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p($\vec{e}$,e)p

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ABSTRACT

We present calculations of the parity violating asymmetry in elastic electron proton scattering . Our goal is to find means to measure the nucleon weak form factors. Such measurements will provide interesting tests of the standard model in a strongly bound regime, as well as revealing details of the proton's weak structure. In addition, by *assuming* the standard model, we produce numerical predictions for the asymmetry.

1. Introduction

Motivated by the possibility of a high precision measurement at CEBAF of the elastic asymmetry between left and right handed polarized electrons scattering from a free nucleon, we have considered some of the details required in a theoretical analysis. We have two primary goals:

1. To find means to accurately measure the electroweak structure of single nucleons.
2. To find means to test the standard model[1] in the strongly bound, non-perturbative regime of the free nucleon.

To do this, we first consider the formula for the asymmetry in some generality,[2] in order to see how one extracts the nucleon weak form factors in a relatively model independent fashion. Next, we discuss some predictions in the standard model of relations between various form factors. Finally, assuming the standard model, and making a few simplifying approximations, we already have enough information from electron elastic nucleon form factors and charge changing neutrino cross sections to make some detailed numerical predictions. In this way we can, for example, look for kinematics which optimize the contribution of the various form factors, or the dependence on the Weinberg angle.

2. Nucleon Form Factors

The calculation of the asymmetry requires the hadronic response functions[3] which in turn can be expressed entirely in terms of combinations of the electromagnetic and weak neutral form factors. Assuming Lorentz invariance to determine the most general possible form for the matrix elements of the currents, ignoring possible second-class currents and intrinsic parity violation in the nucleon wave functions, and using the Dirac equation and the conservation of the vector current to eliminate some terms, we write down

$$\langle p'|\, J_\mu^\gamma(0)\,|p\rangle = \frac{i}{\Omega}\bar{u}(p')[F_1^\gamma + F_2^\gamma \sigma_{\mu\nu} q_\nu]u(p) \tag{1}$$

Here, all form factors are assumed to have the general structure:

$$F = \tfrac{1}{2}(F^S(q^2) + \tau_3 F^V(q^2))$$

where the superscript S and V indicate isoscalar or isovector, respectively. τ_3 is just the usual nucleon isospin operator. Similarly for the weak neutral current:

$$\langle p'|\, J_\mu^{(0)}\,|p\rangle = \frac{i}{\Omega}\bar{u}(p')[F_1^{(0)}\gamma_\mu + F_2^{(0)}\sigma_{\mu\nu}q_\nu + F_A^{(0)}\gamma_\mu\gamma_5 - iF_P^{(0)}\gamma_5 q_\mu]u(p) \tag{1b}$$

3. Results- asymmetry in p($\vec{e}$,e)p

Given these definitions of the form factors, it is now a straightforward calculation to find the parity violation in elastic electron scattering. We compute only the lowest order contribution (1-Z, 1-γ interference, which means we are correct to $O(\alpha)$). We also employ the standard model for the *lepton* current:

$$J_\mu^{(0)}(lepton) = i[\bar{\psi}_e\gamma_\mu(1+\gamma_5)\psi_e - 4\sin^2\theta_W\,\bar{\psi}_e\gamma_\mu\psi_e]$$

This can be generalized quite easily, but we are especially interested in testing the standard model in the strongly bound, hadronic sector. The asymmetry is then given by :

$$A \equiv \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\downarrow} = -Gq^2/(4\pi\alpha)\sqrt{2} \tag{2}$$

$$\times \frac{\left\{\begin{array}{c} 2\cos^2(\theta/2)(F_1^{(0)}F_1^\gamma + q^2F_2^{(0)}F_2^\gamma) \\ +4\sin^2(\theta/2)\frac{q^2}{4M^2}G_M^{(0)}G_M^\gamma \\ -\frac{2}{M}\sin^2(\theta/2)(e_1+e_2)G_M^\gamma(1-4\sin^2\theta_w)F_A^{(0)} \end{array}\right\}}{\cos^2(\theta/2)[F_1^{\gamma\,2} + q^2F_2^{\gamma\,2}] + 2\sin^2(\theta/2)\frac{q^2}{4M^2}G_M^{\gamma\,2}}$$

Where $G_M \equiv F_1 + 2MF_2$, and e_1 and e_2 are incident and final lepton energies. We note that by fixing q^2, and varying laboratory angle (and thus energy, of course, as this is elastic scattering), we can in principle separate the three lines in the braces above.(e_2 has an angular dependence to it, allowing the third line with its axial form factor, to be separated, at least in principle) The first two lines involve independent linear combinations of $F_1^{(0)}$ and $F_2^{(0)}$; since we know the electromagnetic form factors quite well we can easily extract the nucleon weak form factors. If one could make the equivalent measurement on the neutron, then $F^{(0),s}$ and $F^{(0),V}$ could be immediately separated.

