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# PARITY NONCONSERVATION IN POLARIZED ELECTRON SCATTERING AT HIGH ENERGIES*

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## I. Introduction

Parity violation has been well established in particle physics for many years, since the 1950's where it was first seen in beta decay processes. The strong and electromagnetic forces are parity conserving, and the experimental evidence that parity was not conserved in weak processes came somewhat as a surprise. The weak forces are responsible for the decay of radioactive nuclei, and it was in these decay processes where parity non-conservation was first observed. Beta decay occurs through emission of $e^+$ or $e^-$ particles, indicating that the weak force can carry charge of both signs, and it was natural to speculate on the existence of a neutral component of the weak force. Even though weak neutral forces had not been observed it was conjectured that a neutral component of weak decay could exist, and Zel'dovich[1] in 1957 suggested that parity violating effects may be observable in electron scattering and in atomic spectra.

More than 20 years have passed since the early conjectures, and a great deal has been learned. Progress in quantum field theory led to the development of the SU(2) × U(1) gauge theory of weak and electromagnetic interactions and provided a renormalizable theory with a minimum of additional assumptions.[2,3] Gauge theories predicted the existence of a new force, the neutral current interaction. This new interaction was first seen in 1973 in the Gargamelle bubble chamber at CERN.[4] Today we accept the neutral currents as well established, and it is the details of the neutral current structure that occupy our attention. In particular the role that electrons play cannot be tested readily in neutrino beams (recent neutrino-electron scattering experiments are however rapidly improving this situation) and therefore interest in electron-hadron neutral current effects has been high. Parity violation is a unique signature of weak currents, and measurements of its size are a particularly important and sensitive means for determining the neutral current structure.

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It has taken experimental physics more than 20 years to realize the measurements first suggested by Zel'dovich. Techniques have improved enormously during this time. However these measurements are still extremely difficult to make and are subject to experimental problems and systematic troubles of various kinds. Although this workshop is concerned with neutral current effects in atoms, it is appropriate that a high energy measurement be included, since the underlying physics is essentially the same. It is the recent observation of parity violation in inelastic scattering of electrons at high energy that I will discuss here.[5]

The process we look at is

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

Typical kinematic parameters for this process at SLAC are incident beam energies $E_0$ from 16 to 22 GeV, secondary scattered energies from 11 to 16 GeV, and a fixed laboratory scattering angle of $4^o$.

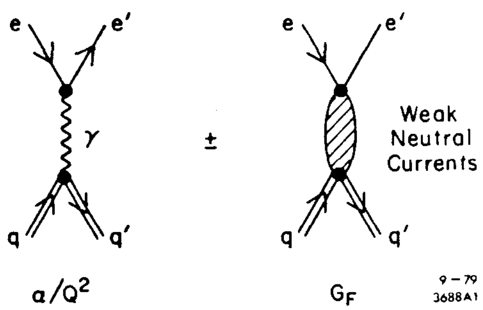


Fig. 1

The amplitude for the reaction (1) consists of two parts, the usual electromagnetic part, of strength $\alpha/Q^2$ shown in Fig. 1 as a single virtual photon exchange, and a weak neutral current piece, of strength $G_F$, where $\alpha$ is the fine structure constant, $G_F$ is Fermi coupling of the weak interactions, and $Q^2$ is the invariant four-momentum squared. The parity nonconserving asymmetry we measure is defined as

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad (2)$$

where $\sigma_{R(L)}$ is the cross section $d^2\sigma/d\Omega dE'$ for right-handed (left-handed) incident electrons scattering from deuterium. This quantity is expected to be non-zero due to interference between the weak and electromagnetic terms and is estimated to be of the order

$$A \cong \frac{G_F Q^2}{2\pi\alpha} \approx 10^{-4} Q^2 / M_p^2 \quad . \qquad (3)$$

It is the smallness of the expected asymmetries that makes the measurements difficult and impose on the experiment special techniques to control the size of statistical and systematic errors.

Within the framework of the simple quark-parton model of the nucleon, where electrons are assumed to scatter off spin 1/2 constituents only, it can be shown that the asymmetry A has the general form

$$\frac{A}{Q^2} = a_1 + a_2 \frac{1-(1-y)^2}{1+(1-y)^2} \qquad (4)$$

where $y = (E_0 - E')/E_0$ is the fractional energy transferred from the electron to the hadrons. For an isoscalar target such as deuterium, the parameters $a_1$ and $a_2$ are expected to be constants. Equation (4) is a general result, independent of gauge theory assumptions. These results can be easily illustrated in models which contain a single $Z^0$ exchange.

