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PARITY VIOLATION IN DEEP INELASTIC ELECTRON SCATTERING*

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Two decades ago Zel'dovich(1) pointed out that a neutral current interaction of strength comparable to weak charged currents could lead to detectable parity violation:

"... in the scattering of electrons by protons the interaction

$$G\left(\bar{p}\gamma_\mu(1+i\gamma_5)p\right)\ \left(\bar{e}\gamma_\mu(1+i\gamma_5)e\right)$$

will interfere with the Coulomb scattering and non-conservation of parity will appear in terms of the first order in the small quantity G."

Zel'dovich estimated that for the scattering of longitudinally polarized electrons with momentum transfer $Q^2 \sim M_p^2$, the variation of the cross section with electron helicity would be in the range from 10^{-3} to 10^{-4}. It took nearly two decades before this effect was observed experimentally. The long time lag reflects the difficulties in producing intense beams of polarized electrons, and, in retrospect, a rather puzzling lack of interest on the part of experimentalists in the 1960's. It was only after the theoretical progress which led to the Weinberg-Salam SU(2) x U(1) model(2), and particularly after t'Hooft(3) showed that such gauge theories with spontaneous symmetry breaking were renormalizable, that the notion of a neutral current interaction became compelling for most experimentalists.

In the Weinberg-Salam model leptons carry weak isospin and weak hypercharge. The left-handed electron and the neutrino form an isospin doublet and the right-handed electron is a singlet. Four intermediate bosons are introduced:

W^+, W^o, W^-, an iso triplet with (V-A) coupling

B^o, an iso singlet

which then describe the weak and electromagnetic interaction through the interaction

$$\mathscr{L}_{int} = g(\vec{J}_\alpha \cdot \vec{W}_\alpha + \tan\theta\ J^Y_\alpha B_\alpha)$$

where $\vec{J}_\alpha$ is the (V-A) weak isospin current and J^Y_α is the weak hypercharge current. The $W^\pm$ mesons mediate the charged current interactions. One linear combination of W^o and B^o corresponds to the photon; the remaining boson is a new particle:

$$\gamma = -\sin\theta_W\ W^o + \cos\theta_W\ B^o, \text{ with (V) coupling}$$

$$Z^o = \cos\theta_W\ W^o + \sin\theta_W\ B^o$$

The Z^o will result in neutral current interactions of strength comparable to the charged weak interaction and with a rather complicated chiral and isospin structure.

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The theory contains one free parameter, θ_W, in terms of which the masses of the intermediate bosons are predicted:

$$M_{W\pm} = 37.5 \text{ GeV}/\sin\theta_W$$

$$M_Z = M_W/\cos\theta_W$$

$$M_\gamma = 0$$

This model then predicts all the weak and electromagnetic interactions of leptons in terms of this one parameter, θ_W. The theory can be extended to include the quarks. When this was first attempted with the up, down and strange quarks, the model predicted rates for strangeness changing decays which were much higher than those observed experimentally.

The advent of the "GIM" mechanism showed how the addition of a fourth (charmed) quark could lead to a cancellation of strangeness changing neutral currents.[4] The left-handed quarks are assigned to doublets (with Cabibbo mixing) and the right-handed quarks are singlets. With this modification the Weinberg-Salam model (often called the "standard model" in this or a later 6 quark incarnation) predicts weak and electromagnetic interactions between all fermions. (Free quarks are hard to come by, so the quark-parton model must be used when predicting the results of experiments involving hadrons. This introduces some ambiguity into the predictions, the importance of which depends on the particular process being studied.) The existence of weak neutral currents appears to be a general property of theories unifying the weak and electromagnetic interactions.

At the Bonn conference in 1973, the observation of neutral currents in the reactions

$$\nu + N \rightarrow \nu + \text{hadrons}$$
$$\bar{\nu} + N \rightarrow \bar{\nu} + \text{hadrons}$$

was announced. The first published results came from the Gargamelle collaboration[5] who were able to demonstrate rather convincingly that they were seeing neutrino induced events with no muon in the final state. Similar results for much higher energy neutrinos were soon published by the Harvard-Penn-Wisconsin collaboration working at NAL[6]. Since then several groups have seen the neutral currents in many different interactions. For each reaction the value of $\sin^2\theta_W$ in the standard (Weinberg-Salam) model can be extracted. Figure 1 shows the status of various determinations of $\sin^2\theta_W$ taken from Baltay's talk in the Proceedings of the Tokyo Conference last year[7].

All these neutrino experiments are consistent with a single value of $\sin^2\theta_W$, and can, therefore, be described by the Weinberg-Salam model.

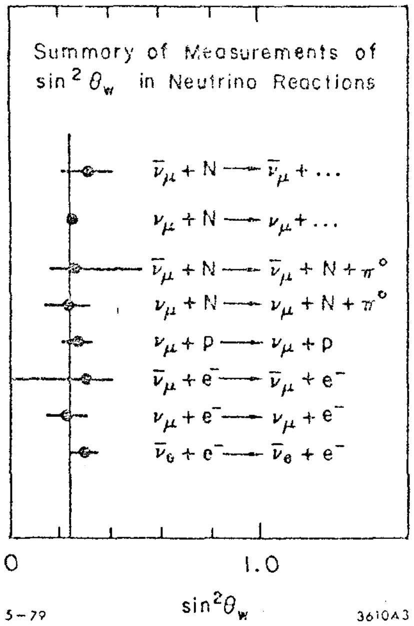


Figure 1

It is clearly of great interest to study processes where electrons interact with hadrons in order to see if couplings which don't involve neutrinos are also correctly described by the theory. In many gauge theory models, including Weinberg-Salam, the neutral current interaction does not conserve parity. (Experiments with neutrinos cannot test parity conservation directly since one cannot compare, for example, reaction rates for left and right-handed neutrinos, but only rates for left-handed neutrinos and right-handed antineutrinos.) Neutral current experiments with electrons face an obvious difficulty in that the coupling of the neutral current is indeed weak compared with electromagnetism. So far, all of the experiments involving electrons search for evidence of parity violation which arises from an interference between the weak and electromagnetic diagrams:

