "Predictions" based on simple models are presented for the ^{12}C experiment currently running at MIT-Bates,[9] and for a possible experiment at higher momentum transfer which one might undertake at CEBAF. The expression for the PV elastic scattering asymmetry for $J=0$, $T=0$ nuclei may be developed from the work of Feinberg.[16] (Note that the axial-vector current cannot contribute to a $J^\pi=0^+$ to 0^+ transition.) If one does *not* assume that only u and d quarks contribute to the electromagnetic and weak neutral currents the expression for the cross sections [Feinberg's Eq. (3.5)] may be written

$$\frac{d\sigma_{R,L}}{d\Omega} =\sigma_M f_{\rm rec}^{-1} Z^2 \mathcal{F}_c^2\left[1\pm\frac{GQ^2}{4\pi^2\alpha^2\sqrt{2}}\frac{\sum_{j=\text{quarks}}\epsilon_{je}^{VA}A\mathcal{F}^j(Q^2)}{Z\mathcal{F}_c}\right], \quad (26)$$

where σ_M is the electron-point charge scattering cross section, $f_{\rm rec}$ is a recoil factor, Z is the nuclear charge, A is the atomic number, $\mathcal{F}_c$ is the nuclear charge form factor, and the $\mathcal{F}^j$ are the *nuclear* charge form factors corresponding to the quark currents, $\bar{u}\gamma^\mu u$, etc. The ϵ_{je}^{VA} are the individual quark couplings (vector quark current V, axial-vector electron current A) which are given in the standard model as

$$\epsilon_{je}^{VA}=\pi\alpha(1-\tfrac{8}{3}\sin^2\theta_W)\ , \quad j=u,c,t\ , \quad (27)$$

$$\epsilon_{je}^{VA}=-\pi\alpha(1-\tfrac{4}{3}\sin^2\theta_W)\ , \quad j=d,s,b, \quad (28)$$

or

$$\epsilon_{je}^{VA}=4\pi\alpha(T_j^3-Q_j\sin^2\theta_W)\ , \quad (29)$$

with the last equation establishing a link to the notation presented in Sec. II. Again specializing to the case where only, u, d, and s quarks are considered, the electromagnetic form factor may be written

$$Z\mathcal{F}_c=A[\tfrac{2}{3}\mathcal{F}^u-\tfrac{1}{3}(\mathcal{F}^d+\mathcal{F}^s)]\ , \quad (30)$$

and the asymmetry is then

$$\mathcal{A}=\frac{d\sigma_R-d\sigma_L}{d\sigma_R+d\sigma_L}=\frac{GQ^2}{4\pi\alpha\sqrt{2}}\frac{(1-\frac{8}{3}\sin^2\theta_W)\mathcal{F}^u-(1-\frac{4}{3}\sin^2\theta_W)(\mathcal{F}^d+\mathcal{F}^s)}{\frac{2}{3}\mathcal{F}^u-\frac{1}{3}(\mathcal{F}^d+\mathcal{F}^s)}\ . \quad (31)$$

The same model for the nucleon form factors described in Sec. III will be applied to the *nuclear* form factors in the following way. First, to engineer strong isospin $T=0$, it is assumed that $\mathcal{F}^u=\mathcal{F}^d\equiv\mathcal{F}^l$. It is easy to see at this stage that the asymmetry then reduces to the standard result if we set $\mathcal{F}^s=0$ in the equation above

$$\mathcal{A}=\frac{GQ^2}{4\pi\alpha\sqrt{2}}\frac{(1-\frac{8}{3}\sin^2\theta_W)\mathcal{F}^l-(1-\frac{4}{3}\sin^2\theta_W)\mathcal{F}^l}{\frac{2}{3}\mathcal{F}^l-\frac{1}{3}\mathcal{F}^l} \quad (32)$$

$$=-\frac{GQ^2}{\pi\alpha\sqrt{2}}\sin^2\theta_W\ . \quad (33)$$

Second, the nonrelativistic impulse approximation is used for the nuclear form factors.[17] This implies that nuclear form factors are products of single-nucleon form factors and nuclear "body" form factors, i.e.,