Within the standard model, there are some simplifications in this formula. We write the hadronic electroweak currents in this model:

$$J_\mu^\gamma = i\Big[\frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) + \frac{1}{6}(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d) - \frac{1}{3}\bar{s}\gamma_\mu s + \ldots\Big]$$

$$\begin{aligned} J_\mu^{(0)} = i\Big[&(1-2\sin^2\theta_w)\frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) + (-2\sin^2\theta_w)\frac{1}{6}(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d) \\ &+ \frac{1}{2}(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d) \\ &- (\frac{3}{2} - 2\sin^2\theta_W)\frac{1}{3}\bar{s}\gamma_\mu s - \frac{1}{2}\bar{s}\gamma_\mu\gamma_5 s + \ldots\Big] \end{aligned} \tag{3}$$

so, for instance

$$F_{1,2}^{0,V} = (1-2\sin^2\theta_w)F_{1,2}^{\gamma,V}$$

This relation is true at *all* q^2, independent of the details of the nucleon's structure, even in the presence of heavy (s,c,...) quarks. In addition,

$$F_{1,2}^{0,S} = -2\sin^2\theta_w F_{1,2}^{\gamma,S}$$
$$F_A^{0,S} = 0$$

These are both true at all q^2, but they are in fact modified slightly by the presence of heavier quarks. As we shall discuss later, we expect the axial isoscalar deviation from its expected value above to be much greater than that of the vector isoscalar.

Given these relations, we can rewrite the proton asymmetry as:

$$A^P = -Gq^2/(4\pi\alpha)\sqrt(2)$$

$$\times\ \frac{\left\{\begin{array}{l} \cos^2(\theta/2)\begin{bmatrix} F_1^{\gamma,P}\,[(1-4\sin^2\theta_W)F_1^{\gamma,P} - F_1^{\gamma,N}] \\ +q^2F_2^{\gamma,P}[(1-4\sin^2\theta_W)F_2^{\gamma,P} - F_2^{\gamma,N}] \end{bmatrix} \\ +2\sin^2(\theta/2)(q^2/4M^2)G_M^{\gamma,P}[(1-4\sin^2\theta_W)G_M^{\gamma,P} - G_M^{\gamma,N}] \\ -(2/M)\sin^2(\theta/2)(e_1+e_2)G_M^{\gamma,P}(1-4\sin^2\theta_W)F_A^{(0),P} \end{array}\right\}}{\text{usual E.M. denominator}} \tag{4}$$

Note that although we have assumed the nuclear domain in the vector form factors, we have left the axial piece general. To the extent that strange quarks do not contribute, $F_A^{(0),S} = 0$, so $F_A^{(0),P} = \frac{1}{2}F_A^{(0),V}$, and is thus known (to perhaps 10%) from charge-changing neutrino experiments. We therefore know all the form factors in this expression (the rest are all just the familiar electromagnetic ones), and can numerically evaluate it. Since the axial form factor is the least well known above, we may want to try to find kinematics which suppress its contribution when trying to measure the Weinberg angle. For example, in the small angle, small q^2 regime the first line in eqn (4) dominates, allowing a measurement of the Weinberg angle which would be fairly insensitive to uncertainties in F_A. Note that for small q^2, $F_1^{\gamma,N} \approx 0$. Since $\sin^2\theta_W \approx \frac{1}{4}$, it turns out that the asymmetry is "accidentally" quite small in this regime.

Another way of demonstrating the relations between the form factors which the standard model implies is to use them to relate experimental quantities. *e.g.* (see Appendix A)

$$A^P\sigma_e^P - A^N\sigma_e^N = c_1(\sigma_e^P - \sigma_e^N) + c_2(\sigma_\nu^P - \sigma_\nu^N - (\sigma_{\bar\nu}^P - \sigma_{\bar\nu}^N)) \qquad (5)$$

Here $\sigma_{e,(\nu,\bar\nu)}$ is just the elastic electron (neutrino, antineutrino) scattering cross section, and c_1 and c_2 are just q^2 dependent constants determined in the standard model. This relation, and the others like it, are *exact, at all q^2*. Like the relations between the form factors themselves, they are invalid only to the extent that isospin is broken, and heavy quarks contribute.

4. Numerical Predictions

We have used eqn (4) to generate numerical predictions for the asymmetry in a wide range of kinematic conditions. One of the more interesting results is the figure of merit. This is defined as A^2N_{tot}, where

$$A \equiv \frac{N\uparrow - N\downarrow}{N_{tot}}$$

and in order to have statistically valid measurements, one requires

$$A^2N_{tot} \gg 1$$

In figures (1) and (2) we show the figure of merit on a 3-d plot, versus the two independent kinematic variables q_μ^2 and θ_{lab}. Although one might naively expect a constant figure of merit (since A $\sim q^2$, and $N_{tot} \sim q^{-4}$), in fact it has a strong peak at $q^2 \approx .3 - .5\,\mathrm{GeV}^2$. The figure of merit is dropping at larger q^2 because of the form factor dependence. At small q^2, the "accidental" value of the Weinberg angle brings us down to near 0. The remaining figures are the parity violation under various kinematically interesting regions. We have shown, for example, the sensitivity of the asymmetry to the Weinberg angle, and the various weak form factors. At small angles, the asymmetry is dominated by the F_1 piece, whereas at larger angles it is in fact dominated by the weak magnetic piece, F_2.