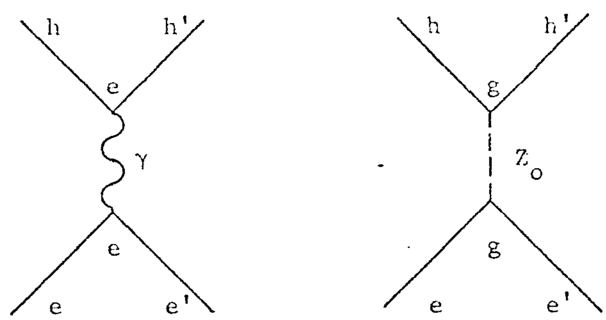


Figure 2

Since the electromagnetic interaction conserves parity to all orders, parity violation is a relatively easy way to observe the effects of neutral weak currents. For energies $\ll M_{Z_0}$ the violations will be proportional to the square of the momentum transfer since the electromagnetic interaction has a $1/Q^2$ dependence whereas the neutral current interaction will behave like $1/(M_{Z_0}^2 + Q^2)$.

Three kinds of electron experiments have been reported to date. Two of these are atomic physics measurements of great ingenuity and the other is the deep inelastic scattering experiment that I will describe below.

The first published experiments with quoted errors small enough to see the effects predicted by the standard model were measurements of the optical rotation of plane polarized light in Bi Vapor. Current values of the rotation are given in Table I for three different experiments.

TABLE I. OPTICAL ROTATION IN ATOMIC BISMUTH

Experiment	Transition Used (10^{-8} cm)	$R=Im(E_1/M_1)$ (10^{-8})	Weinberg-Salam prediction (10^{-8})
Seattle [8]	8757	-2.5 ± 2.7	-10 to -18
Oxford [9]	6480	$+2.7 \pm 4.7$	-13 to -23
Novosibirsk [10]	6480	-19 ± 5	-13 to -23

Publication of early Seattle and Oxford results showing essentially no effect led to the consideration of many different gauge theory models. In some of them parity was conserved, (e.g. $SU(2)_L \times SU(2)_R \times U(1)$ theories with more than one Z^o); in others, an extra heavy neutral lepton was combined with the electron in a right handed doublet; and so on. For many physicists, a theory in which parity is conserved is more elegant than the "lop-sided" Weinberg-Salam model and the early results of the Bismuth experiments were welcome in some quarters. With the publication of the results from Novosibirsk over a year ago, the experimental situation in Bismuth has become somewhat confused and remains so today.

In the Spring of 1978, the first results from the deep inelastic experiment[11] showed significant parity violation and gave considerable support to the standard model. Later in the year, results from the "circular dichroism" experiment on thallium, carried out at Berkeley by Commins et al.[12], also showed a positive effect. The standard model is now almost universally accepted and theoretical interest is shifting rapidly towards understanding the reasons for the replication of leptons and quarks, and attempting to include the strong interactions (and even gravitation) in unified theories.

An interesting sidelight of the unified gauge theories is a parallel unification in experimental physics - it is pleasant to be reminded that fields as disparate as high energy physics, neutrino physics at nuclear reactors and atomic physics are still connected with each other at a fundamental level.

THE SLAC-YALE EXPERIMENT

The experiment measures a difference in the e-d inelastic cross section for right and left-handed electrons. Since the change from right to left-handed electrons is equivalent to a mirror reflection of the whole experiment, it is evident that such a difference is *prima facie* evidence for parity violation.

A schematic of the experimental setup is shown in Figure 3.

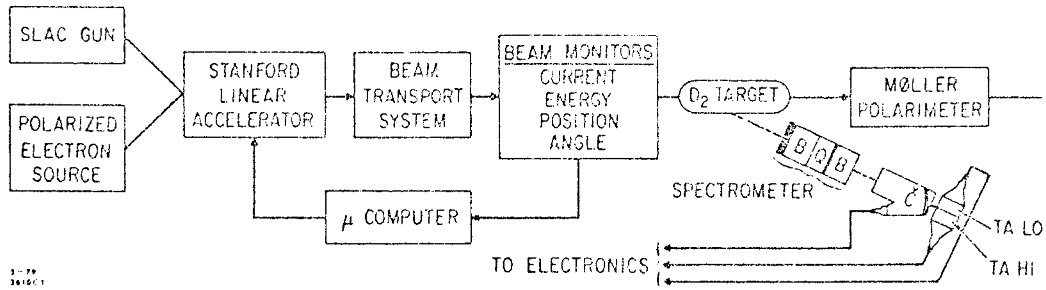


Figure 3

Polarized electrons are accelerated in the SLAC linac and traverse a target of liquid deuterium. A crude spectrometer analyzes electrons scattered (downward) at an angle of 4°. The electrons are detected in a Cerenkov counter and in a total absorption counter made of two lead glass blocks. Since the expected effect is $\sim 10^{-4}$ or less, both statistical and systematic errors must be $\sim 10^{-5}$ or better and much of the experimental effort went into studies of both kinds of error.

