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PARITY VIOLATION IN POLARIZED ELECTRON SCATTERING*

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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 twenty years have passed since the early conjectures, and a great deal has been learned. Progress in quantum field theory

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led to the development of the $SU(2) \times U(1)$ 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.

II. WEAK ELECTROMAGNETIC INTERFERENCE IN POLARIZED ELECTRON SCATTERING

Within nuclei, the weak forces acting in the presence of much larger, but parity conserving, strong forces can lead to parity violation admixtures in nuclear levels. Considerable evidence for these admixtures in nuclei exists. The problem has been in the interpretation of the sources. Separation of neutral current from charged current effects is difficult in nuclei, but enhancements due to neutral current forces appear to be present.[5] When probing nuclei with polarized electrons, parity violating asymmetries are dominated by the single Z^0 exchange interfering with the single-γ exchange, and the details of the nuclear state are unimportant. This has been argued on different grounds by a number of authors.[6-10] Parity violation in polarized electron scattering measured directly the amount of γ-Z interference. At the end, I will remark briefly on ways that details of nuclear states can contribute to our understanding of neutral currents.

The scattering amplitude consists of two parts, an electromagnetic piece and a weak piece. The quark model is a very good description of the scattering process of SLAC energies.[11] For lower energies, the ranges of the forces are larger, and nucleons may be the appropriate constituents, or even the whole nucleus. The basic ideas, however, are the same in all cases. One constructs cross sections from the terms shown in figure 1. The parity violating asymmetry is defined as

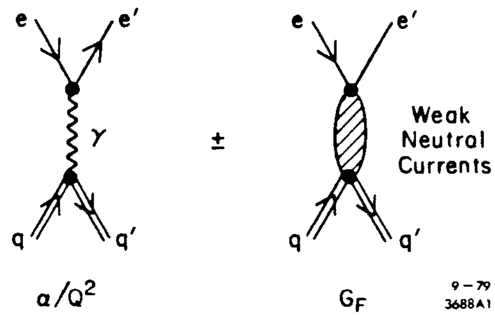

Figure 1.

$$A_{PNC} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad (1)$$

To describe the electron scattering work carried out in SLAC in 1978 and 1979[12,13] one takes the quark model description. Consider an electron scattering from a stationary quark at a CMS angle θ to the initial direction, shown in figure 2. Lorentz transforming to the lab frame gives $E' = E_0/2(1+\cos\theta)$. Define a variable $y = (E_0 - E')/E_0$, which is the fraction of beam energy transferred to the quark, and in terms of y

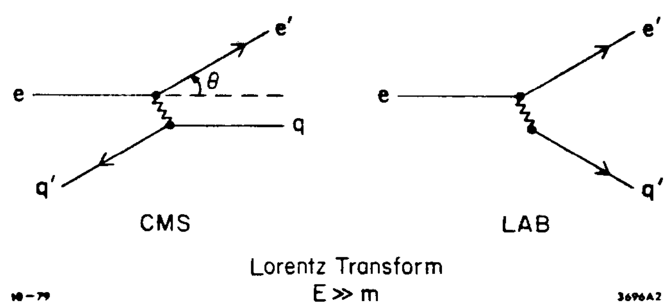

Fig. 2. Electron-quark scattering seen in two frames.

$$\tfrac{1}{2}(1+\cos\theta) = 1 - y \qquad (2)$$

It is easy to show that the asymmetry, equation 1, has the form

$$A_{PNC} = a_1 + a_2\, f(y) \qquad (3)$$

$$f(y) = \frac{1-(1-y)^2}{1+(1-y)^2} \tag{4}$$

$$a_1 = \frac{-G_f\, Q^2}{2\sqrt{2}\,\pi\alpha}\;\frac{9}{10}\left(1-\frac{20}{9}\sin^2\theta_w\right) \tag{5}$$

$$a_2 = \frac{-G_f\, a^2}{2\sqrt{\ }\,\pi\alpha^{\sim}}\;\frac{9}{10}\left(1-4\sin^2\theta_w\right) \tag{6}$$

For $\sin^2\theta_w = \frac{1}{4}$, we expect

$$A_{PNC} \cong -10^{-4}\,Q^2, \text{ independent of } y. \tag{7}$$

III. EXPERIMENTAL TECHNIQUES AND RESULTS

A polarized electron source for injection into the linear accelerator was developed at SLAC based on principles suggested by E. L. Garwin (SLAC), Dan Pierce (NBS), and H. C. Siegmann (ETH, Zürich) in 1974.[14] Development of an operational source as an injector for SLAC took about three years. The source consists of a crystal of gallium arsenide optically pumped by a pulsed dye laser beam at 730 nm wavelength. Circular polarization of the laser light produces polarized electrons in the conduction band of about 50% polarization. Reversing the circular polarization of the laser flips the electrons polarization. Photoemission of the polarized electrons is achieved by coating the GaAs crystal surface with CsO layers. We achieved the following essential properties with the SLAC source:

(i) High beam intensities up to 5×10^{11} e^-'s per 1.5 μsec long pulse, at 120 Hz.