## II. An Idealized Case - Scattering from Free Quark Targets

To high energy physicists the simple concepts of the quark-parton model and the validity of the application to inelastic scattering are well established. These concepts and the language used may not be so familiar to atomic physicists. I will not attempt to justify use of the quark-parton model, which is another subject, but simply summarize by saying that these approximations can be shown to be valid.[6-9] The quark-parton model assumes that inelastic scattering occurs from spin 1/2 constituents (quark or anti-quarks) which comprise the target nuclei, and that each quark contributes incoherently to the amplitude. Consider the simplest hypothetical case where the electron scatters from a free stationary quark, at a center-of-mass angle θ to the initial direction. Figure 2 shows this process in two frames, the center-of-mass frame, and the lab frame.

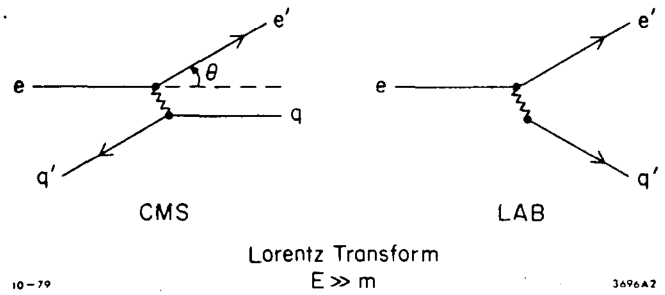


Fig. 2. Electron-quark scattering seen in two frames.

Lorentz transforming to the lab frame gives $E' = E_0/2(1+\cos\theta)$. Define a kinematic variable $y = (E_0 - E')/E_0$, which is the fraction of the beam energy transferred to the quark. In terms of y

$$\frac{1}{2}(1+\cos\theta) = 1-y \quad . \qquad (5)$$

The scattering amplitude, Fig. 3, consists of two parts, an electromagnetic part and a weak part:

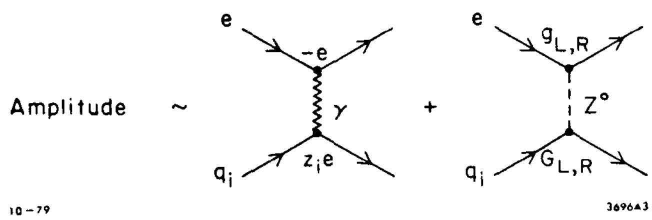


Fig. 3. Amplitude for electron-quark scattering in SU(2) × U(1) models.

where the sign of the electric charge is shown explicity, $z_i = \pm 1/3$ or $\pm 2/3$ depending on the quark or antiquark considered, and $g_{L,R}(G_{L,R})$ are neutral current couplings for left and right-handed electrons (or quarks). Since unpolarized targets are used, we sum over two terms in the cross section corresponding to opposite spin projections for the incoming quark (Fig. 4).

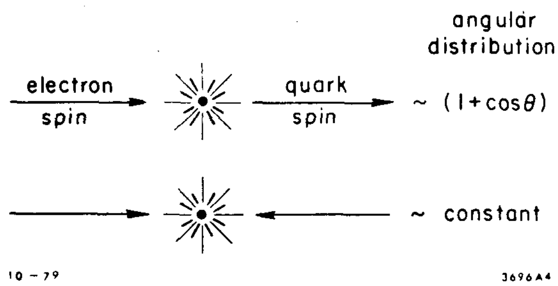


Fig. 4. For unpolarized targets sum over quark spin projections.

$$\sigma_R = \left| \frac{-z_i e^2}{Q^2} + \frac{g_R G_L^i}{Q^2 + M_Z^2} \right|^2 (1-y)^2 + \left| \frac{-z_i e^2}{Q^2} + \frac{g_R G_R^i}{Q^2 + M_Z^2} \right|^2 \qquad (6)$$

A similar expression exists for $\sigma_L$. The parity nonconserving asymmetry, defined in Eq. (2) is found to be

$$A = -\frac{2Q^2}{M_Z^2} \cdot \frac{\left[ g_A \left( z_i G_V^i \right) + g_V \left( z_i G_A^i \right) h(y) \right]}{z_i^2 e^2} \qquad (7)$$

where

$$g_{V(A)} = \frac{1}{2} \left( g_R \overset{+}{(-)} g_L \right)$$

$$G_{V(A)}^i = \frac{1}{2} \left( G_R^i \overset{+}{(-)} G_L^i \right)$$

$$h(y) = \frac{1-(1-y)^2}{1+(1-y)^2}$$

$$\frac{2Q^2}{M_Z^2 e^2} = 1.79 \times 10^{-4} Q^2 \ , \ Q^2 \text{ in } (\text{GeV}/c)^2 \ . \qquad (8)$$