POLARIZED SOURCE

The most essential new element in the experiment is the polarized source, developed by some of the members of the collaboration (13). The source is based on the photo emission of (~ 40%) polarized electrons by circularly polarized light from a crystal of Gallium Arsenide, the surface of which has been treated to lower the work function. Figure 4 shows a schematic of the source. The laser is pulsed 120 times per second, in synchronism with the r.f. pulsing of the linac. Electrons emitted by the crystal are accelerated in the gun structure and focussed into a beam for injection into the linac. Instantaneous currents of up to half an ampere have been achieved and we have accelerated up to 4×10^{11} electrons per pulse through the linac, quite near to the maximum achieved with the regular SLAC guns.

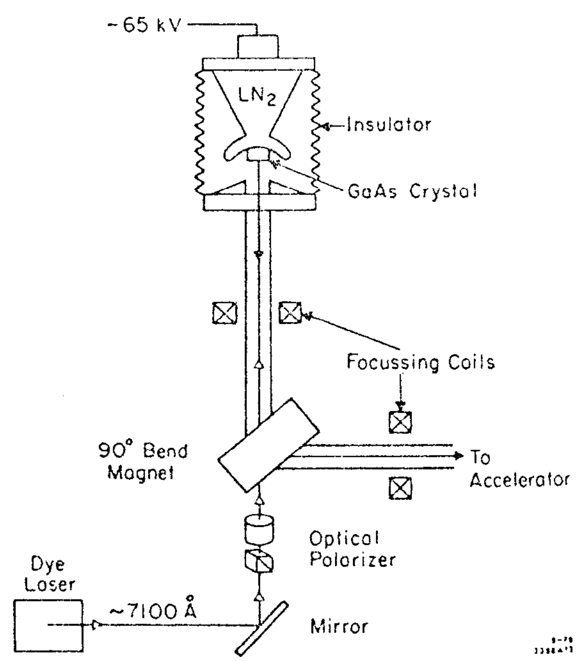


Figure 4

The polarization of the laser light is controlled by a calcite prism which selects linearly polarized light, and a Pockels cell which converts from linear polarization to circular polarization. The sign of the circular polarization can be reversed by changing the sign of the voltage on the Pockels cell, and this change can be made between beam pulses. The sign of circular polarization can also be reversed by rotating the plane of the linear polarization by 90°, and this fact is used in experimental checks of the "fast" reversal scheme. We operate the source with a random choice of sign of the Pockels' cell voltage for each beam pulse. The resulting randomization of electron helicity avoids synchronism of helicity changes with any periodic effects, and the rapid changes in polarization minimize the effects of drifts in the apparatus.

The polarization of the electrons is measured after acceleration, and the polarization is checked every few hours during data runs.

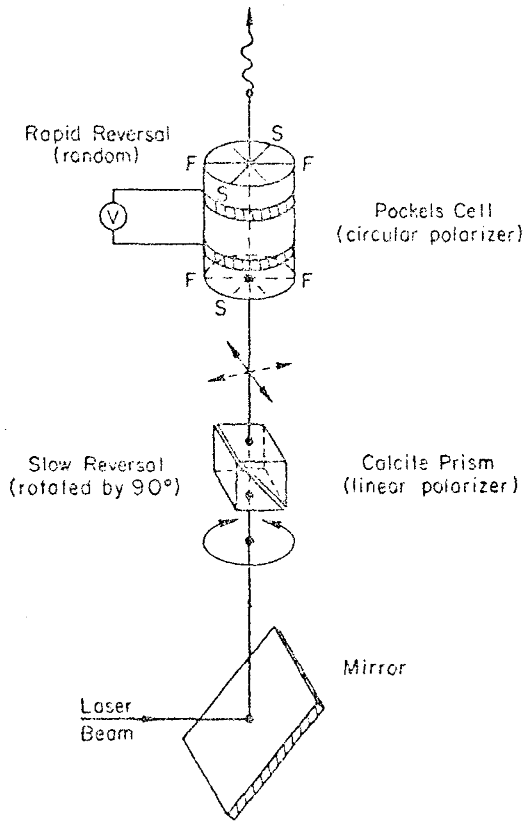


Figure 5

BEAM MONITORS

The fact that the measured scattering cross section depends on beam parameters like beam position, angle of the beam at the target, and beam energy means that these parameters should not vary systematically when the helicity is reversed. A set of beam monitors was developed based on resonant cavities which are excited by the (bunched) electron beam (See Fig. 6).[14] The monitors are sensitive to position changes of a few microns. Sets of cavities are used to measure position and angle both before and after the beam transport system in the "A" line at SLAC. Another monitor measures beam position at a point in the transport system where there is energy dispersion and determines the average beam energy in a given pulse to an accuracy of about 0.01%. Signals from the resonant cavities are used to generate feedback signals (via a microcomputer) to keep average beam position, angle and energy constant. All monitor information is recorded along with other experimental data so that we can determine even very small differences in the beam parameters between "right-handed" and "left-handed"

