Parity Violation at 8 – 12 GeV at Jefferson Lab

Robert Michaels
Thomas Jefferson National Accelerator Facility
July, 1998

1 Introduction

Experiments on parity violation in electron scattering measure the asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

where $\sigma_{R(L)}$ is the cross section for Right(Left) handed longitudinally polarized electrons. This asymmetry arises, in first order, from the interference between photon and Z-boson exchange amplitudes. Experiments make two basic uses of the Z-boson as a probe in electron–quark or electron–nucleon scattering. Historically the first usage was to test the electroweak theory in regions of kinematics where the hadronic structure is sufficiently understood. We will discuss the application of higher energies at Jefferson Lab to repeat the SLAC e-D deep inelastic parity violation experiment [**1**] at a level of precision $\approx$ 0.5% in $\sin^2\theta_W$ which would be a useful constraint on extensions of the Standard Model [**2**]. The second, more recent usage of the Z-boson probe is to assume the Standard Model is correct at about the 1% level and use this as a unique method to address fundamental issues of nucleon structure, such as: 1) Are the strange quarks an important component of the nucleon [**3**] ? 2) In deep inelastic scattering, are the high momentum quarks u or d quarks ? To address the first question, we will discuss the feasiblity of extending the HAPPEX experiment to higher Q^2. For the second question, we discuss a possible measurement of the ratio of valence quarks $\frac{d}{u}$ in the proton using deep inelastic parity violation.

2 Extension of HAPPEX to Higher Q^2

The Hall A Proton Parity Violation Experiment (HAPPEX) measures the asymmetry in elastic electron–proton scattering. This asymmetry may be expressed in terms of the Weinberg angle $\sin^2\theta_W$, Fermi constant G_F, Sach's form factors, and kinematic factors as follows [**4**]:

$$\begin{aligned} A^{PV}(\vec{e},P) \;=\; & -\frac{G_F|Q|^2}{4\pi\alpha\sqrt{2}} \times [(1-4\sin^2\theta_W) - \\ & \frac{\epsilon G_E^P(G_E^n+G_E^S) + \tau G_M^P(G_M^n+G_M^S) - (1-4\sin^2\theta_W)\epsilon' G_M^P G_A^P}{\epsilon(G_E^P)^2 + \tau(G_M^P)^2}] \end{aligned}$$

The expression contains the neutral weak axial form factor G_A^P which is obtainable by combining information from neutron beta decay and polarized deep inelastic scattering [**5**], and which is suppressed in the formula. The interesting strange form factors G_E^S and G_M^S are measured by A^{PV}.

Figure 1 shows the the range of feasible measurements in the 2–dimensional space of four-momentum transfer Q^2 and scattered electron energy E'. The feasibility requirement was a running time of less than 500 hours, for a 5% statistical error, assuming a polarization of 0.8 and 100μA beam current. The spectrometer angle was assumed to exceed 12.5°, which is a constraint in Hall A if both HRS are used. Using HRS spectrometers, a Q^2 of up to $\approx 1.5\text{GeV}^2$

is reachable. To go higher in Q^2 would require a larger momentum spectrometer like the HMS, as well as the energy upgrade. Also shown in figure 1 are possible data that might be obtained, and comparison to the range of variation in the asymmetry calculated using five models. The calculations used values of the strangeness radius parameter ρ_s and magnetic moment μ_s from published low-Q^2 models [**6-9**] and a dipole form for the E and M form factors which are similar to their nonstrange counterparts as discussed in [**4**]. These calculations illustrate the plausible range in $\Delta A/A$ and suggest that 5% accuracy is a useful goal for each point. These accuracies are obtained in 250 to 500 hours of running time for the data points shown, where this running time increases with Q^2.

