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FURTHER TESTS OF PARITY VIOLATION IN INELASTIC ELECTRON SCATTERING *

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ABSTRACT

Further measurements of parity violating asymmetries in inelastic scattering of polarized electrons from deuterium have been made for a range of y values from 0.15 to 0.36. Only a small y-dependence is observed in the asymmetries. Using the quark-parton model our results are in good agreement with the Weinberg-Salam predictions. We obtain a value of the parameter $\sin^2\theta_W = 0.224 \pm 0.020$.

The evidence for parity non-conservation in electron scattering was reported last year.[1] Today I wish to report on further measurements of the parity violating asymmetries we have made in the process

$$e(\text{polarized}) + D(\text{unpolarized}) \rightarrow e' + X \quad . \tag{1}$$

These further measurements refine and extend our earlier results over a wider kinematic range and provide more stringent tests of gauge theory models. The parity violating asymmetry we measure is defined as

$$A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L) \tag{2}$$

where $\sigma_{R(L)}$ is the cross-section $d^2\sigma/d\Omega dE'$ for right-handed (left-handed) electrons scattering from deuterium.

If we make the usual quark-parton model assumptions that the electrons scatter off spin ½ constituents of the nucleons, the asymmetry has the general form

$$A/Q^2 = a_1 + a_2 \frac{(1 - (1 - y)^2)}{(1 + (1 - y)^2)} \tag{3}$$

where Q^2 is the invariant four-momentum transfer-squared, and $y = (E_o - E')/E_o$ is the fractional energy transferred from the electron to the hadrons.[2] For an isoscalar target such as deuterium, the coefficients a_1 and a_2 are expected to be constants. Gauge theory models predict values for a_1 and a_2, and in the Weinberg-Salam version of the SU(2) x U(1) gauge theory, equation (3) becomes[3,4,5]

$$A/Q^2 = \frac{G_F}{2\sqrt{2}\pi\alpha} \cdot \frac{9}{10} \left[(1 - \frac{20}{9} \sin^2\theta_W) + (1 - 4 \sin^2\theta_W) \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right] \quad . \tag{4}$$

Under these more restrictive assumptions, measurements of the reaction (1) can be used to determine a value for the mixing parameter $\sin^2\theta_W$. I will show fits to our data for the Weinberg-Salam model, equation 4, for the more general form, equation 3, and for a second SU(2) x U(1) model which assigns the right-handed electron to a doublet with an hypothesized heavy neutral lepton. I will conclude my remarks with a brief discussion of the sources of errors in our results, and connections our results have to parity violation in the atomic physics experiments.

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The asymmetry A arises from weak-electromagnetic interference and was expected to be less than 10^{-4} in our kinematic range. The experimental objective, therefore, was to control statistical and systematic errors at the 10^{-5} level. The smallness of this error made the measurements technically difficult. Figure 1 shows the experiment in a highly schematic form.