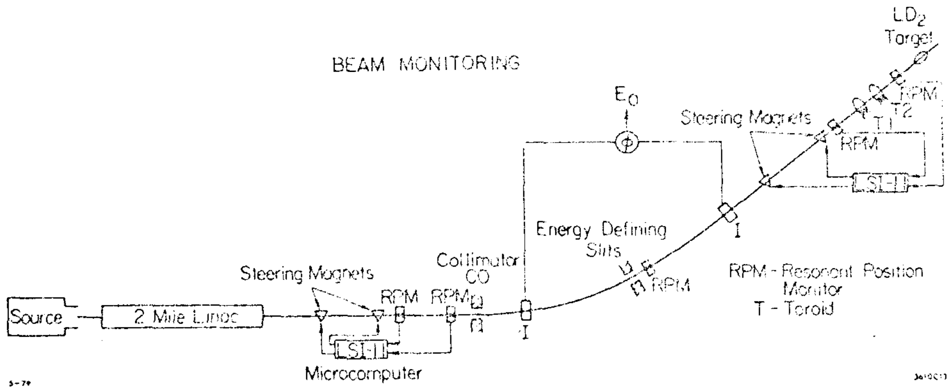


Figure 6

beam pulses. Our aim was to reduce such differences to the point where corrections to the data could be ignored. We succeeded to the extent that the errors from beam differences are smaller than the statistical errors on our measurements.

Included in the monitoring system are two independent toroidal ferrite loop current monitors[15] which measure the number of electrons in a pulse to ~ 0.1%.

THE SCATTERING EXPERIMENT

The beam passes through a 30 cm long deuterium target and some of the electrons scattered in the target pass through a spectrometer consisting of 2 bending magnets separated by a quadrupole which is focussing in the bend plane. $\Delta p/p$ for this arrangement is ~30%. Electrons are detected in a gas Cerenkov counter filled with N_2 at atmospheric pressure and also in two lead glass blocks which act as total absorption counters. The lead glass blocks are side by side in the bend plane, so one sees high momentum electrons, the other low. Figure 7 shows the spectrum of 19.4 GeV electrons scattered at 4° obtained with a high resolution spectrometer in 1975. The blocks marked TAHI and TALO show momentum acceptance of the two glass counters when the central momentum of the spectrometer is set at 14.5 GeV, with the quadrupole setting used in the Fall 1978 runs. In the earlier run, the quadrupole was set to a lower value (to maximize counting rate) and the published

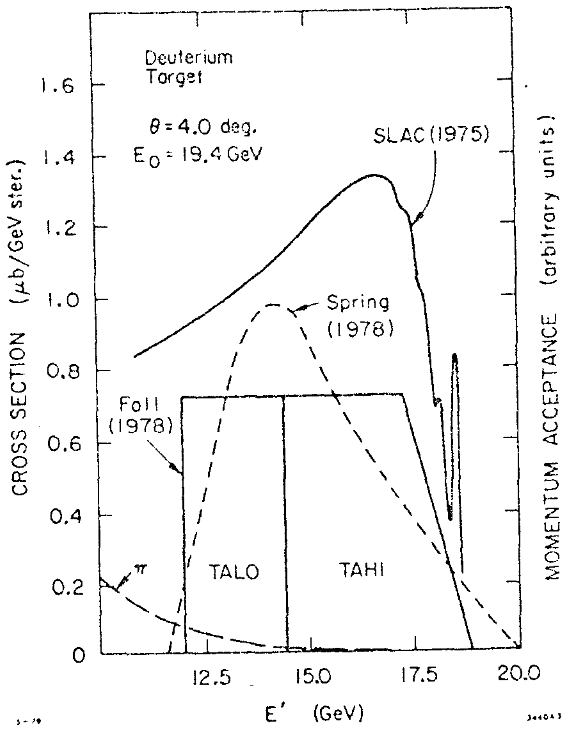


Figure 7

results were based on the sum of the signals from the two blocks.[11] The momentum acceptance for the sum "TAHI plus TALO" is shown by the dotted curve in Figure 7. TAHI and TALO are less sharply defined for the Spring run than in the Fall run. For the combined data shown in Table II and in Figure 11, the two blocks were analyzed separately for both runs.

Slits are mounted in front of the spectrometer and just after the quadrupole to minimize backgrounds. Photo-produced π^- accompany the electrons through the spectrometer. Small corrections are made based on the measured pion yields and asymmetries.

We measure the change in cross section with helicity as a difference in yield for the two polarization states of the beam. We observe the yield of scattered particles for pulses of right-handed electrons (helicity = +1) and of left-handed electrons and calculate the asymmetry, the difference divided by the sum.

To attain the required statistical precision of a few parts per million in the asymmetry the yields have to be based on data samples containing about 10^{11} events. To accumulate this many events in a reasonable time requires counting rates of the order of 1000 events per (1 μsec) beam pulse. Conventional counting techniques are, therefore, not appropriate. In our counters, we integrate the total light output for an accelerator pulse and use this signal as a measure of the number of electrons in the counter. We carefully investigated the response of the counters to be sure that the signals varied linearly with the number of scattered particles and also that the variation in observed yield for constant beam current was consistent with the expected statistical fluctuation in the number of scattered particles.

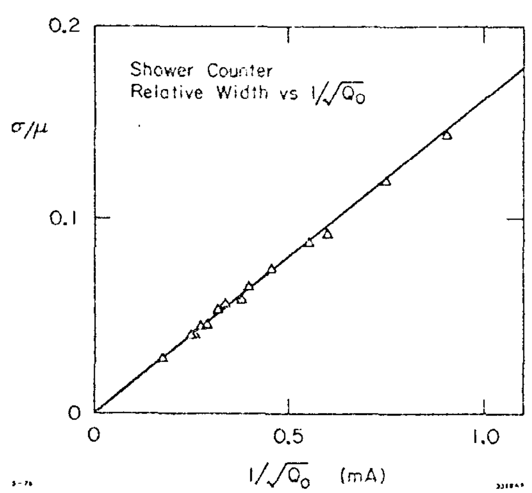


Figure 8

The latter test is crucial to our estimation of statistical errors on the measured asymmetry. Some test results are shown in Figure 8. The solid line is not a fit, but a calculation based on the response of the counter to single scattered electrons, and it is evident that the observed fluctuations are consistent with expectations.