In the standard model, the neutral current couplings are given by

$$G^i_{L(R)} = T^i_{3L(R)} - z_i \sin^2\theta_W \quad \text{(quarks)}$$

$$g_L = -\frac{1}{2} + \sin^2\theta_W \quad \text{(left-handed electron)}$$

$$g_R = 0 + \sin^2\theta_W \quad \text{(right-handed electron)} \ . \qquad (9)$$

Real targets, like deuterons or protons, consist of a mix of quarks, each with a momentum distribution function $f_i(x)$, where x is the usual scaling variable $Q^2/2M\nu$. In the spirit of simple quark-parton model, each quark contributes incoherently to the cross section by an amount $f_i(x)$. For the parity violating asymmetry the factor $\sum_i f_i(x)$ must be inserted in both the numerator and denominator of Eq. (7). However, for isoscalar targets such as deuterium, $f_u(x) = f_d(x)$, and only $\sum_i$ must be inserted in the numerator and denominator in Eq. (7) (the x dependence drops out).

Taking free quarks for targets we get the following predictions for asymmetries, shown in Fig. 5. Here we set $\sin^2\theta_W = 1/4$, which simplifies the expressions. (Experimentally measured values are near 1/4.) For the antiquark target asymmetries, relative to its quark, $z_i$ and $G^i_V$ change sign, while $G^i_A$ does not. This means that asymmetries for u and $\bar{u}$ targets are equal, and likewise for d and $\bar{d}$ targets. In the parton model the deuteron consists of 3u quarks, 3d quarks, and a "core" or "sea" of $u\bar{u} + d\bar{d} + s\bar{s}$ quark pairs. The amount of $q\bar{q}$ sea contribution does not significantly modify predicted asymmetries; only the $s\bar{s}$ part of the quark sea affects the values, and that part is expected to be small.

Based on the standard model and the simple quark-parton model of inelastic scattering, the conclusions are:

(i) For isoscalar targets such as deuterons, $A/Q^2$ is independent of x $\left(f_u(x) \equiv f_d(x)\right)$.

(ii) We expect $A/Q^2$ to be nearly independent of y, since $\sin^2\theta_W \simeq 1/4$ experimentally, and y-dependence vanishes at that value.

(iii) We expect $A/Q^2$ to be insensitive to $q\bar{q}$ sea terms.

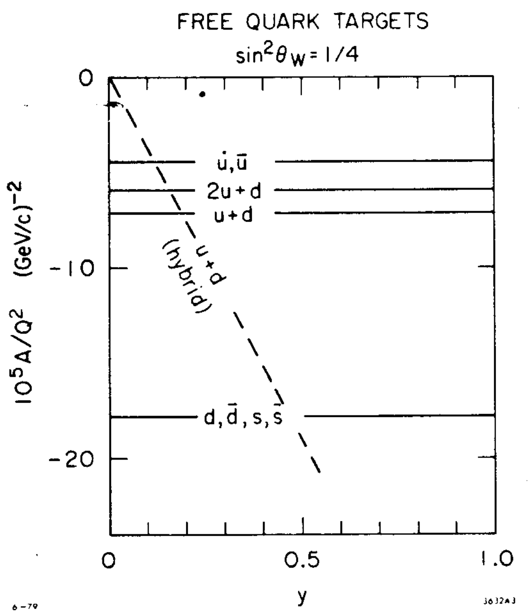


Fig. 5. Asymmetries predicted for free quark targets in two SU(2)× U(1) models (— W-S model, --- hybrid model).

Let me take a brief look at another SU(2) × U(1) gauge theory model. Suppose there exists a heavy neutral particle, call it $E^o$, which sits in a right-handed doublet with the electron, $\begin{pmatrix} E^o \\ e^- \end{pmatrix}_R$. This model, called the "hybrid" model, changes the neutral current couplings of the electron, according to Eq. (9). Because of the relation given by Eq. (9), measured asymmetries are sensitive to the existence or non-existence of other particles not involved in the process! Our recent results strongly disfavor the hybrid model.

## III. Experimental Techniques and Results

I will describe here only the more important techniques and the major results obtained at SLAC in 1978 for polarized e-d scattering. Many of the details will be omitted.

First and most important, we needed a polarized electron source for injection into the linear accelerator which had the following properties:

(i) High beam intensity (up to $5 \times 10^{11}$ $\bar{e}$'s/pulse, 120 pulses per second).

(ii) Good polarization ($\sim 40\%$).

(iii) Reversal of polarization, rapid and randomized from one pulse to next.

(iv) All other beam parameters not effected by reversal of polarization.