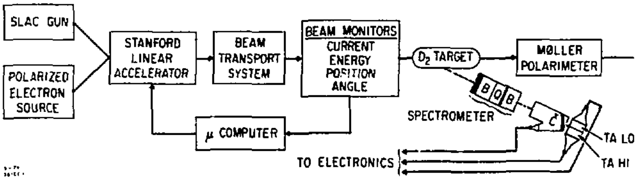


Fig. 1

We had available for our use either ordinary unpolarized electrons from the SLAC gun, or polarized electrons from the newly developed GaAs photoemission source. The polarized electron source was developed over the past 4 years as a high intensity injector for SLAC, based on a proposal in 1974 by Garwin (SLAC), Pierce and Siegmann (Zurich) that circularly polarized laser light could photoemit longitudinally polarized electrons from gallium arsenide crystal surfaces. Such a device was developed at SLAC and installed as an injector for the accelerator in late 1977. It now routinely provides full SLAC beam intensities at a polarization around 40%. Polarization is fixed for the short 1.5 μsec long beam pulses at SLAC, but can be reversed between beam pulses by reversing the circular polarization of the laser light. Most importantly, influences these reversals have on beam parameters such as current, position, or phase space are virtually non-existent, and cross-section comparisons between + and - helicity can be meaningfully made. We chose to randomize the pattern of + and - pulses to remove any biases due to systematic drifts in apparatus or periodic effects in the accelerator. The accelerator operated at 120 pulses per second for this work, at energies from 16.2 GeV to 22.2 GeV. No problems with depolarization of longitudinal spin were seen (or expected). A beam transport system defined the energy of the beam ($\Delta E/E \approx 1.5\%$ FW) and delivered it to the target. The beam transport system is instrumented with beam toroids that measure the charge delivered in each pulse to the target, and with resonant microwave position monitors to monitor position and angle of each beam pulse at the target. A microwave cavity placed in the beam transport system where energy is dispersed horizontally permitted measurement of beam energy within the 1.5% acceptance. Signals derived from these cavities were monitored by a microcomputer and correction signals were generated to null out drifts seen in beam energy, position and angle. The phase of two of the accelerating klystrons was varied forward or backward from 90° to add or subtract beam energy, and currents in beam magnets were adjusted to correct position and angle. This procedure significantly improved stability in these beam parameters.

Signals from these monitors were read for each beam pulse and stored along with other data for analysis. This information was later used in the analysis of our systematic errors. The beam passed first through a 30 cm long liquid D_2 target (0.04 radiation lengths) and then through a polarimeter which monitors beam polarization. By scattering longitudinally polarized beam electrons off polarized target electrons (Møller scattering) the beam polarization could be measured. Polarized target electrons are obtained by magnetizing an iron foil. This process, calculated to good accuracy in QED, provides an important normalization for the measurements. The experimental asymmetries are related to the parity violation asymmetry, Eq. (2) by

$$A_{exp} = P_e A . \tag{5}$$

The Møller polarimeter was used frequently during the course of the data (several times per day), and obtained an average polarization, $P_e = 37 \pm 2\%$. We also monitored the polarization at the source by the traditional low energy technique of Mott scattering from gold foils. For the latter technique the value obtained was $P_e = 39 \pm 4\%$. We use the more accurate high energy value.

Cross-sections for electrons scattered at 4^o were measured in a spectrometer. The spectrometer defined acceptances in angles and momentum which varied from 11 to 16.5 GeV/c. Electrons passing through the acceptances are counted by two counters. The first was a 3 meter long gas Cerenkov counter, and the second a lead glass shower counter divided into high and low momentum halves. These counters operated independently through separate electronic channels (never in coincidence), and served as a cross check on each other. Because of the high counts needed to achieve $\Delta A < 10^{-5}$, cross-sections were measured by counting fluxes of scattered electrons. For each beam pulse, the photomultiplier anode currents were integrated and digitized for each counter. These signals, taken as a measure of the flux of electrons, were normalized in the computer to the charge delivered to the target. For each beam pulse we obtained in each counter a cross-section in ·itrary units. Although the spectrometer was calibrated, precise normalization is not important because such factors cancel for asymmetries defined in equation 2. By averaging over sufficiently large numbers of beam pulses, the statistical errors could be reduced to the 10^{-5} level. But at this level, the question of non-statistical sources of error becomes a primary concern.

One critical source of error could arise if reversals of polarization between + and - helicity caused changes in beam parameters. Extensive monitoring of all important parameters (current, energy, position and angle) ruled out systematic errors of this nature at the 10^{-5} level. To rule out other sources of systematic errors, we appeal to the several null measurements included in our measurements. An example is found in the next figure, which also shows the best evidence we have for parity violation in this process.