$$\mathcal{F}^j=F^jF_{\rm body}\ . \quad (34)$$

It is assumed that $F_{\rm body}^p=F_{\rm body}^n\equiv F_{\rm body}$ for these $J=0$, $T=0$ nuclei. Third, consistent with the nonrelativistic nuclear form factors, the nonrelativistic reductions of the relativistic nucleon form factors[18] of Sec. III are used. With this reduction the longitudinal nucleon form factor (the only contributing form factor for elastic scattering from a spin-0 nucleus is the longitudinal or charge monopole) is simply

$$F_c=F_1^p \quad (35)$$

neglecting terms of order Q^2/M_N^2. Thus the ordinary elastic scattering charge form factor is

$$\mathcal{F}_c=F_1^pF_{\rm body}\ . \quad (36)$$

The "light"-quark-nucleon form factor $\mathcal{F}^l$ can now be eliminated from Eq. (31) in favor of the overall charge form factor using Eq. (30):

$$Z\mathcal{F}_c=A(\tfrac{1}{3}\mathcal{F}^l-\tfrac{1}{3}\mathcal{F}^s)=ZF_1^pF_{\rm body}\ . \quad (37)$$

Recalling that $\mathcal{F}^s$ may be written (again assuming $F_1^{s,p}=F_1^{s,n}\equiv F_1^s$)

$$\mathcal{F}^s=F_1^sF_{\rm body} \quad (38)$$

and noting that the $F_{\rm body}$ factors cancel leaves

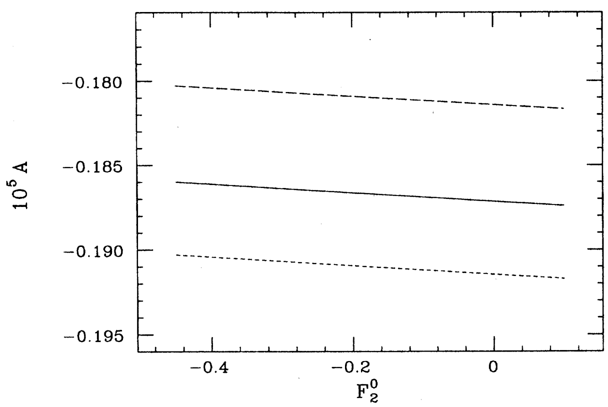

FIG. 8. Variation of ${}^{12}\mathrm{C}(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of $F_2^0(0)$: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2. Kinematics are $E=250$ MeV, $\theta=35°$, and $Q^2=0.023$ GeV^2 matching the experiment currently running at MIT-Bates (Ref. 9).

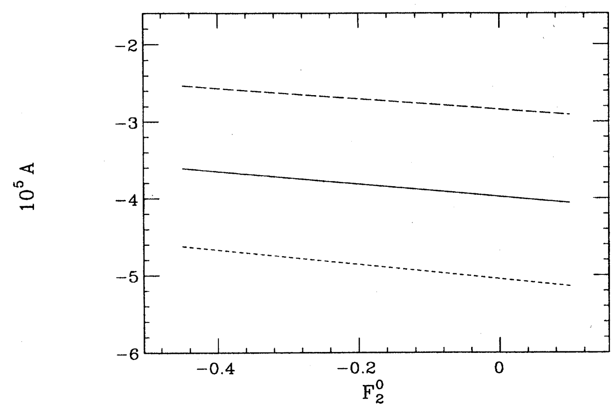

FIG. 9. Variation of ${}^{4}\mathrm{He}(\vec{e},e')$ asymmetry $\mathcal{A}$ as a function of $F_2^0(0)$: solid, $M_V^0=\sqrt{0.71}$ GeV^2; long dash, $M_V^0=0.9\sqrt{0.71}$ GeV^2; short dash, $M_V^0=1.1\sqrt{0.71}$ GeV^2. Kinematics are $E=2.0$ GeV, $\theta=20°$, and $Q^2=0.43$ GeV^2.