(ii) Good polarization (40%)

(iii) Easily reversed polarization between beam pulse; randomized pattern.

(iv) All other beam parameters not affected by reversals.

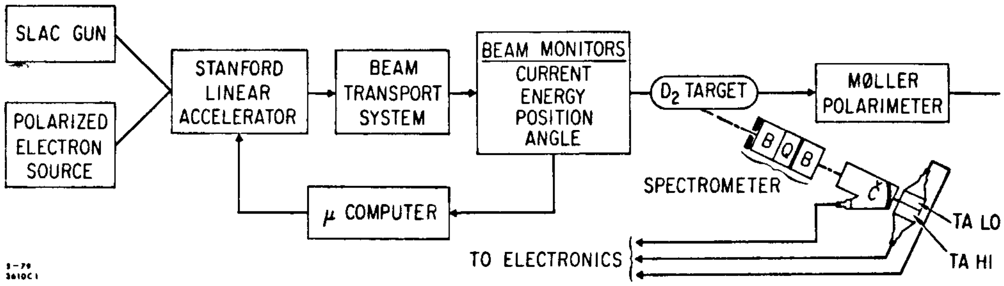

Fig. 3. Schematic layout of experiment.

Figure 3 shows a schematic of the experiment. Cross section measurements were made in a spectrometer sitting at 4° to the incident beam. Incident beam energies were mostly fixed at 19.4 GeV, but data at 16.8, 17.8 and 22.2 GeV were also taken.

Secondary scattered energies were from 11 to 16.5 GeV. Counting rates in the counters were very high. Fluxes of electrons were measured by integrating photomultiplier output signals. Each beam pulse was measured, digitized and recorded on magnetic tape. For cross sections, two separate counters were used. A gas Čerenkov counter first counted electrons which passed through the spectrometer aperture. The electrons then passed into a lead-glass shower counter which detected the same electrons. Asymmetries were separately obtained in the Čerenkov counter and in the lead-glass counter (called TA for total absorption). Separate low and high momentum halves of the TA counter were later used for a y-dependence measurement of these asymmetries. The purpose of the two counters measuring the same electrons was to check the internal consistency of the experimental apparatus and techniques by different particle counters. Cross sections, and subsequently asymmetries, were obtained by normalizing measured scattered fluxes to incident beam fluxes, measured in beam toroids on the beam line before the target.[15] A run consisted of a large number of beam pulses of randomly mixed + and - polarizations. Two distributions were tabulated: cross sections for + and cross sections for - polarizations were the main essential data.

Beam monitoring of important beam parameters looked for systematic effects which could lead to apparent, but false, asymmetries. Small systematic effects were seen, but at a low level, and these have been included in the analysis of our systematic errors.

By averaging asymmetries over sufficiently long runs, errors from statistical counting can be reduced to a level small enough to see weak effects, providing systematic problems are under control. In our case, the weak interactions, at the level of the W-S model, were reached in approximately thirty minutes to two hours of beam time, depending on kinematic conditions. Systematic errors were considerably smaller than statistical errors.

An important factor in the experimental confidence lies in demonstrating control of systematic errors, demonstrated by consistency of data and measurement of zero asymmetry for known null points. We incorporated several such tests into our work. Figure 4 shows the optical setup for polarizing and reversing the laser light which drives the source. The laser beam first is polarized by a Glan-Thompson calcite prism polarizer. Circular polarization is then obtained in a quarter-wave plate. We chose to use a Pockels cell which can be driven into retardation electrically. Positive voltage of approximately 2 KV drives the Pockels cell into $+\lambda/4$ retardation, giving $+100\,\%$ circular