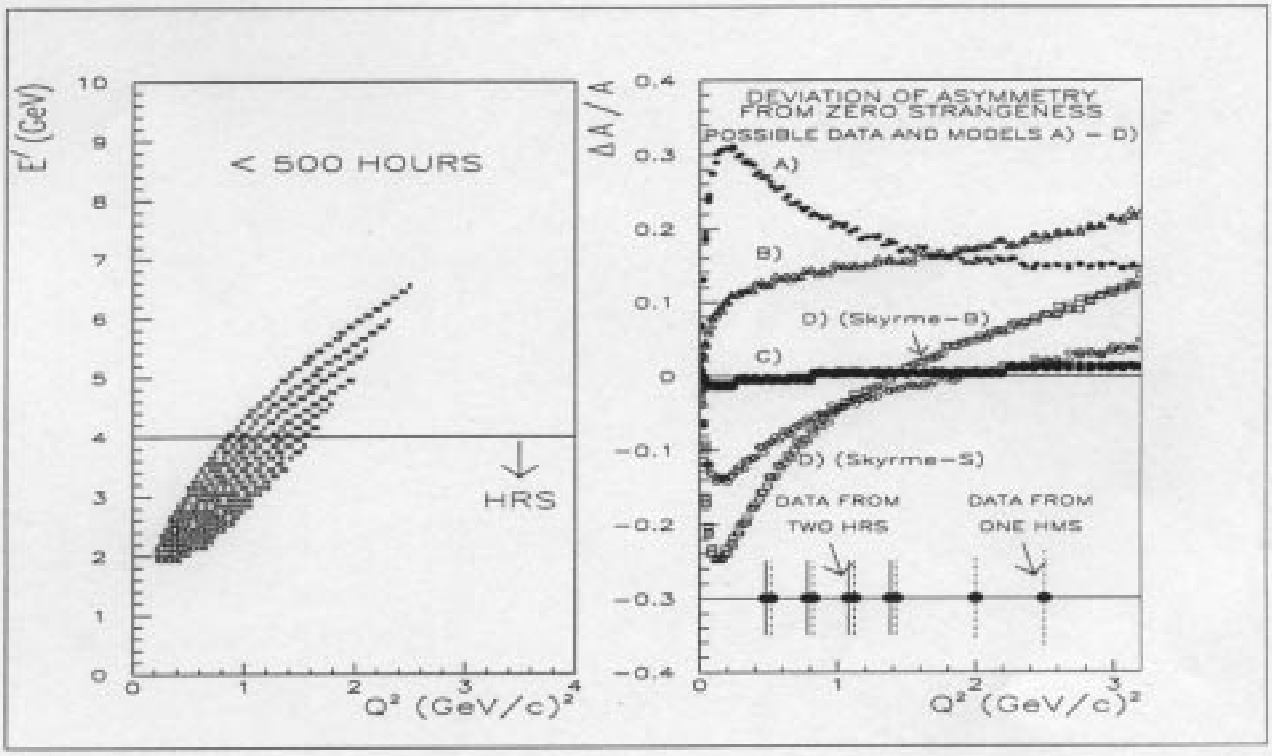

Figure 1: Asymmetry in Elastic e-P Scattering. Left: The feasible range of ≤500 hour runs for a 5% accurate measurement. Right: The deviation in the asymmetry from the case of zero strangeness. The models A)-D) correspond to parameters from references [6-9]. The possible data are from runs of 250 to 500 hours, increasing with Q^2. The points with solid (dashed) error bars correspond to HRS (HMS). Points on the farthest right in each set require 500 hours.

3 Extraction of d/u Ratio in DIS

With energies in the 8–12 GeV range, a range of deep inelastic scattering is reached, which we define as $Q^2 \geq 4\,\mathrm{GeV}^2$, and invariant mass $W \geq 2\,\mathrm{GeV}$, and bounded from above by the maximum energy. In the quark–parton model, the asymmetry is given by:

$$\mathrm{A}_{\mathrm{DIS}}^{\mathrm{PV}} \;=\; \frac{\mathrm{G_F} Q^2}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\, b(x)\right]$$

where

$$a(x) = \frac{\sum_i q_i(x) C_{1i} Q_i}{\sum q_i(x) Q_i^2} \qquad b(x) = \frac{\sum_i q_i(x) C_{2i} Q_i}{\sum q_i(x) Q_i^2}$$

and where $q_i(x)$ are the quark distributions for flavor i as a function of Feynman x, and Q_i is the quark charge, and the constants C_{1i} and C_{2i} may be written in terms of $\sin^2\theta_W$ in the Standard Model.