5. Corrections and complications

As stated, the simplified eqn (4)(used to generate the plots) is not exact. One source of inaccuracy is our assumption of good isospin for the nucleons. For instance, matrix elements of the pure iso*vector* quark current, $(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)$, can contribute a small amount to F^{Scalar}. This is because we have *defined* $F^S = F^P + F^N$, but the proton and neutron are not exact isospin eigenstates. The extent of this contribution is extremely difficult to predict, however, and certainly must be investigated further. Similarly, parity is not exact; however, it is possible that the q^2 dependence of the measured asymmetry caused by the nucleon's intrinsic wrong parity component may be completely different, and so in principle can be separated.[4]

As mentioned earlier, heavy quarks also make corrections to eqn (4). Note that *this only modifies isoscalar weak form factor relations* . The correction for the Lorentz vector -isoscalar form factors should certainly be small, but the exact value is again extremely difficult to predict. However, it turns out that the correction for the axial vector - isoscalar form factor may not be so small. This is due to the presence of anomalous strong correction graphs which induce an effective axial isoscalar vertex.[8] A crude estimate gives this effective vertex a strength of about 10% of the axial-isovector vertex. Thus, for example, the form factor $F_A^{(0),P}$ may differ from the one found in charge-changing neutrino scattering, $\frac{1}{2}F_A^{(0),V}$, by 10%. Careful measurements of the proton and neutron axial form factor would give an experimental measure of the interesting quantity $F_A^{(0),S}$.

Finally, an important correction we have left out is higher order graphs (radiative corrections). These are exactly calculable in the standard model,[8] and should contribute at $O(\alpha)$. To the extent that these calculations dominate the corrections at this level, we would have a test of the renormalizability of the standard model, a critical feature and one which is not trivial to check.

6. Summary

The proton is a complicated, confined, strongly interacting many quark/anti-quark system. A priori, predictions for the weak form factors, and the parity-violating asymmetry in electron scattering are extremely difficult. However, the standard model predicts remarkable relations between the weak and electromagnetic form factors as a consequence of the unification of these forces. By measuring parity violation on the proton, we have a fairly clean means to measure the weak form factors. Since parity violation is an interference effect, we basically gain a factor of G over pure elastic $p(\nu,\nu)p$ scattering. Careful measurements of these weak form factors allows us to *test* the predicted relations; in particular,we can test CVC and the simple relations for the different isospin components as functions of momentum transfer. In addition, assuming the standard model allows us to make precise measurements of the Weinberg angle, the weak magnetic structure the weak charge distribution in the proton, and the axial structure as well.

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APPENDIX A

Relations in the Standard Model

We first write out the general formulae for all the basic electroweak single nucleon cross sections:

$$\left(\frac{d\sigma}{d\Omega}\right)^{P}_{ee'} = \left(\frac{4\alpha^2 e_2^2 r}{q^4}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)\left[(F_1^{\gamma,S}+F_1^{\gamma,V})^2 + q^2(F_2^{\gamma,S}+F_2^{\gamma,V})^2\right] \\ +\frac{1}{4}2\sin^2(\theta/2)\left[(q^2/4M^2)(G_M^{\gamma,S}+G_M^{\gamma,V})^2\right] \end{bmatrix}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{N}_{ee'} = \left(\frac{4\alpha^2 e_2^2 r}{q^4}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)\left[(F_1^{\gamma,S}-F_1^{\gamma,V})^2 + q^2(F_2^{\gamma,S}-F_2^{\gamma,V})^2\right] \\ +\frac{1}{4}2\sin^2(\theta/2)\left[(q^2/4M^2)(G_M^{\gamma,S}-G_M^{\gamma,V})^2\right] \end{bmatrix}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{P}_{\substack{\nu\nu' \\ \bar\nu\bar\nu'}} = \left(\frac{G^2 e_2^2 r}{2\pi^2}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)\left[(F_1^{(0),S}+F_1^{(0),V})^2 + q^2(F_2^{(0),S}+F_2^{(0),V})^2 + (F_A^{(0),S}+F_A^{(0),V})^2\right] \\ +\frac{1}{4}2\sin^2(\theta/2)\left[(q^2/4M^2)(G_M^{(0),S}+G_M^{(0),V})^2 + (1+q^2/4M^2)(F_A^{(0),S}+F_A^{(0),V})^2\right] \\ \mp\frac{1}{4}2\sin^2(\theta/2)(e_1+e_2)/M\left[(F_A^{(0),S}+F_A^{(0),V})(G_M^{(0),S}+G_M^{(0),V})\right] \end{bmatrix}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{N}_{\substack{\nu\nu' \\ \bar\nu\bar\nu'}} = \left(\frac{G^2 e_2^2 r}{2\pi^2}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)\left[(F_1^{(0),S}-F_1^{(0),V})^2 + q^2(F_2^{(0),S}-F_2^{(0),V})^2 + (F_A^{(0),S}-F_A^{(0),V})^2\right] \\ +\frac{1}{4}2\sin^2(\theta/2)\left[(q^2/4M^2)(G_M^{(0),S}-G_M^{(0),V})^2 + (1+q^2/4M^2)(F_A^{(0),S}-F_A^{(0),V})^2\right] \\ \mp\frac{1}{4}2\sin^2(\theta/2)(e_1+e_2)/M\left[(F_A^{(0),S}-F_A^{(0),V})(G_M^{(0),S}-G_M^{(0),V})\right] \end{bmatrix}$$