$$\mathcal{A}=\frac{GQ^2}{4\pi\alpha\sqrt{2}}\,\frac{-\frac{4}{3}\sin^2\theta_W\mathcal{F}^l-(1-\frac{4}{3}\sin^2\theta_W)\mathcal{F}^s}{\frac{1}{3}\mathcal{F}^l-\frac{1}{3}\mathcal{F}^s}=\frac{GQ^2}{4\pi\alpha\sqrt{2}}\,\frac{-\frac{4}{3}\sin^2\theta_W(3ZF_1^p+AF_1^s)-(1-\frac{4}{3}\sin^2\theta_W)AF_1^s}{(ZF_1^p+\frac{1}{3}AF_1^s)-\frac{1}{3}AF_1^s}$$

$$=-\frac{GQ^2}{\pi\alpha\sqrt{2}}\left[\sin^2\theta_W+\frac{AF_1^s}{4ZF_1^p}\right]. \qquad (39)$$

The results of Eq. (39) are now applied to two sets of kinematics. It should be noted that, for example, ^{4}He and ^{12}C are equivalent in this simple model because the asymmetry depends only on A/Z. The first set of kinematics to be considered is that of the MIT-Bates ^{12}C PV experiment which is now running.[9] Figure 8 shows the effect of the same variations considered in Sec. IV A above: namely, a 10% variation in M_V^0 and the range covered by the Skyrme and chiral-Lagrangian estimates for $F_2^0(0)$. The largest effect is only about 3% of the asymmetry and is therefore probably unobservable in the current experiment. The change is small because the momentum transfer in the experiment is only 0.02 GeV^2 and the normalization of F_1^s is zero; i.e., the nucleon has no net strangeness.

The second set of kinematics, which is more interesting, concerns a possible experiment at higher momentum transfer using the forthcoming CEBAF accelerator. The kinematics are chosen to be the same as in the example of Fig. 5. In this case, where the momentum transfer is now 0.47 GeV^2, the effects are on the order of 30% for the standard variations as is shown in Fig. 9. The sensitivity is large because the nuclear system has $T=0$ (leaving only a term $\propto \sin^2\theta_W$) and because at $Q^2=0.47$ GeV^2 a 10% change in M_V^0 can result in a relatively large F_1^s [see Fig. 1(b)]. If the strange-quark-nucleon form factors are large enough to measure in such experiments, it would, in principle, be possible to compare the strange-quark distributions in the proton and in the nucleus.

V. SUMMARY

There is some evidence from πp scattering, from elastic νp scattering, and from polarized deep-inelastic μp scattering that the $\langle p|\bar{s}s|p\rangle$ and $\langle p|\bar{s}\gamma^5\gamma^\mu s|p\rangle$ matrix elements may be significant relative to the corresponding u and d matrix elements. In this paper the implications of sizable strange-quark vector currents $\langle p|\bar{s}\gamma^\mu s|p\rangle$ were considered. The effects on the elastic PV electron scattering reaction were studied for the cases of nucleon targets and $J=0$, $T=0$ nuclear targets. The contributions from the strange quarks are important to consider in electron scattering PV reactions because the relative couplings to u quarks and to d and s quarks differ for the electromagnetic and weak neutral probes. The form factors corresponding to the quark currents $\langle p|\bar{q}\gamma^\mu q|p\rangle$ and $\langle p|\bar{q}\gamma^5\gamma^\mu q|p\rangle$ were parametrized with reference to the SU(3) matrix generators. The normalizations of two of the nine form factors so-defined, F_2^0 and G_1^0, are essentially unknown. In addition, the Q^2 dependences of the singlet form factors, F_1^0, F_2^0, and G_1^0, are not known. Using a simple model with dipole nucleon form factors and the nonrelativistic impulse approximation for the nuclear form factors, the effects of perhaps plausible variations in two of the form factor parameters, $F_2^0(0)$ and M_V^0, were shown to be significant for both nucleon and nuclear targets in certain kinematic regimes. It appears to be impossible to determine either G_E^n or $\sin^2\theta_W$ (Refs. 13 and 15, respectively) in a model-independent way from such experiments. A series of measurements might, however, provide some further insight as to the strange-quark content of the nucleon.

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