For a given beam pulse the integrated output of a counter N_i divided by the measured charge for that pulse is a measure of the scattered electron yield (which is proportional to cross section). Each beam pulse is tagged "+" or "-" corresponding to the voltage applied to the Pockels cell. We accumulate two distributions of the yield

$$Y_i^{\pm} = N_i^{\pm}/Q_i^{\pm} \text{ for } n^{\pm} \text{ pulses}$$

and form an experimental asymmetry

$$A_{exp} = \frac{\langle Y^+\rangle - \langle Y^-\rangle}{\langle Y^+\rangle + \langle Y^-\rangle}$$

where $\langle Y^+\rangle$ is the mean of the Y^+ distribution. The error is obtained from the distribution of Y where $\Delta\langle Y\rangle = \Delta Y/\sqrt{n}$. Tests with unpolarized (SLAC gun) beam showed no significant asymmetries.

With polarized beams, we do observe significant asymmetries. Dividing A_{exp}, the observed asymmetry, by P_e, the beam polarization, we arrive at the physics asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \qquad \sigma_R = \left(\frac{d\sigma}{d\Omega dE'}\right)_{R'}$$, the differential cross section for right-handed electron scattering

for the case where positive voltage on the Pockels cell corresponds to right-handed helicity at the target.

CHECKS OF THE HELICITY DEPENDENCE

By rotating the plane of polarization of the light entering the Pockels cell we can vary the helicity of the electrons for a fixed Pockels cell voltage and test the fast reversal system. If we rotate the plane polarization by 45° we will get no circular polarization of the light coming out of the Pockels' cell and therefore no net electron helicity so the experimental asymmetry should vanish. For a 90° rotation the helicity for positive Pockels cell voltage will change sign, and so will A_{exp}, since it is measured with respect to Pockels cell voltage. Results of this test are shown in Figure 9 for both the Cerenkov and TA counter with a 19.4 GeV electron beam on deuterium.

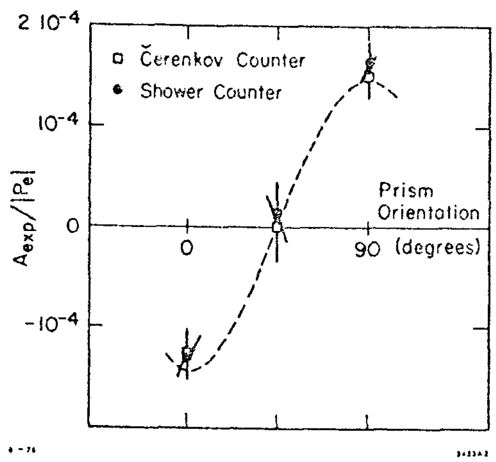
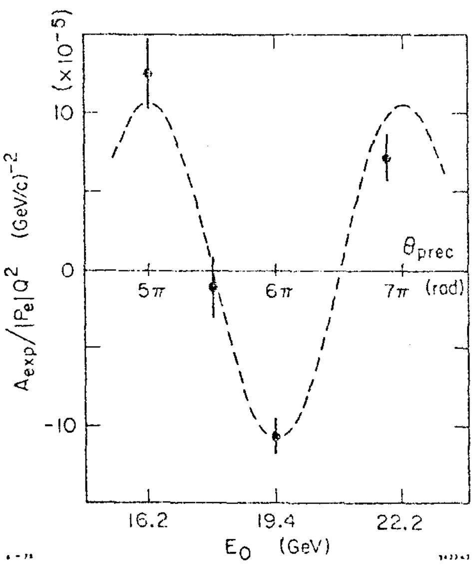


Figure 9

To a good approximation the counters see the same particles, so the results for a given prism orientation are not statistically independent. The two types of counters do have different responses to backgrounds, however, and the fact that the measurements agree well confirms that backgrounds are small. This test is encouraging evidence that the observed asymmetry is due to helicity.

Figure 10



A second stringent test can be made by repeating the experiment with different beam energies. The beam transport system connecting the linac and the experiment bends the polarized electrons through 24.5°. Because of the anomalous magnetic moment of the electron, its spin processes in the transport system, reversing direction each time the beam energy is increased by 3.237 GeV. Figure 10 shows that this reversal actually does occur. (Since the mean value of Q^2 is different for the different energies, we divide A_{exp} by Q^2, which should remove the Q^2 dependence.) This is strong evidence that the effects are helicity dependent.

RESULTS

Combining the data at 19.4 GeV and 22.2 GeV we obtained a value for

$$A/Q^2 = (-9.5 \pm 1.6) \times 10^{-5}$$

at an average value of $y = \frac{E - E_Q}{E_0} = 0.21$. Small corrections were made for beam parameter asymmetries (3.3%), π backgrounds (2%), and radiative effects (3%). In the standard model this value of A/Q^2 corresponds to a value of $\sin^2\theta_W = 0.20 \pm 0.03$, in good agreement with the value of this parameter in neutrino experiments.