At $x \geq 0.5$, this expersion for A_{DIS}^{PV} should be an excellent approximation and serves to measure the ratio of d to u valence quarks in a unique way. Statistically precise measurments of the ratio $\frac{d}{u}$ have been obtained from the ratio of cross sections for proton and for deutrium **[10]**, but this is problematic due to the bound state problem of deuterium, for which the corrections are comparable to the measurements and somewhat uncertain at high x **[11]**. Figure 2 shows the range of feasible experiments for DIS in the (Q^2, E') plane. In this case, deuterium was chosen for the calculation, the required accuracy was 3%, running time $\leq$ 500 hours, the polarization 0.8 and the beam current 100μA. (For the energy upgraded accelerator, less current may be available.) From this calculation, we see that a fair amount of the kinematical space is available using the HMS and SHMS spectrometers in Hall C. Also shown in figure 2 are some possible measurements from the proton, for about 2 months of running time, indicating the discriminating power between the QCD prediction **[12]** that as $x \to 1$, $\frac{d}{u} \to \frac{1}{5}$, versus the assumption used in most phenomenological fits that $\frac{d}{u} \to 0$.

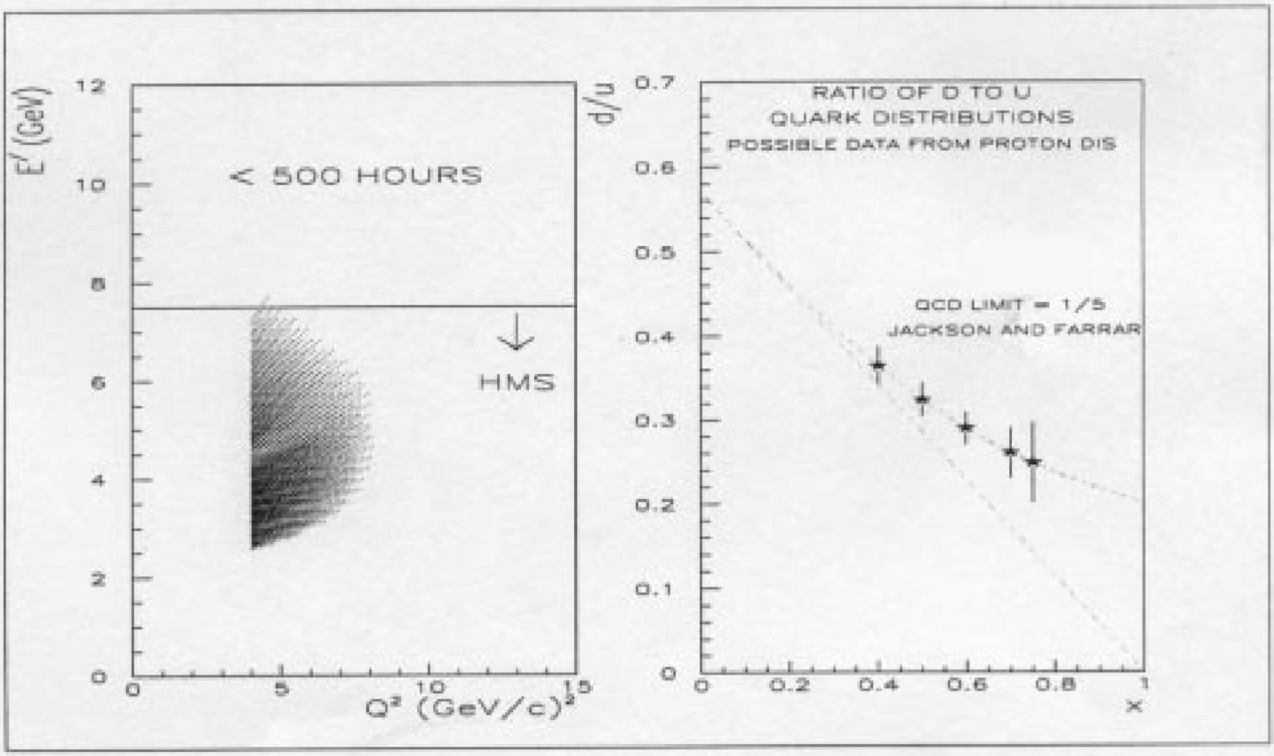

Figure 2: Deep Inelastic Scattering. Left: The feasible range for e-D scattering requiring a 3% accuracy in $\leq$ 500 hours. Right: Possible data on the ratio of d to u valence quark distributions from DIS proton scattering, for a two month running period. The data at high x allows to distinguish between the QCD limit [12] and the common assumption that $\frac{d}{u} \to 0$.