Owing to the anomolous magnetic moment of the electron, and to the $24\frac{1}{2}^o$ bend in the transport system, the electron spin will precess ahead of the momentum by an amount

$$\begin{aligned} \theta_{prec} &= \gamma \frac{g-2}{2} \theta_{bend} \\ &= \frac{E_o \pi}{3.237\,(\mathrm{GeV})} \text{ radians.} \end{aligned} \tag{6}$$

The majority of our data were taken at 19.4 GeV ($\theta_{prec} = 6\pi$) where positive helicity at the source resulted in positive helicity at the target. But at 16.2 GeV and 22.2 GeV this was not so. The experimental asymmetries measured by our computer relative to the source polarization should be modulated by the g-2 precession according to

$$A_{exp}/Q^2 = P_e A/Q^2 \cos\left(\frac{E_o \pi}{3.237}\right) . \qquad (7)$$

Figure 2 shows the asymmetries measured separately in two counters for four energies, and a fit of the form given by equation 7. The point at 17.8 GeV corresponds to spin transverse to the scattering plane, where asymmetries are expected to vanish. This point limits the contribution due to unobserved systematic effects, and rules out asymmetries arising from transverse spin components which would be maximum for this point. No systematic errors we know of can mimic the g-2 modulation of our results, and we take the results of Figure 2 to be clear evidence of parity violation in electron scattering.

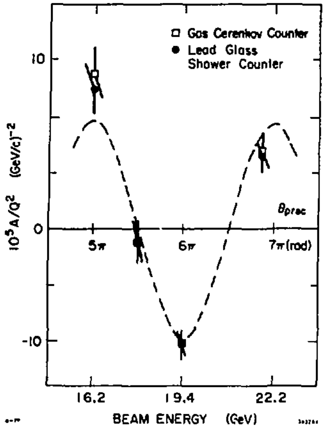


Fig. 2

Figure 3 shows the latest results taken mostly at E_o = 19.4 GeV for secondary energies E' = 11 to 14.5 GeV. Earlier data taken at E_o = 16.2, 19.4, and 22.2 GeV are also included. We plot asymmetries normalized to Q^2 for the different mean y values of each setting. For these points, the separate high and low momentum halves of the lead glass counter are used, resulting in two points per kinematic setting. For the lowest energy, 16.2 GeV, one half has been deleted because it contained strong elastic peak and resonance production contributions. This results in 11 data points. Each point is shown with double error bars. The inner errors are the statistical part only. The outer errors are the systematic and statistical errors combined. An additional ± 5% uncertainty in overall scale, due to the error on P_e, is not shown.

We fit these data to three models. The first is the Weinberg-Salam model combined with the simple quark-parton model for the nucleon, equation (4). The fit depends on a single parameter, $\sin^2\theta_W$. The best value is

$$\sin^2\theta_W = 0.224 \pm 0.020 \qquad (8)$$

and the chi-squared value for the fit is 1.04 per degree of freedom.

A second SU(2) x U(1) model, which assumes the right-handed electron has a heavy neutral partner, $\left(\frac{E^o}{e^-}\right)_R$, is shown. In this "hybrid" model the asymmetry must go to 0 at y = 0 due to the vanishing of the electron axial-vector coupling. The data rule this case out. A third fit to the data is shown for the "Model Independent" form of equation 3. "Model Independent" refers to the absence of gauge theory assumptions, although quark-parton model ideas are still used. This fit is a two parameter form, nearly a straight line. I will return to

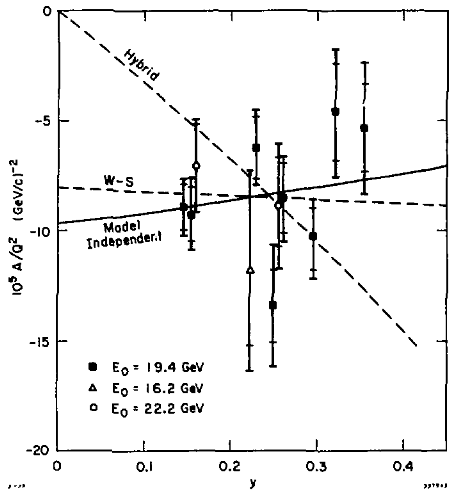


Fig. 3

this fit in a moment. But first let me say a few words about errors.