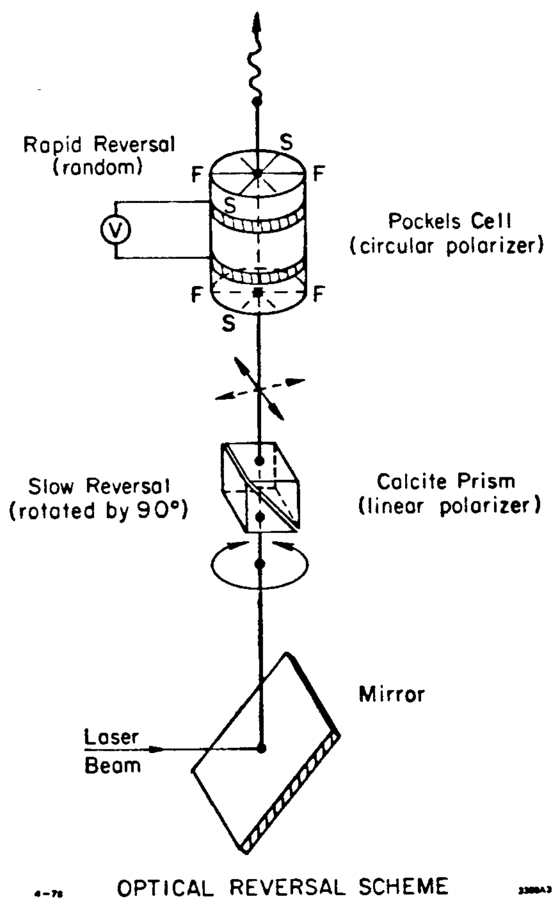

Figure 4.

polarization (and hence positive longitudinal polarization of photoemitted electrons from the GaAs). Negative voltage reverses the retardation to $-\lambda/4$, and gives $-100\,\%$ circular polarization (and similarly negative electron polarization). We form an experimental asymmetry according to the Pockels cell voltage. That is, some beam pulses occur with +V on the Pockels cell and the others have -V on the Pockels cell. These are randomly mixed during the course of a run. The asymmetry

$$A_{exp} = \frac{\sigma(+V) - \sigma(-V)}{\sigma(+V) - \sigma(-V)}$$

is obtained over the course of each run. After a series of runs, the orientation of the calcite prism polarizer is changed by 90° (or later by 45°). Rotating the prism 90° about the axis of the laser beam means that +V would now give $-100\,\%$ polarized light (and negative electron polarization). More generally, we expect the experimental asymmetry, equation 9, to satisfy the relation

$$A_{exp} = P_e A_{pnc} \cos(2\phi_p) \tag{9}$$

Where P_e is the magnitude of the electron beam polarization, and ϕ_p is the prism orientation angle. Figure 5 shows the results for the two independent counters in the spectrometer. The point at 45° corresponds to depolarizing the polarized electron source. This is a null point which shows that

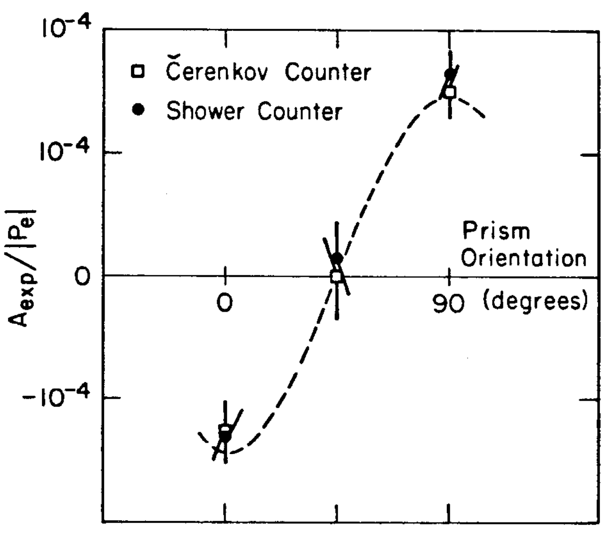

Fig. 5. Asymmetries vs prism orientation for two counters, Čerenkov counter and the shower counter. Dashed curve is expected form, normalized to data.

no large systematic errors are present. The errors are statistical only. The dashed curve is the expected cosine form, with the amplitude adjusted to fit the data. The agreement between the Čerenkov counter and the lead-glass counter is excellent. This shows that independent electronic channels and independent types of counters achieve the same answer. But note that the electrons are common to these two counters; that is they are highly correlated statistically, and we therefore do not combine the results.

A second test of consistency in our data comes from the g-2 precession of the electron spin in our beam transport system. Due to the electron's anomolous magnetic moment, and the $24\frac{1}{2}^{\circ}$ bend in our transport line, the spin will precess ahead of the momentum by an amount which increases with energy

$$\theta_{prec} = \frac{E_0}{M_e}\left(\frac{g-2}{2}\right)\theta_{bend} = \frac{E_0\,(\mathrm{GeV})}{3.237}\,\pi \text{ radians} \quad . \qquad (10)$$

By varying the beam energy, the spin of the electron at the target changes relative to the spin at the source. We expected the experimental asymmetries to vary according to

$$A_{exp} = P_e A_{pnc} \cos\left(\frac{E_0\pi}{3.237}\right) \qquad (11)$$

We took data at four energies, 16.2, 17.8, 19.4 and 22.2, corresponding to the precession angles of 5π, $5\frac{1}{2}\pi$, 6π and 7π, respectively. Figure 6 shows the results compared to the form, equation 11, with the amplitude of the dashed curve adjusted to fit the data.