The principle of operation, photoemission from gallium arsenide surfaces, was proposed by Ed Garwin (SLAC), Dan Pierce (NBS) and H. C. Siegmann (ETH Zurich) in 1974.[10] Development of a suitable source at

SLAC took about 3 years. Cross section measurements were made by scattering accelerated beams of polarized electrons in a 30 cm liquid deuterium target, and detecting them in a magnetic spectrometer. The spectrometer contained two electron counters, a gas Gerenkov counter (C) and a lead glass shower counter (TA). Figure 6 shows a schematic of the experiment. Counting rates in the counters were very high (typically 1000 electrons per 1.5 μsec pulse) so that fluxes of electrons, rather than individual counters, were measured. We took the anode current from the photomultiplier tubes in each counter as a measure of electron flux. Each beam pulse provided a cross section measurement when fluxes were normalized to incident beam charge obtained from beam toroid monitors. A run consisted of a large number of pulses of randomly mixed + and - polarizations. In our computer we form two distributions of the cross sections, one for beam pulses of right-handed electrons and one for pulses of left-handed electrons (Fig. 7). The experiment consists in looking for a small relative shift in the means of these two distributions. The asymmetry is independent of the normalization used, so arbitrary cross section units work well. Absolute calibration of the apparatus is unnecessary. The method is essentially a difference measurement of two nearly equal quantities. By averaging over sufficiently long runs, the errors on the means can be reduced to a level small enough to see weak interference effects. The widths of the histograms reflected the statistical counting fluctuations, and these were monitored carefully during the experiment.

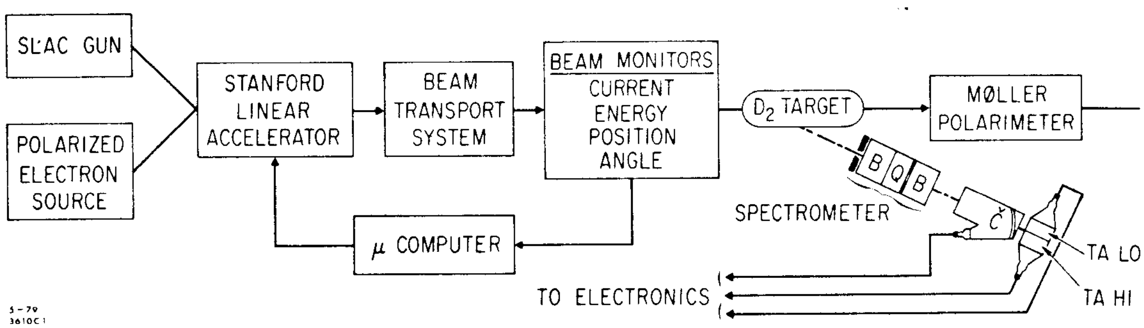


Fig. 6. Schematic layout of experiment.

An important factor in the experimental work lies in the control of systematic effects as demonstrated by consistency of data and null measurements contained in the data. Systematic effects most likely arise from influence that reversals at the polarized source have on other beam parameters. The important parameters (position and angle at the target, beam energy, intensity) were monitored with a set of devices positioned along the beam line to look for problems. The monitoring system was based on resonant microwave cavities which had a node placed on the beam axis. Displacements transverse to the beam line induced signals proportional to the current times the displacement. The high resolution obtained (typically 10 μm accuracy for a single pulse) resulted in position, angle and energy changes monitored to great sensitivity. These beam monitoring measurements ruled out systematic problems related to beam parameter changes when polarization was reversed.

The proof that parity violation exists lies in control of electron spin. Polarized electrons are photoemitted when one illuminates gallium arsenide surfaces with circularly polarized light. Monochromatic light ($\lambda$ = 710 nm) from a pulsed dye laser is linearly polarized in a Glan-Thompson calcite prism and circularly polarized in a Pockels cell quarter wave plate (Fig. 8). Voltage, approximately ±2 kV, applied to the ring electrodes drives the Pockels cell into $\pm\lambda/4$ retardation. By reversing the applied voltage, reversal of polarization is accomplished rapidly and easily within the 8.3 msec spacing between beam pulses. The pattern of + or - is randomized, and each beam pulse is tagged for the computer by the + or - Pockels cell voltage.

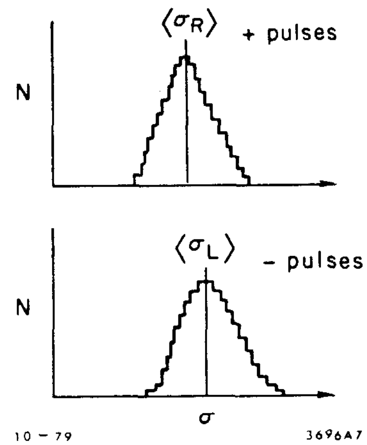


Fig. 7. Each beam pulse provides a cross section measurement, sorted by the computer into + helicity (right-handed) and - helicity (left-handed) pulses.