$$A^P\left(\frac{d\sigma}{d\Omega}\right)^{P}_{ee'} = \left(\frac{G\alpha e_2^2 r}{\pi q^2\sqrt{2}}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)(-2)\left[(F_1^{(0),S}+F_1^{(0),V})(F_1^{\gamma,S}+F_1^{\gamma,V}) + q^2(F_2^{(0),S}+F_2^{(0),V})(F_2^{\gamma,S}+F_2^{\gamma,V})\right] \\ +\frac{1}{4}2\sin^2(\theta/2)(-2)\left[(q^2/4M^2)(G_M^{(0),S}+G_M^{(0),V})(G_M^{\gamma,S}+G_M^{\gamma,V})\right] \\ +\frac{1}{4}2\sin^2(\theta/2)(e_1+e_2)(1-4x)/M\left[(F_A^{(0),S}+F_A^{(0),V})(G_M^{\gamma,S}+G_M^{\gamma,V})\right] \end{bmatrix}$$

$$A^N\left(\frac{d\sigma}{d\Omega}\right)^{N}_{ee'} = \left(\frac{G\alpha e_2^2 r}{\pi q^2\sqrt{2}}\right) \begin{bmatrix} \frac{1}{4}\cos^2(\theta/2)(-2)\left[(F_1^{(0),S}-F_1^{(0),V})(F_1^{\gamma,S}-F_1^{\gamma,V}) + q^2(F_2^{(0),S}-F_2^{(0),V})(F_2^{\gamma,S}-F_2^{\gamma,V})\right] \\ +\frac{1}{4}2\sin^2(\theta/2)(-2)\left[(q^2/4M^2)(G_M^{(0),S}-G_M^{(0),V})(G_M^{\gamma,S}-G_M^{\gamma,V})\right] \\ +\frac{1}{4}2\sin^2(\theta/2)(e_1+e_2)(1-4x)/M\left[(F_A^{(0),S}-F_A^{(0),V})(G_M^{\gamma,S}-G_M^{\gamma,V})\right] \end{bmatrix}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{ERL}_{\substack{\nu l^- \\ \bar\nu l^+}} = \left(\frac{G^2 e_2^2 r}{2\pi^2}\right) \begin{bmatrix} \cos^2(\theta/2)\left[F_1^{\pm\,2} + q^2 F_2^{\pm\,2} + F_A^{\pm\,2}\right] \\ +2\sin^2(\theta/2)\left[(q^2/4M^2)G_M^{\pm\,2} + (1+q^2/4M^2)F_A^{\pm\,2}\right] \\ \mp 2\sin^2(\theta/2)(e_1+e_2)/M\; F_A^{\pm}G_M^{\pm} \end{bmatrix}$$

We next define some temporary variables:

$$E^{\binom{P}{N}} \equiv \left(\frac{q^4}{4\alpha^2 e_2^2 r}\right) \sigma_{ee'}^{\binom{P}{N}}$$

$$E^+ \equiv 2(E^P + E^N)$$

$$C \equiv \left(\frac{2\pi^2}{G^2 e_2^2 r}\right) (\sigma_{\nu l^-} + \sigma_{\bar{\nu} l^+})/(2\cos^2\theta_C)$$

$$\nu 1 \equiv \left(\frac{2\pi^2}{G^2 e_2^2 r}\right) \left(\sigma_\nu^P - \sigma_\nu^N - (\sigma_{\bar{\nu}}^P - \sigma_{\bar{\nu}}^N)\right)/(2x)$$

$$\nu 2 \equiv \left(\frac{2\pi^2}{G^2 e_2^2 r}\right) \left(\sigma_\nu^P + \sigma_\nu^N - (\sigma_{\bar{\nu}}^P + \sigma_{\bar{\nu}}^N)\right)/(2x-1)$$

$$\nu 3 \equiv \left(\frac{2\pi^2}{G^2 e_2^2 r}\right) \left(\sigma_\nu^P + \sigma_\nu^N + (\sigma_{\bar{\nu}}^P + \sigma_{\bar{\nu}}^N)\right)/(2)$$

$$\nu 4 \equiv \left(\frac{2\pi^2}{G^2 e_2^2 r}\right) \left(\sigma_\nu^P - \sigma_\nu^N + (\sigma_{\bar{\nu}}^P - \sigma_{\bar{\nu}}^N)\right)/(2x)(2x-1)2$$

$$\bar{A}^{\binom{P}{N}} \equiv \left(\frac{\pi q^2\sqrt{2}}{G\alpha e_2^2 r}\right) A^P \sigma_{ee'}^{\binom{P}{N}}$$

and finally:

$$T \equiv \nu 3 - 4x^2 E^+ - (1-4x)C$$

(Note the essential feature that all the above are *directly* determined from experimental quantities!) Now, as discussed in section (3) (assuming nuclear domain and good isospin) the relations between form factors given by the standard model are:

$$F_{1,2}^{(0),S} = -2xF_{1,2}^{\gamma,S}$$

$$F_{1,2}^{(0),V} = (1-2x)F_{1,2}^{\gamma,V}$$

$$F_{1,2}^{\gamma,V} = F_{1,2}^{\pm}/\cos\theta_C$$

$$F_A^{(0),V} = F_A^{\pm}/\cos\theta_C$$

$$F_A^{(0),S} = 0$$

which immediately yield exact relations between the experimental quantities defined above. For example:

$$(\sigma_{\nu l^-}^{ERL} - \sigma_{\bar{\nu} l^+}^{ERL}) = \left(\frac{2\cos^2\theta_C}{1-2x}\right)\left[\sigma_\nu^P + \sigma_\nu^N - (\sigma_{\bar{\nu}}^P + \sigma_{\bar{\nu}}^N)\right]$$