Again we show separately the Čerenkov and lead-glass counters, which have good agreement. The point at 17.8 GeV is particularly important. At this energy, the electron spin is <u>normal</u> to the scattering plane, and any asymmetries arising from <u>transverse</u> spin projections would be largest for this energy. The null measurement rules out transverse spin components as a source of systematic error.

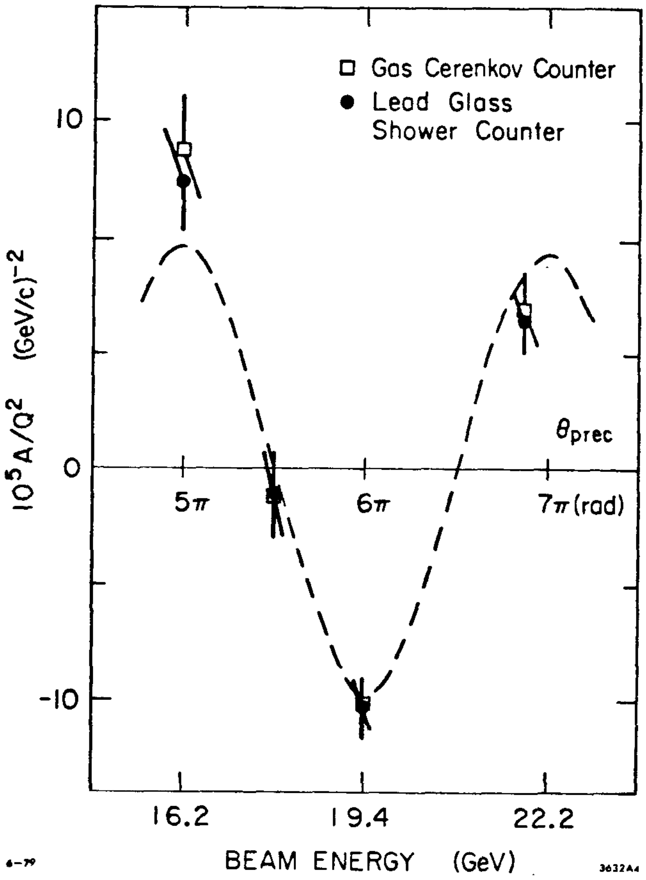

Fig. 6. The g-2 precession of the experimental asymmetries. Data are shown for both Čerenkov and shower counter measurements. Dashed curve is expected form, normalized to data.

The g-2 precession of the experimental asymmetries constitutes the best proof that the interaction has a helicity-dependent piece. We infer that the cause is the expected weak-electromagnetic interference because of the excellent agreement with predictions.

Data were taken at different E' values for the scattered electron for the deuterium target. The W-S model predicts no y variation in A/Q^2 for $\sin^2\theta_W = \frac{1}{4}$. Our results are close to this value. The best fit for our deuterium data, assuming the standard model and the simple quark-parton description of this process, is

$$\sin^2\theta_W = .224 \pm .020 \quad .$$

Figure 7 shows the data plotted against y, and compares it to three models or fits. The first, marked "W-S", is for $\sin^2\theta_W = .224$.