In the fall of 1978 we continued the measurements for kinematics which cover a range in y. These measurements were made with $E_0 = 19.4$ for three settings of the spectrometer momentum. The data were analyzed for each half of the lead glass total absorption counter, resulting in six measurements of the asymmetry. We also reanalyzed the Spring data* for the separate lead glass counters, and Table II summarizes the results. The largest fraction of the errors comes from counting statistics. Three types of systematic error can cause point to point variation in data: a) imbalance in beam parameters (average of ~0.025A); b) uncertainty in background subtractions (average ~0.03A) and; c) uncertainty in polarization (0.025A). These errors are combined in quadrature at each point and are added (linearly) to the statistical error. An additional uncertainty in the polarization measurement corresponds to a 5% uncertainty in the scale common to all asymmetries, which is not included in the errors given in the table.

TABLE II

E_0 (GeV)	Q^2 $(GeV/c)^2$	x	y	π/e Fraction (%)	$10^5\ A/Q^2$ Asymmetry $(GeV/c)^{-2}$		Total Error $(GeV/c)^{-2}$	Statistical Error Only $(GeV/c)^{-2}$
16.2 *	0.92	0.14	0.22	2.1	-11.8	±	4.5	± 3.4
19.4	1.53	0.28	0.15	0.8	- 8.9	±	1.3	± 1.1
19.4 *	1.52	0.26	0.16	0.9	- 9.2	±	1.7	± 1.2
19.4	1.33	0.16	0.23	2.1	- 6.3	±	1.7	± 1.4
19.4 *	1.28	0.14	0.25	2.8	-13.4	±	2.8	± 1.6
19.4	1.25	0.13	0.26	3.3	- 8.6	±	2.0	± 1.6
19.4	1.16	0.11	0.29	6.0	-10.4	±	1.8	± 1.4
19.4	1.07	0.09	0.32	10.8	- 4.6	±	2.9	± 2.2
19.4	0.93	0.07	0.36	25.0	- 5.3	±	3.0	± 2.0
22.2 *	1.96	0.28	0.17	1.0	- 7.0	±	2.1	± 1.9
22.2 *	1.66	0.15	0.26	2.9	- 8.9	±	2.8	± 2.2

In the quark parton model a parity violating asymmetry has the general form

$$A/Q^2 = a_1 + a_2\left[\frac{1 - (1 - y)^2}{1 + (1 - y)^2}\right]$$

For an isoscalar target like deuterium, the coefficients a_1 and a_2 are expected to be constants. In the standard model

$$a_1 = -8.94 \times 10^{-5}\ \mathrm{GeV}^{-2}\ (9/5 - 4\sin^2\theta)$$

$$a_2 = -8.94 \times 10^{-5}\ \mathrm{GeV}^{-2}\ 9/5\ (1 - 4\sin^2\theta)$$

In Figure 11 we show our data along with some fits. The data is consistent with the standard (W-S) model and gives a value of $\sin^2\theta_W = 0.224 \pm 0.02$. This corresponds to the vertical line drawn through the neutrino determinations of $\sin^2\theta_W$ in Figure 1. The hybrid model contains a heavy lepton in a doublet with the right-handed electron. This will not change any predictions for neutrinos, but could account for the absence of parity violation in the early atomic physics experiments. Such a model is not supported by the present data. The other curve shown on the graph is a best fit to the form of the equation for A/Q^2 where