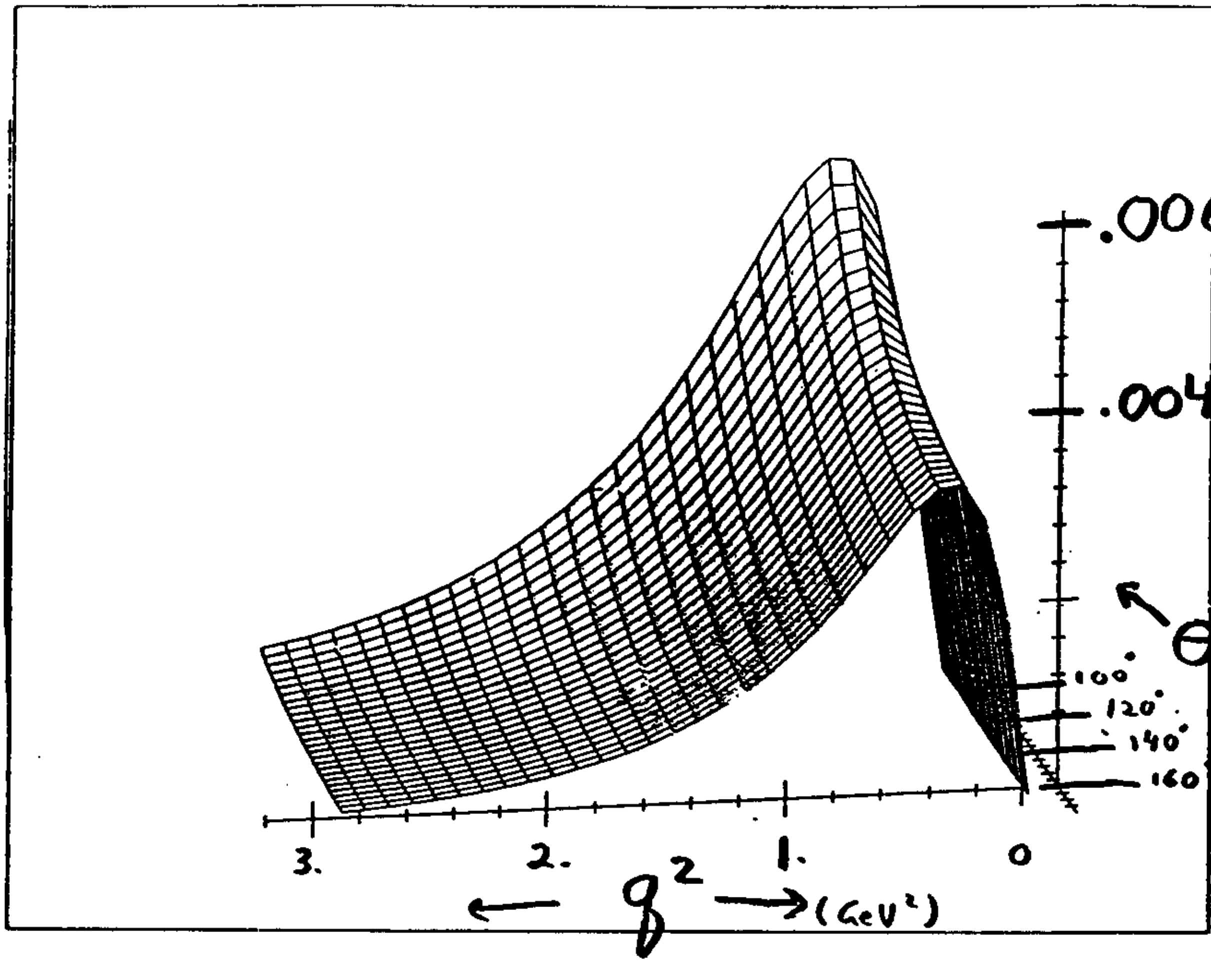
$$(\sigma_{ee'}^P - \sigma_{ee'}^N) = \left(\frac{8\alpha^2\pi^2}{G^2q^4}\right)\left(\frac{1}{2(2x)(2x-1)}\right)(\sigma_\nu^P - \sigma_\nu^N + (\sigma_{\bar{\nu}}^P - \sigma_{\bar{\nu}}^N))$$

$$\bar{A}^P = -(1-4x)E^P - \tfrac{1}{2}(C - \tfrac{1}{2}E^+ - T/4x) + \frac{(1-4x)}{4}(\nu 1 + \nu 2)$$

$$\bar{A}^P - \bar{A}^N = -(1-4x)(\nu 4 + \tfrac{1}{2}\nu 1)$$

$$= -(1-4x)(E^P - E^N + \tfrac{1}{2}\nu 1) \qquad \text{(this is equation (5))}$$

Fig. of Merit A N_{TOT}.



$(\sin^2\theta_w = .23)$

Fig.1

Figure of merit versus q_μ^2 and θ_{lab}. We assume a target density × luminosity of $7.8 * 10^{28}$ nuclei – electrons/sec, and a fixed solid angle of detection of 1sr. This is only reasonable experimentally for backward scattering.

