Strangeness contribution to the vector and axial form factors of the nucleon

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Abstract. The strangeness contribution to the vector and axial form factors of the nucleon is presented for momentum transfers in the range 0.45 \( Q^2 \) < 1.0 GeV\(^2\). The results are obtained via a combined analysis of forward-scattering parity-violating elastic \( \vec{e}p \) asymmetry data from the \( G_0 \) and HAPPEx experiments at Jefferson Lab, and elastic \( \nu \)\( p \) and \( \bar{\nu} p \) scattering data from Experiment 734 at Brookhaven National Laboratory. The parity-violating asymmetries measured in elastic \( \vec{e}p \) scattering at forward angles establish a relationship between the strange vector form factors \( G_s^E \) and \( G_s^M \), with little sensitivity to the strange axial form factor \( G_s^A \). On the other hand, elastic neutrino scattering at low \( Q^2 \) is dominated by the axial form factor, with still some significant sensitivity to the vector form factors as well. The combination of the two data sets allows the simultaneous extraction of \( G_s^E \), \( G_s^M \), and \( G_s^A \) over a significant range of \( Q^2 \) for the very first time.

Electroweak Currents and the Elastic Form Factors of the Nucleon: The static properties of the nucleon are described by elastic form factors defined in terms of matrix elements of current operators. The electromagnetic (one \( \gamma \) exchange) interaction involves two vector operators and thus two vector form factors, \( G_{E}^{\gamma,N}(Q^2) \) and \( G_{M}^{\gamma,N}(Q^2) \), where \( Q^2 = -(p - p')^2 \) is the momentum transfer between two nucleon states, and \( N \) is for proton (\( p \)) or neutron (\( n \)). Similarly, the neutral weak current (one \( Z \) exchange) involves two analogous vector form factors \( G_{E}^{Z,N}(Q^2) \) and \( G_{M}^{Z,N}(Q^2) \) and also an axial form factor \( G_{A}^{Z,N}(Q^2) \). Due to the point-like interaction between the gauge bosons (\( \gamma \) or \( Z \)) and the quarks internal to the nucleon, these form factors can be expressed as separated contributions from each quark flavor; for example, the electromagnetic and neutral weak electric form factors of the proton can be expressed in terms of up, down, and strange quark form factors:

\[
G_{E}^{\gamma,p} = \frac{2}{3} G_{E}^{u} - \frac{1}{3} G_{E}^{d} - \frac{1}{3} G_{E}^{s},
\]

\[
G_{E}^{Z,p} = \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) G_{E}^{u} + \left( -1 + \frac{4}{3} \sin^2 \theta_W \right) G_{E}^{d} + \left( -1 + \frac{4}{3} \sin^2 \theta_W \right) G_{E}^{s}.
\]

The same quark form factors are involved in both expressions; the coupling constants that multiply them (electric or weak charges) correspond to the interaction involved (electromagnetic or weak neutral current). These measurements are most interesting for low momentum transfers, \( Q^2 < 1.0 \) GeV\(^2\), as the \( Q^2 = 0 \) values of these form factors represent static integral properties of the nucleon. Of most significance here is the fact that the \( Q^2 = 0 \) value of \( G_A^s \) is the strange quark contribution to the nucleon spin, \( \Delta s \).
which is also the first moment of the polarized strange quark momentum distribution \( \Delta s(x) \) measured in deep-inelastic scattering: \( \Delta s = G_A^s(Q^2 = 0) = \int_0^1 \Delta s(x) \, dx \).

**Parity-violating forward scattering \( ep \) data:** Several experiments\(^1\) have now produced data on forward PV \( \bar{e}p \) elastic scattering \([1, 2, 3, 4, 5]\). Of most interest here are measurements that lie in the same \( Q^2 \) range as the BNL E734 experiment, which are the original HAPPEX measurement \([1]\) at \( Q^2 = 0.477 \text{ GeV}^2 \) and four points in the recent \( G^9 \) data \([4]\). These forward scattering data are most sensitive to \( G_E^s \), somewhat less sensitive to \( G_M^s \), and almost completely insensitive to the axial form factors due to suppression by both the weak vector electron charge \( (1 - 4 \sin^2 \theta_W) \) and by a kinematic factor that approaches 0 at forward angles. Thus, the forward PV \( ep \) data do not provide information directly about the strange axial form factor, but provide an important constraint on the vector form factors which is needed to make the neutrino data useful.

**Elastic neutrino-proton data:** The world’s only data on elastic \( \nu p \) and \( \bar{\nu} p \) scattering comes from the BNL E734 experiment \([6]\), and cover the range \( 0.45 < Q^2 < 1.05 \text{ GeV}^2 \). Due to a variety of experimental and analytical difficulties, these data have large total uncertainties, typically 20-25\%. These data are primarily sensitive to the axial form factor of the proton — the axial contribution dominates at low \( Q^2 \). However, knowledge of the strange vector form factors is still necessary for a clean extraction of the strange axial form factor from these data, as was demonstrated in Ref. \([7]\). Previous analyses of these data \([4, 8, 9]\) were hampered by a lack of knowledge of the strange vector form factors and so had to assume a form for the \( Q^2 \)-dependence of \( G_A^s \) — no such assumption is necessary any longer, now that the PV \( ep \) data are available to constrain the strange vector form factors.

**Combining the two data sets:** The basic technique for combining these two data sets has already been described \([7]\) and the details of the present analysis will be published soon \([10]\). The results are displayed in Figure 1. The uncertainties in all three form factors are dominated by the large uncertainties in the neutrino cross section data. Since those data are somewhat insensitive to \( G_E^s \) and \( G_M^s \), then the uncertainties in those two form factors are generally very large. However the results for the strange axial factor are of sufficient precision to give a hint of the \( Q^2 \)-dependence of this important form factor for the very first time. There is a strong indication from this \( Q^2 \)-dependence that \( \Delta s < 0 \), i.e. that the strange quark contribution to the proton spin is negative. However the data are not of sufficient quality to permit an extrapolation to \( Q^2 = 0 \), so no quantitative evaluation of \( \Delta s \) from these data can be made at this time.

A new experiment called FINeSSE \([11]\) has been proposed to measure the strange axial form factor to sufficient precision to determine \( \Delta s \), by measuring the ratio of the neutral-current to the charged-current \( \nu N \) and \( \bar{\nu} N \) processes. A measurement of \( R_{NC/CC} = \sigma(\nu p \to \nu p)/\sigma(\nu n \to \mu^- p) \) and \( \bar{R}_{NC/CC} = \sigma(\bar{\nu} p \to \bar{\nu} p)/\sigma(\bar{\nu} n \to \mu^+ n) \) combined with the world’s data on forward-scattering PV \( ep \) data can produce a dense set of data points for \( G_A^s \) in the range \( 0.25 < Q^2 < 0.75 \text{ GeV}^2 \) with an uncertainty at each point of about \( \pm 0.02 \), resulting in the first form factor extraction of \( \Delta s \).

\(^1\) See talks by Doug Beck and Jianglai Liu.
FIGURE 1. Results of this analysis: Open circles are from a combination of HAPPEx and E734 data, while the closed circles are from a combination of $G^0$ and E734 data. [Open squares are from Ref. 3 and involve PV ep data only.]

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REFERENCES

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