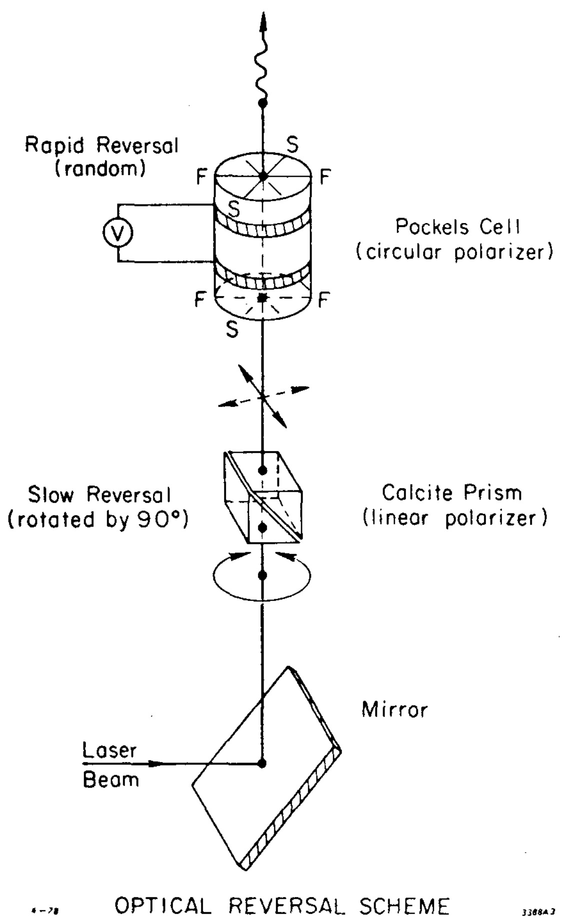


Fig. 8

Normally + or - 100% circular polarization gives + or - longitudinal polarization. However, if the prism is rotated by 90$^o$ about the laser beam axis, the fast and slow axes of the Pockels cell are interchanged relative to the plane of linear polarization. In this orientation + voltage on the Pockels cell gives - longitudinal polarization for the electron beams. The experimental asymmetries are formed in our computer according to the sign of Pockels cell voltage

$$A_{exp} = \frac{\sigma(v=+) - \sigma(v=-)}{\sigma(v=+) + \sigma(v=-)} \tag{10}$$

and we would expect this asymmetry to change sign when the prism is rotated to 90°. More generally, we expect

$$A_{exp} = P_e A \cos(2\phi_p) \tag{11}$$

where $P_e$ is the magnitude of the electron beam polarization and A is the parity nonconserving asymmetry the theorist calculates, defined by Eq. (2).

Figure 9 shows the results for each of the counters, the gas Cerenkov and the lead-glass shower counter, superimposed.

The two counters serve as a consistency check. They have different responses to backgrounds, different physical processes producing signals, and different electronics monitoring the fluxes. The only thing common to these counters is the electron signal, monitored simultaneously in both. That is, they count the same electrons and are, therefore, statistically highly correlated.

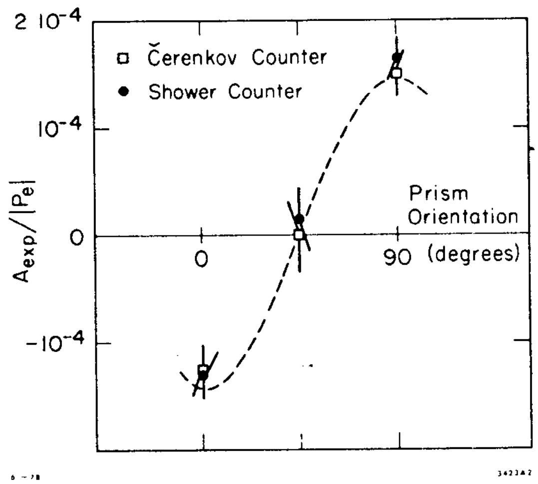


Fig. 9. Asymmetries vs. prism orientation for two counts, Cerenkov counter and the shower counter. Dashed curve is expected form, normalized to data.

The point at 45° is particularly important, since in this configuration the source is producing unpolarized electrons. Parity violating asymmetries must vanish, but systematic problems which mask or fake parity violation would still be present. The 45° measurements are consistent with 0 as expected. The agreement between the gas Cerenkov and lead-glass shower counters strengthen the belief that the observed asymmetries arise from parity violation.

The data shown in Fig. 9 are the average of a long series of runs, each lasting one to three hours in length. We can look at the individual runs which comprise the 0° and 90° points. Figure 10 shows the sequence of 44 runs. A solid line is drawn through the average of the points, showing the pattern for the prism orientation. These 44 runs constitute only one of our kinematic points. If we take into account the change of sign for the 90° runs. The mean asymmetry is $(-14.9 \pm 1.5) \times 10^{-5}$.