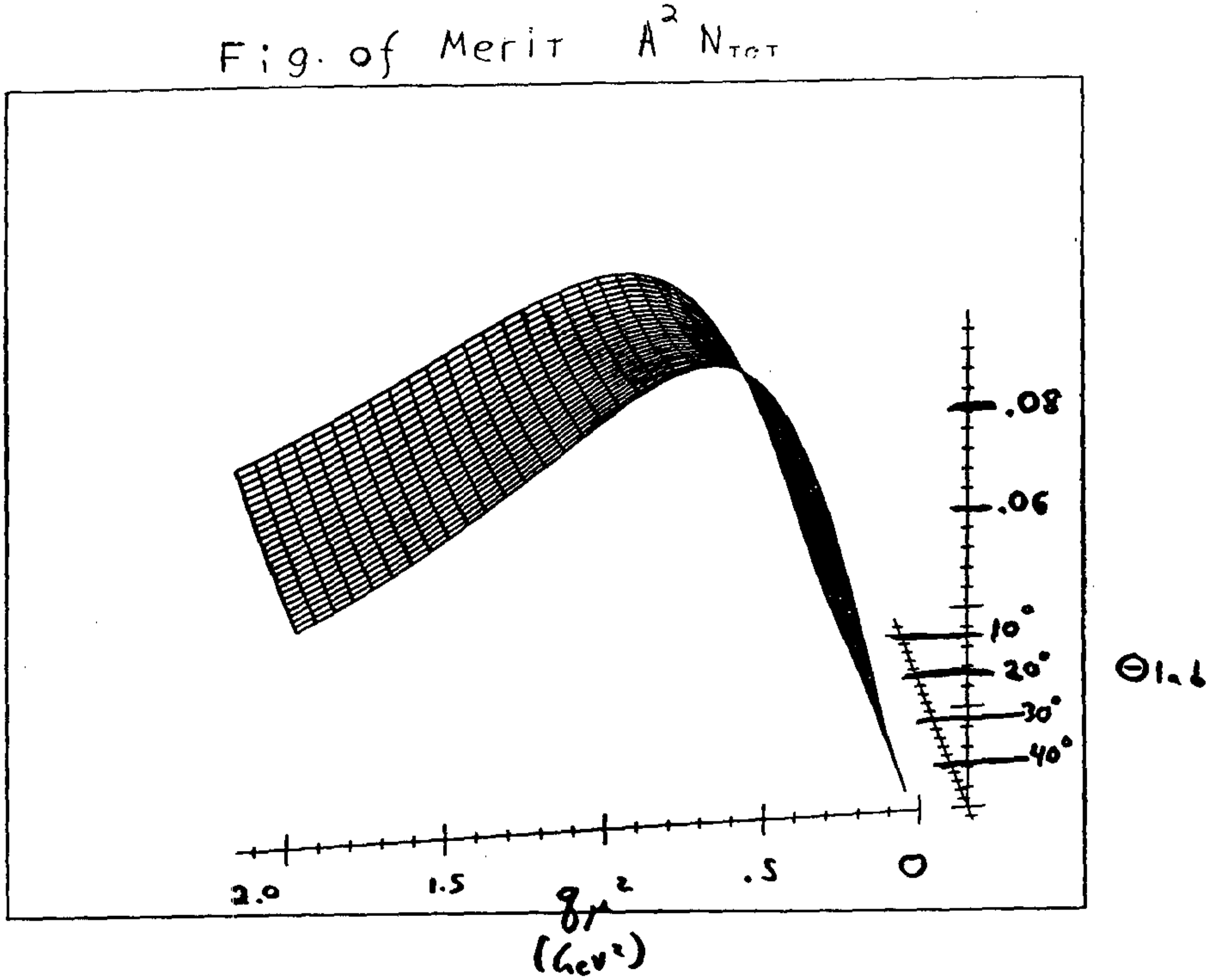


Fig.2

Same as fig(1), but now for forward scattering. We assume a spectrometer with a fixed bite of $\Delta q^2/q^2 \approx 2$.