Within the context of the Weinberg-Salam model and the simple quark-parton model, the parity violating asymmetry, equation (2), is expressed in terms of a single parameter, $\sin^2\theta_W$. We determine the best value and its errors by fitting the experimental data to the form, equation (4). The error consists of a statistical part (0.012) and a systematic part (0.008) added linearly. The systematic error comes from several sources; beam monitoring and background subtractions contribute point-to-point systematic errors and uncertainty in P_e contributes the largest part, an overall scale uncertainty in A. Beyond these experimental errors, there exist uncertainties in the "theory" due to the quark-parton model assumptions. If we add a 10% $q\bar{q}$ sea contribution, the best value for $\sin^2\theta_W$ is a nearly-identical 0.226. Quark-antiquark sea terms have insignificant effects on A. However, what about effects outside the framework of the simple parton model? Several authors have addressed this specific question, and we use their parameterizations for estimating effects on $\sin^2\theta_W$ values.[2,6,7] Equation (4), from the simple-quark parton model, is a special case of equation (2). Modified forms replace equation (4); the a_1 part is modified ± a few percent by coherent scattering effects. The form of the y-dependence is modified by finite non-zero $R = \sigma_L/\sigma_T$ values, and a_2 picks up factors from non-scaling effects at low $- Q^2$ that probably exist, based on neutrino bubble chamber data. For the modified forms of equation (4), and for the range of variations suggested, best fits are obtained for $\sin^2\theta_W$ that vary from 0.210 to 0.230. The limits on $\sin^2\theta_W$ are not precisely defined, but we find an error due to parton model uncertainties of ± 0.010. We have not included this in the experimental error of ± 0.020, but conclude that the error on the "theory" may be as large as experimental errors.

I would like to conclude with a few brief remarks about the connections this work has to parity violation in atomic physics. We have taken note of the remarkable success of the Weinberg-Salam model of weak and electromagnetic interactions, but in the spirit of objective experimental investigation let's ignore for now all gauge theory ideas and look at the model independent approach. This approach has been emphasized by a number of authors,[8] particularly with regard to neutrino neutral current interactions, but can be extended to parity violating effects in electron-hadron interactions. Parity violation phenomenology has its basis in the neutral current piece of the interaction between electron and quarks, where the form of the interaction is regarded as an unknown. The leptonic neutral current interaction has both a vector part and an axial-vector part. Likewise, the hadronic part couples to neutral currents through vector and axial-vector couplings. The parity-violation part of the interaction arise from the cross-products; that is, from the leptonic vector-hadronic axial-vector product and the leptonic axial-vector-hadronic vector product. Vector-vector and axial vector-axial vector terms in the neutral current interaction exist but do not contribute to parity violation. Likewise, S, P, or T terms, if they exist in neutral currents, do not contribute. The most general parity violation effective Lagrangian can be written as

$$\mathscr{L}_{\text{eff}} = -\frac{G}{\sqrt{2}} \sum_{\text{quarks}} \quad \varepsilon_{VA}(e,q)\ \bar{e}\gamma_\mu e \quad \bar{q}\gamma_5\gamma_\mu q \ + \ \varepsilon_{AV}(e,q)\ \bar{e}\gamma_5\gamma_\mu e \quad \bar{q}\gamma_\mu q \qquad (9)$$

where the ε coefficients (Bjorken's notation[2]) are undetermined, but can be related to measureable parameters in different processes. In the simple quark-parton model the heavier quarks (s, c, ...) are neglected, while the light quarks (u, d) are summed over. In terms of these phenomenological couplings, the asymmetry in e D scattering becomes[2]

$$A/Q^2 = -\frac{3G}{10\pi\alpha\sqrt{2}} \left\{ \left[2\varepsilon_{AV}(e,u) - \varepsilon_{AV}(e,d)\right] + \left[2\varepsilon_{VA}(e,u) - \varepsilon_{VA}(e,d)\right] \frac{1-(1-y)^2}{1+(1-y)^2} \right\} \quad (10)$$

which is the basis of equation (3). The model independent fit of figure 3 gives

$$a_1 = -\frac{3G}{10\pi\alpha\sqrt{2}} \left[2\varepsilon_{AV}(e,u) - \varepsilon_{AV}(e,d)\right] = (-9.7 \pm 2.6) \times 10^{-5}$$

and

$$a_2 = -\frac{3G}{10\pi\alpha\sqrt{2}} \left[2\varepsilon_{VA}(e,u) - \varepsilon_{VA}(e,d)\right] = (4.9 \pm 8.1) \times 10^{-5} \qquad (11)$$

which is insufficient information to determine the fundamental parity violating coupling parameters between electron and quarks.