Figure 11 shows the standard deviations of these 44 runs about this mean. The distribution has a standard deviation 1.00 ± .11, in good agreement with expectations. We conclude that the assigned statistical error adequately represent the scatter in the data, and no additional significant contributions from systematic errors are seen at this level.

Additional control of electron spin can occur because of spin precession in the beam transport system. Due to the electron's anomalous magnetic moment, at relativistic energies the spin will precess faster than momentum in the uniform magnetic field by

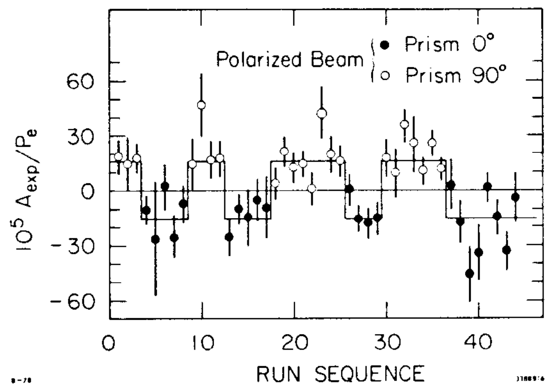


Fig. 10. Asymmetries measured in a sequence of 44 runs in two prism orientations.

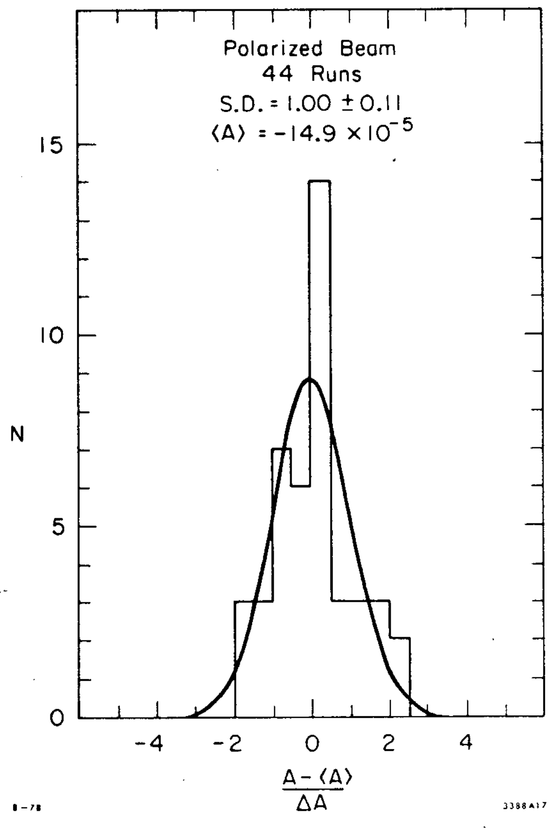


Fig. 11. Standard deviation about the mean for the 44 runs of Fig. 10 (with signs of asymmetries changed for runs with prism at 90°). Data are consistent with normal distribution (solid curve).

$$\theta_{prec} = \frac{E_o}{m_e}\left(\frac{g-2}{2}\right)\theta_{bend} = \frac{E_o}{3.237\ \text{GeV}}\ \pi\ \text{radians} \qquad (12)$$

By varying the beam energy, the spin of the electron at the target changes relative to the spin at the source, and we expect experimental asymmetries to vary according to

$$A_{exp} = P_e A \cos\left(\frac{E_o \pi}{3.237\ \text{GeV}}\right) \qquad (13)$$

where for these measurements the prism orientation is taken into account. The results shown in Fig. 12 are in good agreement with this form. The point at 17.8 GeV is consistent with zero as expected. This point has additional significance. The spin orientation is transverse here, normal to the plane of scatters and therefore transverse spin components as a possible source of asymmetries is ruled out.