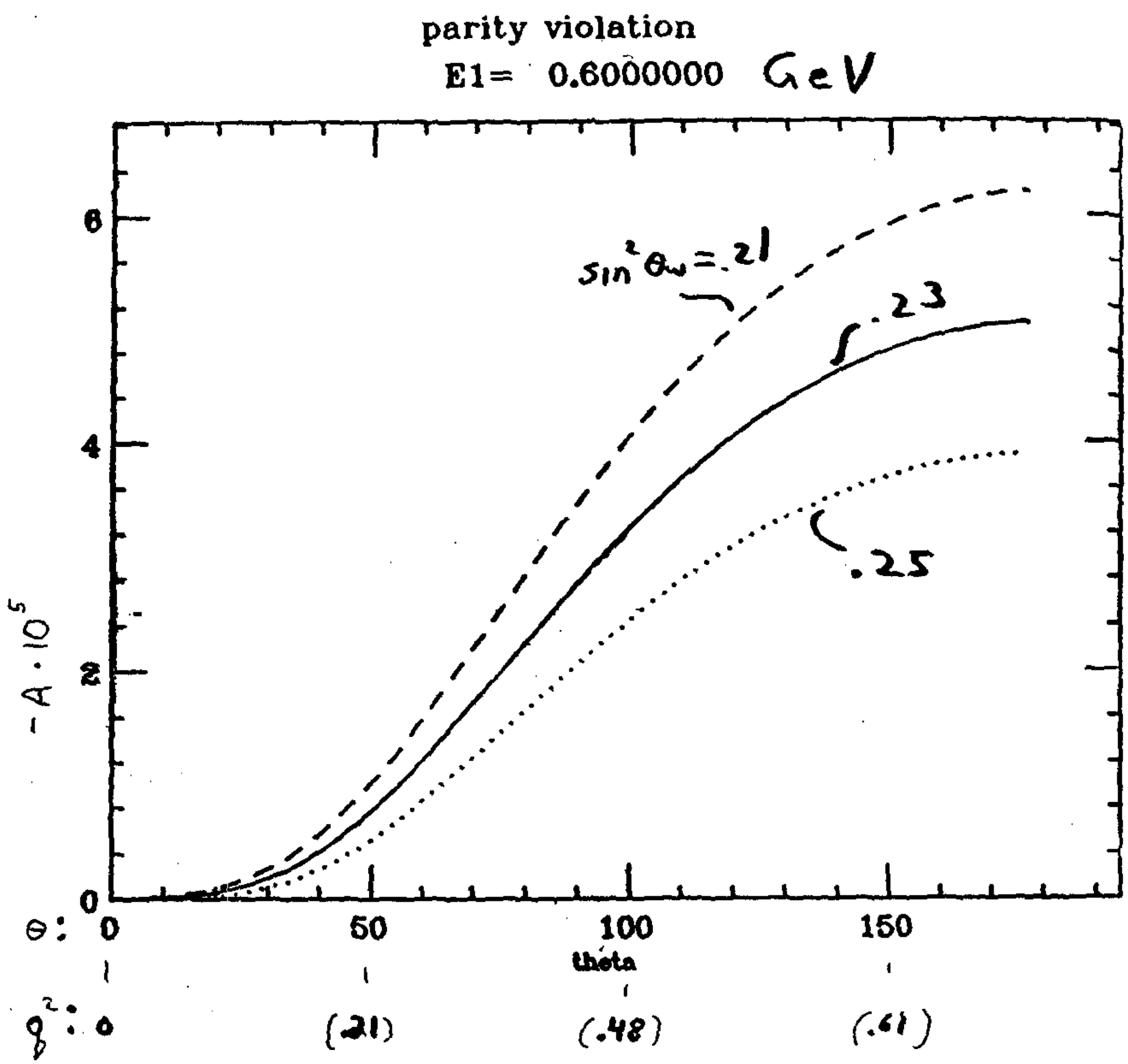


Fig.3

Parity violating asymmetry versus lab angle, with a fixed beam energy of .6 GeV. (q^2 values at several angles are indicated below the axis)

3 different values of $\sin^2\theta_W$ are shown for comparison.