$$a_1 = (-9.7 \pm 2.6) \times 10^{-5}$$

$$a_2 = (\ 4.9 \pm 8.1) \times 10^{-5}$$

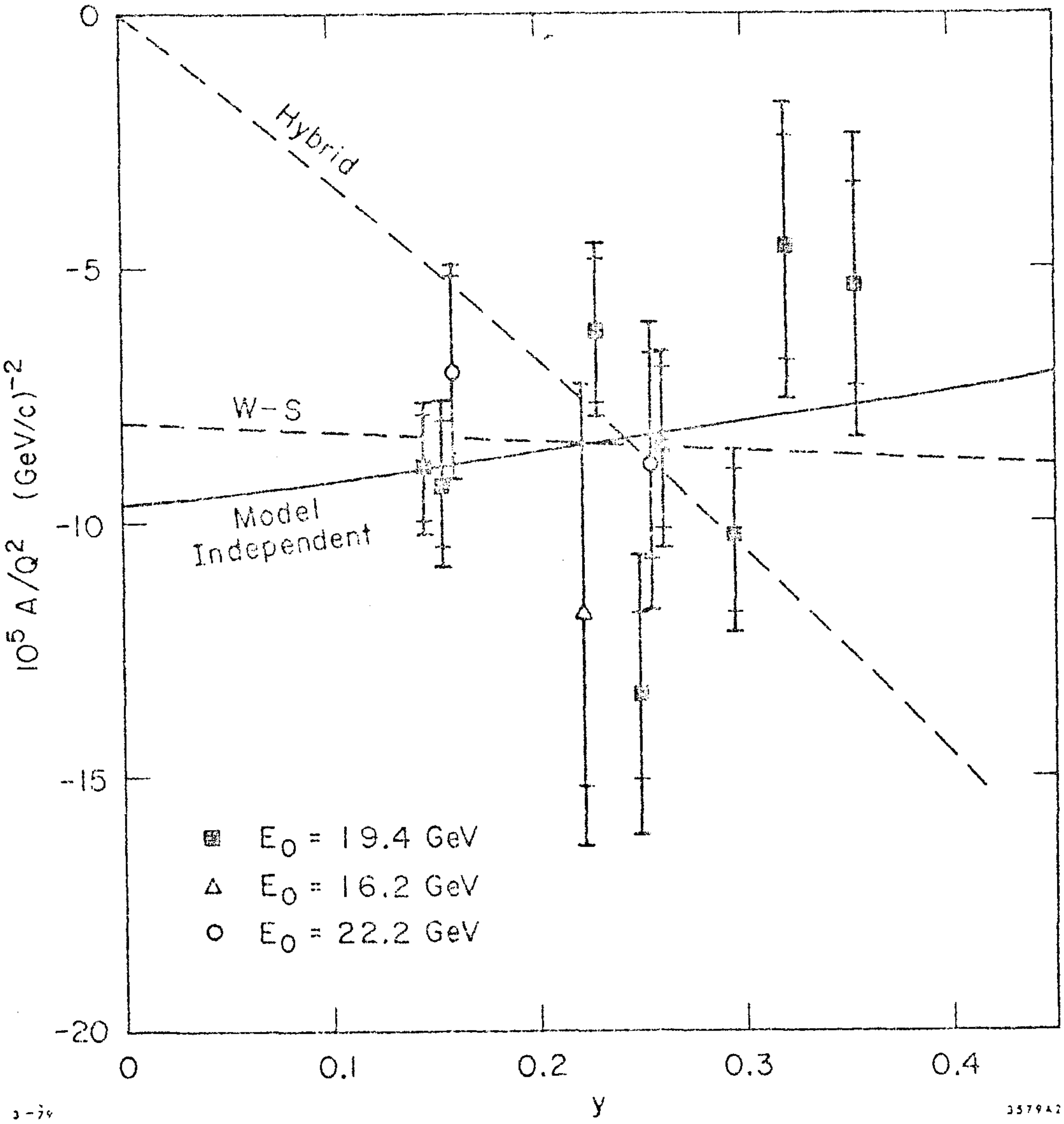


Figure 11. Asymmetries measured at three incident energies are plotted against $y = (E_0 - E')/E_0$. The total error bar gives the combined statistical and systematic error. The inner error corresponds to the statistical errors only. The data are compared with the standard (Weinberg-Salam) model and the hybrid model. In each case $\sin^2\theta_W$ has been adjusted to minimize χ^2. The two-parameter model-independent fit (see text) is also shown. Not shown in the figure is an overall scale uncertainty of 5% arising from errors in the determination of the electron polarization.

Figure 12 shows contours of constant χ^2 for the two (correlated) variables a_1 and a_2. The standard model is shown as a straight line passing through the region of high χ^2 probability. In determining the value of θ_W from these results the use of the quark model in the analysis may be a significant source of error. The question has been treated by several authors[16], and, using their results, we find that errors from this source are probably no greater than our quoted error on $\sin^2\theta_W$, but could be of comparable size.

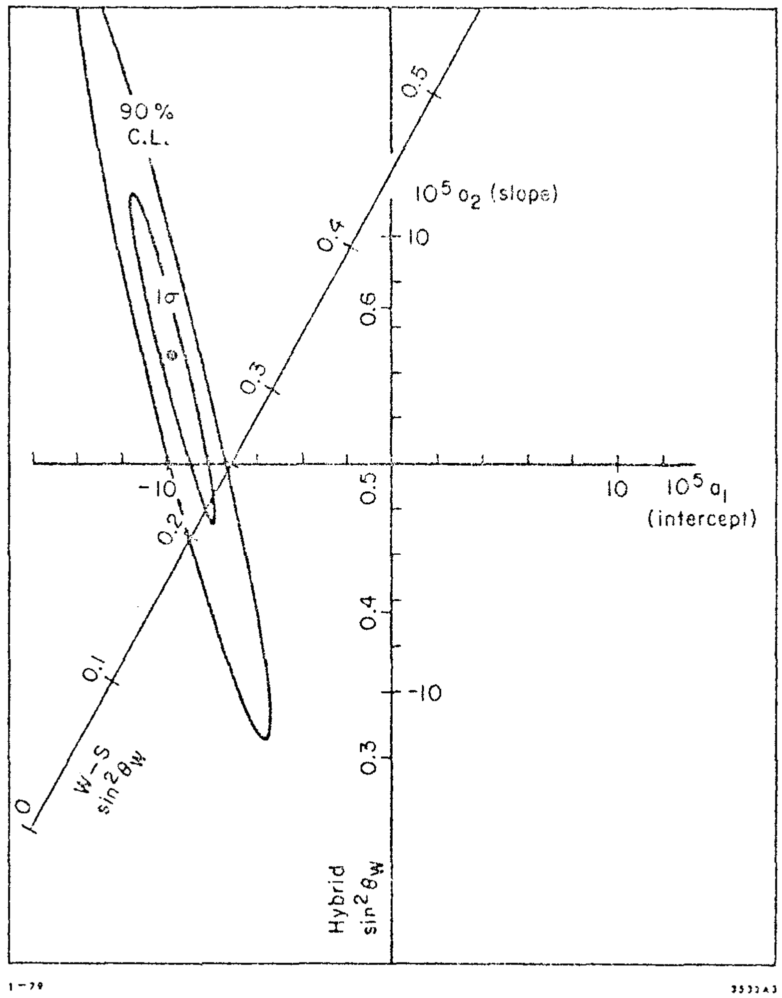


Figure 12

We conclude that our data is in agreement with the model of Weinberg and Salam, and that the best value of $\sin^2\theta_W$ for our data is in excellent agreement with the average values of that parameter deduced from neutrino experiments.