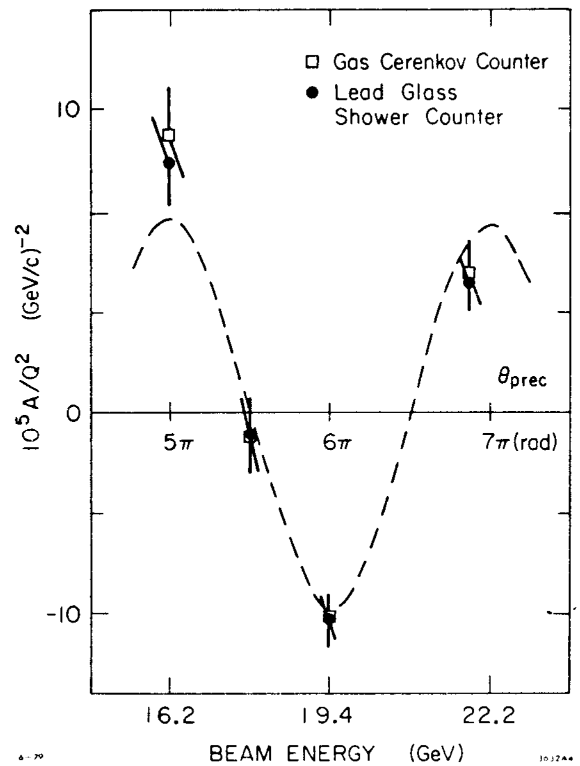


Fig. 12. The g-2 precession of the experimental asymmetries. Data are shown for both Cerenkov and shower counter measurements. Dashed curve is expected form, normalized to data.

The g-2 precession of the experimental asymmetries constitutes the proof that the interaction has a helicity dependent part, which is equivalent to parity violation in this reaction. The statement that this arises from weak-electromagnetic interference is inferred, because these measurements are in good agreement with models of weak-electromagnetic interactions, as we will see.

Data were also taken at different E' values for the electron, corresponding to different y values, defined earlier. The standard model predicts no y variation in $A/Q^2$ for $\sin^2\theta_W = 1/4$. Our results are close to this value; the best fit for the data, using the standard model and the simple quark-parton picture, is $\sin^2\theta_W = 0.224 \pm 0.020$. Figure 13 shows the data plotted against y values, and three different fits. The first, marked "W-S", is the standard model for $\sin^2\theta_W = 0.224$. A second fit, marked "Model Independent" corresponds to the two-parameter form

$$\frac{A}{Q^2} = a_1 + a_2 \frac{1-(1-y)^2}{1+(1-y)^2} \qquad (14)$$

which comes from the parton model independent of gauge theory assumptions. The fit parameters are $a_1 = (-9.7 \pm 2.6) \times 10^{-5}$ $(GeV/c)^{-2}$ and $a_2 = (4.9 \pm 8.1) \times 10^{-5}$ $(GeV/c)^{-2}$, which agree with standard model predictions. The best fit for the hybrid model is also shown. It has a poor $\chi^2$ and is strongly disfavored.

The errors shown in Fig. 13 have two parts. The inner error has correspond to the statistical error only. We have added to each point a systematic error that comes from beam monitoring errors, background subtraction uncertainties, and beam polarization errors.

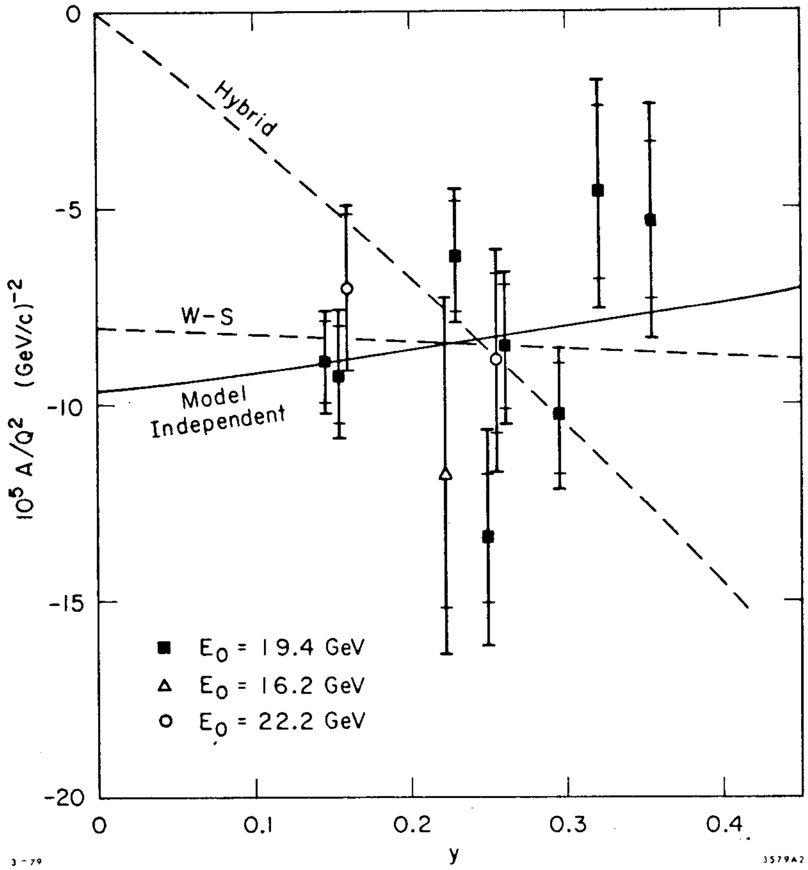


Fig. 13. The y-dependence of $A/Q^2$.