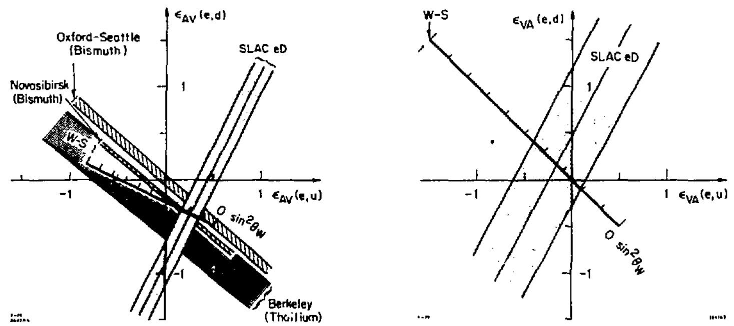
To make the separations, we must turn to other processes which can provide different combinations of the ε's. Inelastic scattering from protons in principle provides new information, but the difference from e D scattering is so small ($\leq$ 10%) that in practice this case would provide no new information. Elastic scattering at high Q^2 is prohibitively difficult but at medium energies, elastic scattering off protons, deuterons, and higher Z nuclei, is possible, and experiments being planned may ultimately provide us new information. At present we are limited to atomic physics parity violation measurements from bismuth and thallium,[9-12] where the results are sensitive to the nearly orthogonal combination

$$\varepsilon_{AV}(e,u) + 1.15\ \varepsilon_{AV}(e,d) \quad . \qquad (12)$$

For high Z nuclei, the hadronic axial-vector terms do not contribute measurable effects but in atomic hydrogen they do, and we may have to wait for atomic hydrogen parity violation results to obtain experimental separation of the hadronic axial-vector terms.

Figures 4a and 4b summarize the present experimental situation. The SLAC e D results can be separated into hadronic vector parts, which contribute to the intercept parameter a_1, and hadronic axial-vector parts which contribute to a_2. In figure 4a, the two axes correspond to $\epsilon_{AV}(e,u)$ and $\epsilon_{AV}(e,d)$, and the SLAC e D results map out a stripe in this two-parameter space. The atomic physics parity violation results map out stripes that are nearly orthogonal to the SLAC results. I show four experimental results, three from bismuth and one from thallium. Two of the bismuth experiments, Oxford and Seattle groups, have reported absence of parity violating effects at the level predicted by the Weinberg-Salam model, and two experiments, Novosibirsk (bismuth) and Berkeley (thallium) have reported evidence for parity violation at the level consistent with the Weinberg-Salam model. The discrepancies between the groups is at present not resolved. I also wish to point out that in the model independent framework, our results from e D parity violation can be regarded as consistent with any of the results from atomic physics. The Weinberg-Salam model predicts values for these phenomenological couplings, and they are shown in figures 4a and 4b. In figure 4b, we see the stripe mapped out by the slope parameter a_2 from our e D results. At present this is the only experiment sensitive to these hadronic axial-vector parameters.

In conclusion, we have measured parity violating asymmetries in inelastic e D scattering at SLAC for a range of y values from 0.16 to 0.36. In the framework of the Weinberg-Salam model and using the simple quark parton model for the nucleon, we find good agreement with our data for a value of $\sin^2\theta_W$ that is consistent with the world average for that parameter in neutrino interactions.[13] The experimental errors approach the errors we obtain from uncertainties in the quark-parton model. From the model independent point of view, the experimental determination of the parity violating neutral current couplings is still unresolved, and much difficult experimental work is still needed to measure these parameters.



(a) (b)

Fig. 4

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