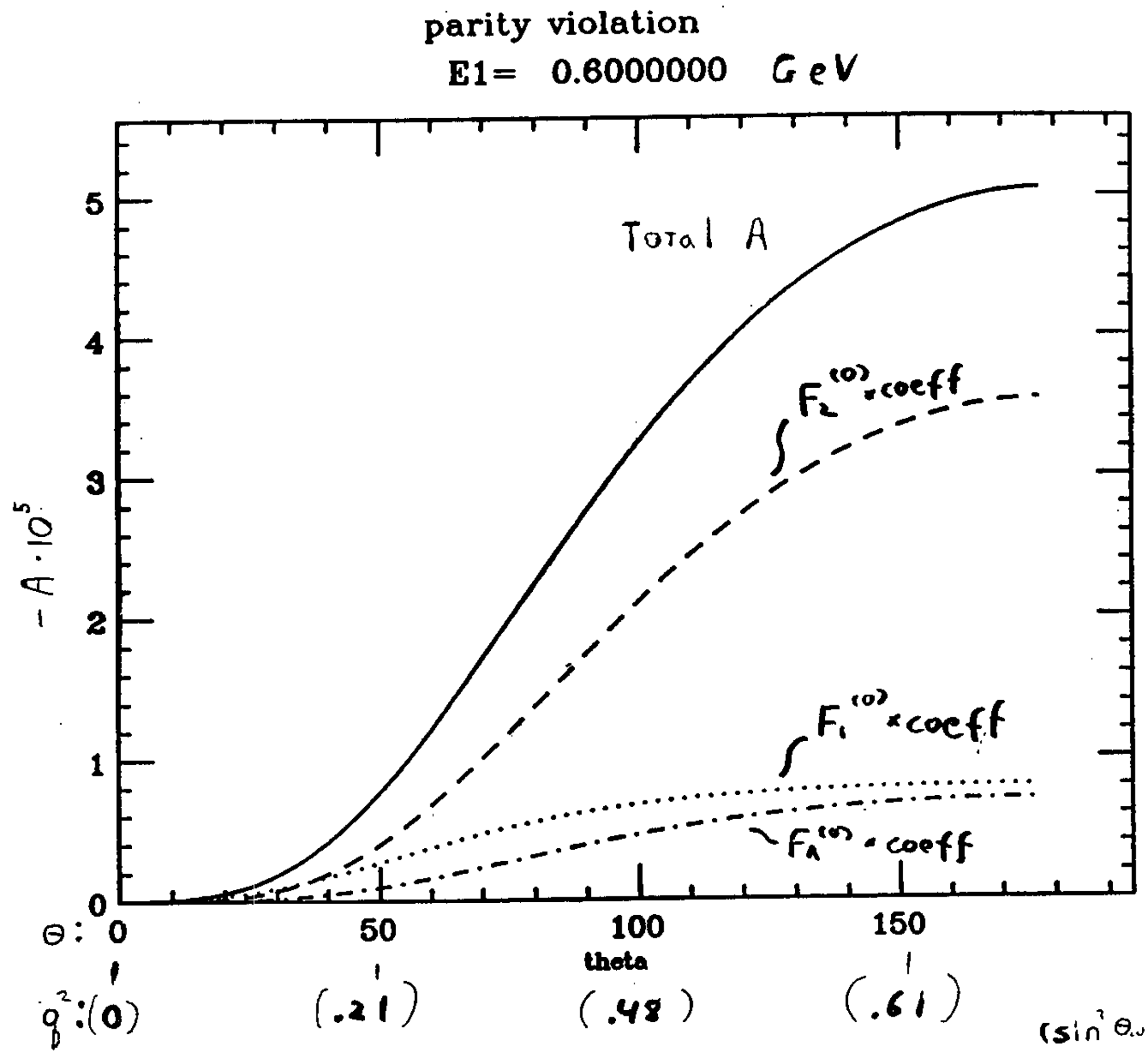


Fig.4

Parity violating asymmetry versus lab angle, with a fixed beam energy of .6 GeV. Shown separately are the contributions to the asymmetry from terms proportional to $F_1^{(0)}$, $F_2^{(0)}$, and $F_A^{(0)}$.

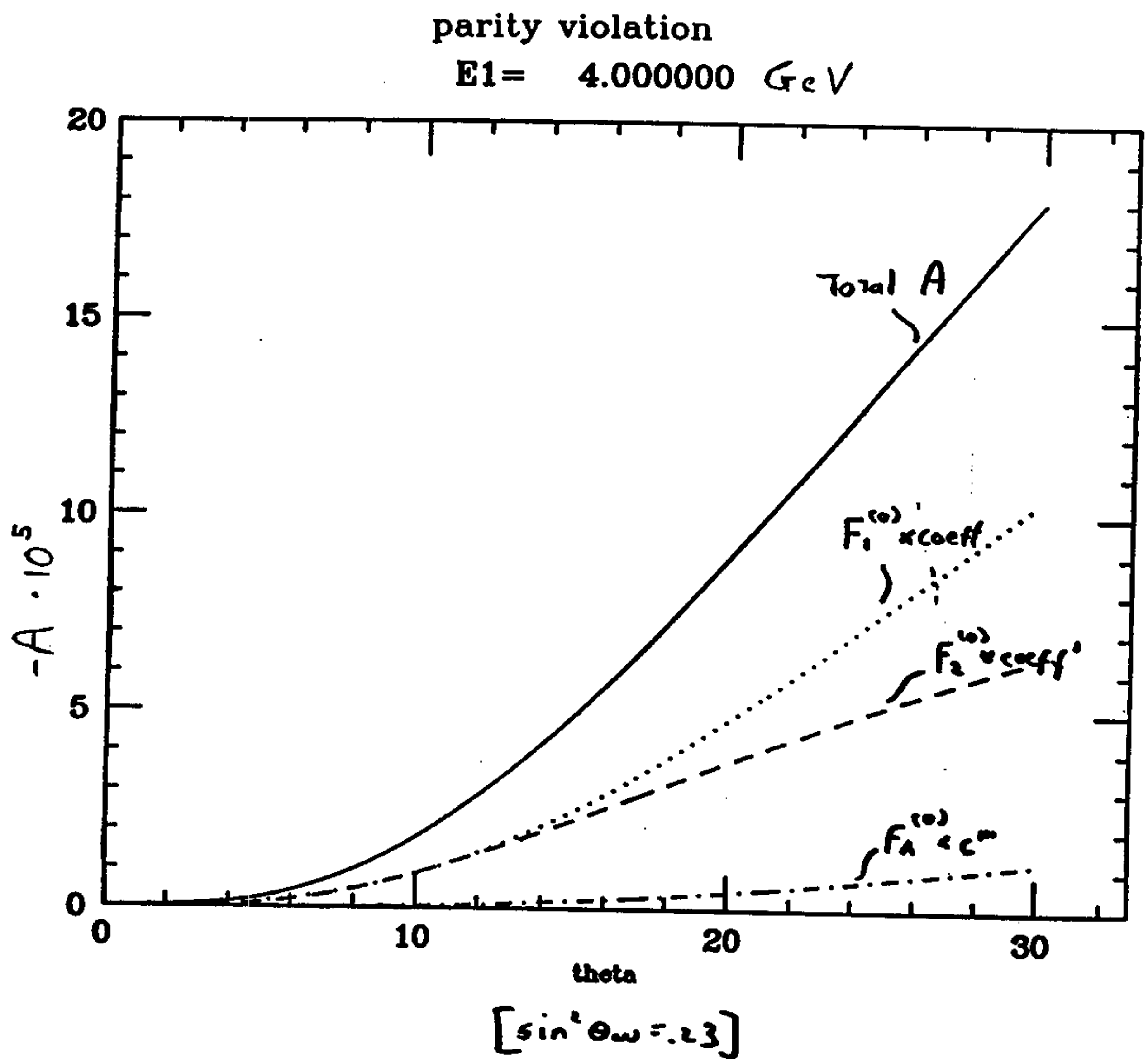


Fig.5

Same as fig(4), but with incident beam energy of 4 GeV.