In addition, not shown, there is a ±5% uncertainty in scale for $A/Q^2$ due to an overall uncertainty in $P_e$ values. The $\chi^2$ per degree of freedom is 1.07 for the W-S fit, where we take the combined errors to be gaussian standard deviations. (Taking the statistical part of the error only, the W-S fit has a $\chi^2$/d. of f. = 2.0 and an artificially small error for $\sin^2\theta_W$. However the best value is not significantly different from .224.) Our value of $\sin^2\theta_W$ is in excellent agreement with the world's average of .23 ± .02 from neutrino induced neutral current interactions.

## IV. Connections to Atomic Physics

I would now like to make a few brief remarks about progress in the model independent analysis of neutral current reactions and the connections our work has to parity violation in bismuth and thallium atoms. 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 one can ignore all gauge theory ideas and look at the model independent approach. This approach has been emphasized by a number of authors[11-17] particularly with regard to neutrino neutral current interactions, but is now being extended to include the parity violation results in electron-hadron interactions.

The neutral current interaction has both a vector part and an axial-vector part. Where ordinary hadronic matter is involved (as is the case in eD or e-nuclei interactions) each of these parts can be decomposed into isovector and isoscalar pieces. That is, there are four phenomenological couplings, the vector-isovector term, the vector-isoscalar term, the axial-vector-isovector term, and the axial-vector-isoscalar term. In the notation of Hung and Sakurai,[12,16] these terms are denoted $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, and $\tilde{\delta}$ respectively. In the simple quark parton model the heavier quarks (s,c,b,...) are neglected. In terms of these phenomenological couplings, the asymmetry, Eq. (2), becomes

$$\frac{A}{Q^2} = \frac{G_F}{2\sqrt{2}\pi\alpha} \cdot \frac{9}{10}\left[(\tilde{\alpha}+\tilde{\gamma}/3) + (\tilde{\beta}+\tilde{\delta}/3)\,\frac{1-(1-y)^2}{1+(1-y)^2}\right] \quad . \qquad (11)$$

The results of the model-independent fit, Eq. (10), then determines the linear combinations

$$\tilde{\alpha} + \tilde{\gamma}/3 = -0.60 \pm 0.16$$

$$\tilde{\beta} + \tilde{\delta}/3 = 0.31 \pm 0.51$$

which is insufficient information to complete the determination of the four fundamental parameters. To make the separations we must turn to other processes which can measure different combinations of these four parameters. Comparison of ep and eD asymmetries in inelastic scattering in principle can provide the new information, but the differences are so small that the measurements in practice would be extremely difficult to make meaningfully. Elastic scattering off protons, deuterons and higher Z nuclei at medium energies looks more promising, and experiments now being planned may ultimately provide us new information. At present we are limited to atomic physics parity non-conservation in bismuth and thallium, where the weak charge can be expressed in the nearly orthogonal combinations

$$Q_W\ (\text{bismuth}) = 43\tilde{\alpha} - 627\tilde{\gamma}$$

and

$$Q_W\ (\text{thallium}) = 42\tilde{\alpha} - 612\tilde{\gamma}$$

and the parity violation results in atoms, plus our eD results, can determine the parameters $\tilde{\alpha}$, $\tilde{\gamma}$. However two other terms, $\tilde{\beta}$ and $\tilde{\delta}$, are not present for atomic physics parity violation, and these remain unseparated.

The recent work of Hung and Sakurai[16] make an important step in the determination of these parameters. They point out that the world's data on neutral currents show consistency with factorization of these phenomenological couplings into a product of leptonic and hadronic (i.e., quark) parts. The experimental evidence is not conclusive, but just suggestive. Assuming factorization to be valid, Hung and Sakurai proceed to complete the separation of all the phenomenological neutral current coupling parameters. Although not completely free of assumptions their analysis provides for the first time a complete separation of the electron-hadron neutral current couplings. I believe the real message from their analysis is the need to improve all neutral current data and the importance of testing the factorization relations.

Why should we care about factorization and the experimental determination of these parameters? These parameters can be indirectly related to the questions of the Higgs structure of gauge theories and to the question of how many $Z^o$'s exist. The single $Z^o$ hypothesis of the minimal $SU(2) \times U(1)$ model implies factorization of the neutral current couplings (but the converse is not necessarily true). Careful measurements, and much improved experimental errors will permit more precise testing of these gauge theory predictions. In particular we will be looking for deviations from the Weinberg-Salam model as an indication of more complicated Higgs structure or a larger vector boson complement than the present theory contains. Until the day comes when we directly produce the $Z^o$ in the laboratory, low energy experiments are the only tools we have, and it is important to pursue these difficult measurements if we are to further our understanding of the fundamental questions.

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