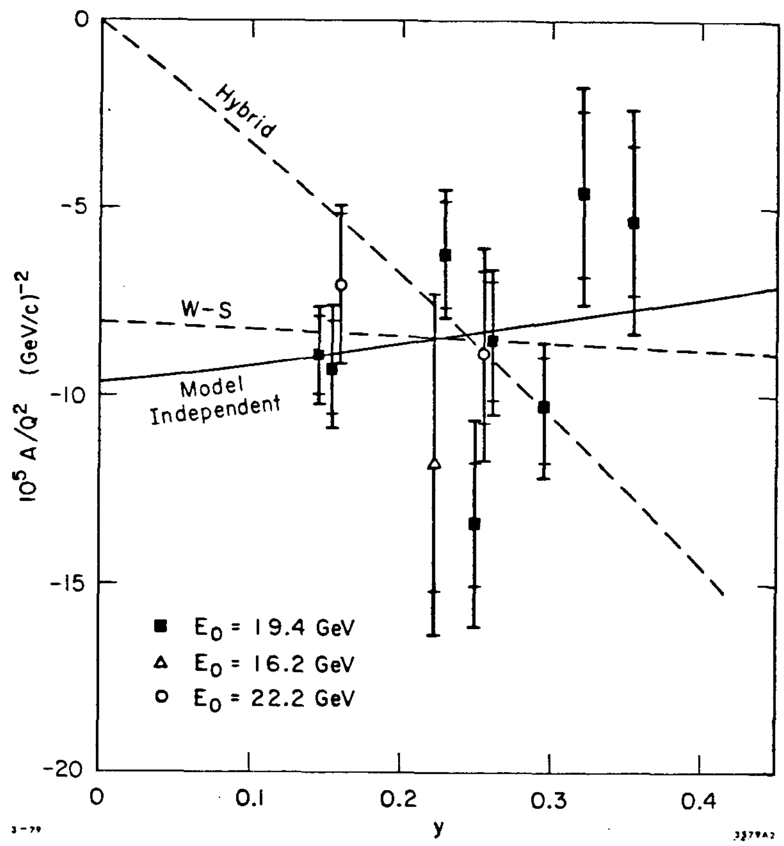

Fig. 7. The y-dependence of A/Q^2.

The second fit, marked "Model Independent", corresponds to the general form

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

which comes from the quark-parton model without any gauge theory assumptions. The fit parameters are $a_1 = (-9.7 \pm 2.6) \times 10^{-5}$ (GeV/c)$^{-2}$ $a_2 = (4.9 \pm 8.1) \times 10^{-5}$ (GeV/c)$^{-2}$ which agrees with W-S's predictions within the 1-σ errors. The hybrid model results from placing the e_R into a doublet with an hypothesized heavy neutral lepton. It has a poor χ^2 and is strongly disfavored by the data.

What issues remain at low energies? Nuclear physics has an important role to play in understanding the neutral current, but the experiments that need to be done look difficult. The issues that need to be tested are the space-time structure and isospin structure of the neutral currents. Suggestions on uses of nuclear levels to measure these properties have been tentatively offered.[9]

Hadronic neutral currents are generally assumed to consist of vector and axial vector pieces. Each of these pieces can be further broken into isoscalar and isovector components. This decomposition, however, is an assumption based on theoretical prejudices and absence of experimental evidence to the contrary. Under this hypothesis, the neutral current couplings can be decomposed into four terms:

	Type	Symbol
(i)	Vector, $I = \phi$	$\tilde{\alpha}$
(ii)	Vector, $I = 0$	$\tilde{\gamma}$
(iii)	Axial-Vector, $I = 0$	$\tilde{\delta}$
(iv)	Axial-Vector, $I = 1$	$\tilde{\beta}$

In terms of the parameters, the relation, equation 3, becomes

$$A/Q^2 = \frac{G_f}{2\sqrt{2}\pi\alpha} \cdot \frac{9}{10} \left[\left(\tilde{\alpha} + \tilde{\gamma}/3\right) + \left(\tilde{\beta} + \tilde{\delta}/3\right) \frac{1 - (1-y)^2}{1 - (1-y)^2} \right] . \qquad (15)$$

Asymmetry measurements in deep inelastic scattering serve only to measure linear combinations of the four fundamental couplings. The complete separation of these couplings has yet to be done.

Transitions between nuclear levels which are eigenstate of spin, parity and isospin can act as filters to preferentially select components of the neutral current of the $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$ or $\tilde{\delta}$ type. Measurement of a polarization asymmetry for a $\Delta I = 0$, 0^+ to 0^- nuclear transition would isolate the $\tilde{\delta}$ contribution. It is predicted to be zero in the standard model. Elastic scattering from C^{12} selects

$\tilde{\alpha}$ couplings, and a T = 1 state at 12.8 MeV in O^{16} selects $\tilde{\beta}$. Expected asymmetries are exceedingly small, of the order of 10^{-6}, so that the experimental feasibility of such tests depend on many details. Such measurements require extremely careful work, and the time and effort required should not be underestimated. Nevertheless, the decomposition of the neutral currents, one of natures fundamental forces, is an important task yet to be completed.

The future for neutral current phenomenology is brightest at the new storage rings, PETRA and PEP now, and for the future, the $\bar{p}p$ collider at CERN and e^+e^- ring at LEP. The prospects for measuring effects of the Z^0 is good at high energies where the effects are relatively large. In the future lies the production of the Z^0 and the observation of its many decay modes. However, there are present tools in our laboratories now to test some of these ideas. The effects are quite small, but we are limited only by lack of good ideas. Until the day comes when we produce the Z^0, we should continue to apply our experimental skills to test these fundamental concepts.

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