4 Standard Model Test in e-D

For an isocaler target such as deuterium, the above expression for A^{PV}_{DIS} yields a simple result independent of the quark distributions, involving the constants C_{1u}, C_{1d}, C_{2u}, and C_{2d}, which in turn can be written in terms of $\sin^2\theta_W$. A measurement from deuterium at $x = 0.5$ and $y = 0.5$, where the quark–parton model works well, and complications due to sea quarks, higher twist effects, etc, are minimal, may therefore be a clean test of the Standard Model.

Given the history of precision Standard Model tests, the question arises how such a measurement can compete. As reviewed by Langacker et al [13], low energy tests at a sufficient level of precision (less than 1% in the Weinberg angle) can provide useful constraints on physics beyond the Standard Model. Examples of new physics include extra Z bosons that don't mix with the known Z, leptoquarks, new heavy fermions, and composite structure of the fermions. To take one of these examples, a contact interaction between composite electron and quark is governed by a mass scale Λ, and measurements of the constants in the $e - q$ Lagrangian, at a level of precision anticipated by atomic parity violation or possibly e-D DIS, can constrain Λ at the ≈20 TeV mass scale, which is competitive with high energy physics searches.

Count rate estimates were performed for an e-D DIS experiment, assuming a polarization of 0.8 and 100μA current. The angle was constrained to be $\geq 12.5°$, though one may be able to go more forward, and the properties of the HMS–SHMS pair of spectrometers were used. The experimental goal was 1% in the asymmetry, which implies a 0.5% accuracy in $\sin^2\theta_W$. The kinematics are $Q^2 = 4\,\mathrm{GeV}^2$, $x = 0.5$, and $y \approx 0.45$. For incident energy E = 11.8 GeV (y=0.4), the running time is 400 hours, while for E = 8 GeV (y=0.5), the running time is 1800 hours. At the lower energy, the rates are ≈ 10 kHz per spectrometer, which might be within reach of DAQ speeds for event counting and would allow for better background rejection. The required 1% precision in the polarization, and the theoretical control of higher twist effects, are significant challenges for such a measurement.

References

[**1**] C.Y. Prescott *et al.*, Phys. Lett. **B77** (1978) 347; C.Y. Prescott *et al.*, Phys. Lett **B84** (1979) 524.

[**2**] S.L. Glashow, Nucl. Phys. **22**, (1961) 579; S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264; A. Salam in Elementary Particle Theory, Nobel Symposium No. 8, ed. by N. Svartholm (Almquist Forlag, Stockholm, 1968) 367.

[**3**] R.D. McKeown, Phys. Lett. **B219**, (1989) 140; D.H. Beck, Phys. Rev. D **39** (1989) 3248.

[**4**] M.J. Musolf, *et al.*, Phys. Rep. **239** (1994) 1; M.J.Musolf, T.W.Donnelly, Nucl. Phys. **A546** (1992) 509.

[**5**] Particle Data Group, R.M. Barnet *et al.*, Phys. Rev. D **54** (1996) 1; K. Abe *et al.*, Phys. Rev. Lett. **74** (1995) 346.

[**6**] R.L. Jaffe, Phys. Lett. **B229** (1989) 275.

[**7**] M.J. Musolf, M. Burkardt, Z. Phys **C61** (1994) 433.

[**8**] W. Koepf, E. M. Henley, S. J. Pollock, Phys. Lett. **B288** (1992) 11.

[**9**] N.W. Park, J. Schechter, H. Weigel, Phys. Rev. **D43** (1991) 869.

[**10**] L.W. Whitlow *et al.*, Phys. Lett. **B282** (1992) 475 ; J. Gomez *et al.*, Phys. Rev. D49 (1994) 4348.

[**11**] W. Melnitchouk, A.W. Thomas, Phys. Lett. **B377** (1996) 11.

[**12**] G.R. Farrar, D.R. Jackson, Phys. Rev. Lett **35** (1975) 1416.

[**13**] P. Langacker, M. Luo, A.K. Mann., Rev. Mod. Phys. **64** (1992) 87.