FUTURE EXPERIMENTS WITH POLARIZED ELECTRONS

In spite of the impressive agreement of the e-d results with the standard model, experimental work on the weak electron-hadron interaction is obviously just beginning. Several theorists[17] have stressed the need for phenomenological analysis of the neutral current couplings. Parity non-conservation experiments involving electrons and hadrons can be described using four coupling constants ε_{AV}^{eu}, ε_{AV}^{ed}, ε_{VA}^{eu}, ε_{VA}^{ed} where ε_{VA}^{eu} refers to the coupling of the vector electron current to the axial vector up quark current etc. Linear combinations of these constants $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, $\tilde{\delta}$, can be chosen to refer to axial and vector electron currents coupling to the currents of isovector and isoscalar configurations.

$$\tilde{\alpha} = \varepsilon_{AV}^{eu} - \varepsilon_{AV}^{ed} \qquad \tilde{\beta} = \varepsilon_{VA}^{eu} - \varepsilon_{VA}^{ed} \qquad (I = 1)$$

$$\tilde{\gamma} = \varepsilon_{AV}^{eu} + \varepsilon_{AV}^{ed} \qquad \tilde{\delta} = \varepsilon_{VA}^{eu} + \varepsilon_{VA}^{ed} \qquad (I = 0)$$

The deep inelastic experiments provide a direct measurement of the interaction between electrons and the basic quarks (in the quark-parton model). From the e-d results we obtain

$$(\tilde{\alpha} + \frac{1}{3}\tilde{\gamma}) = -0.60 \pm 0.16 \quad (\tilde{\beta} + \frac{1}{3}\tilde{\delta}) = -0.3 \pm 0.5$$

While the errors are still large, the quark-parton model uncertainties referred to above limit the usefulness of pushing immediately for much more accurate data. It would be interesting to check the asymmetry at higher Q^2 to verify that the Q^2 dependence is as anticipated. Experiments on hydrogen targets give similar information, but with an expected dependence on $F_2^{en}(x)/F_2^{ep}(x)$.

Asymmetries in elastic electron scattering from nuclei can be effective in isolating particlar spin and iso spin states. In general the asymmetries in such experiments arise from the *axial vector* electron currents and depend on nuclear form factors.[18] For the special case of spin zero, isospin zero nuclei, the form factors drop out and one obtains the isoscalar combination of coupling constants $(\varepsilon_{AV}^{eu} + \varepsilon_{AV}^{ed})$ directly. The rapid decrease in nuclear cross sections with Q^2 drives the experiments to low values of Q^2, and consequently very small asymmetries. (The proposal at Bates to look at C^{12} elastic scattering expects an asymmetry of $\sim 2 \times 10^{-6}$ or some 50 times smaller than that observed at SLAC.) For electron-proton elastic scattering the electric (GE) scattering is similarly dominated by isoscalar contributions, but the magnetic (GM) scattering is dominated by isovector terms as is the case in deep inelastic scattering.

The excitation of specific levels by inelastic scattering of polarized electrons can also be studied. Generally the situation will be even more complex than in elastic scattering. For transitions from initial states which have $J^P = 0^+$ to another 0^+ state with the same isospin the asymmetries will be similar to those for elastic scattering, but the experiments are probably more difficult. A more interesting case is $0^+ \rightarrow 0^+$ with a change in isospin, in which case the asymmetry will be proportional to $(\varepsilon_{AV}^{eu} - \varepsilon_{AV}^{ed})$. A combination of these results with results from elastic scattering will allow separate determination of the individual constants. In principle, the transitions from $0^+ \rightarrow 0^-$ are interesting because they contain strong contributions from *vector* electron currents but experimentally the outlook seems rather bleak. It appears that scattering experiments with longitudinally polarized electrons will be most useful in further studies of the axial vector electron (vector quark) currents.

Two other experiments should be mentioned, namely, electron-electron (Møller) scattering where one of the electrons is polarized, and e^+e^- annihilation into $\mu^+\mu^-$. In each case Z_o exchange can occur and, since the processes are purely leptonic, they are excellent tests for theory. In the standard model, Møller scattering gives asymmetries proportional to $(1 - 4 \sin^2\theta_W)$, which is close to zero for $\sin^2\theta_W = 0.23 \pm 0.02$).

Further, since $E_{com} = \sqrt{2m_e E_o}$, the maximum Q^2 obtainable is much lower than in the corresponding e-nucleon scattering, and the asymmetries end up very small indeed. The annihilation experiments (with unpolarized electrons) will be attempted by many groups at PETRA and PEP, and results should not be long in coming. (These experiments look for forward backward charge asymmetries and measure different coupling constants than the ε's.)

Atomic physics experiments are closely related to the scattering experiments. The heavy atom experiments are mostly sensitive to axial electron current isoscalar ($\tilde{\gamma}$) terms. Difficult theoretical calculations of the electronic configurations are required to extract accurate quantitative answers. In the proposed H_2 and D_2 atomic experiments one can have much more confidence in the theoretical framework, but the experiments appear even more difficult than those on heavy atoms.

Weak-electromagnetic interference experiments supply new information about neutral currents. The fundamental importance of gauge theories and weak-electromagnetic unification justifies extraordinary efforts to study more examples of this interference. The next crucial test of the standard model is likely to come when colliding beam machines reach the energies where the massive intermediate bosons can be directly produced. This could happen at the CERN collider within a couple of years, but detailed studies of the Z_o will likely have to wait for colliding electron-positron beams of suitable energy.

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