PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

J.E. CLENDENIN, V.W. HUGHES, N. SASAO [3] and K.P. SCHÜLER
Yale University, New Haven, CT 06520, USA

M.G. BORGHINI
CERN, Geneva, Switzerland

K. LÜBELSMEYER
Technische Hochschule Aachen, Aachen, West Germany

and

W. JENTSCHKE
II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

Received 14 July 1978

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%.

We have observed a parity non-conserving asymmetry in the inelastic scattering of longitudinally polarized electrons from an unpolarized deuterium target. In this experiment a polarized electron beam of energy between 16.2 and 22.2 GeV was incident upon a liquid deuterium target. Inelastically scattered electrons from the reaction

$$\mathrm{e(polarized)} + \mathrm{d} \to \mathrm{e}' + \mathrm{X}, \tag{1}$$

were momentum analyzed in a magnetic spectrometer at 4° and detected in a counter system instrumented to measure the electron flux, rather than to count individual scattered electrons. The momentum transfer, Q^2, to the recoiling hadronic system varied between 1 and 1.9 $(\mathrm{GeV}/c)^2$ (see table 1).

Parity violating effects may arise from the interference between the weak and electromagnetic amplitudes. Calculations of the expected effects in deep inelastic experiments have been reported by several authors [1–7], and asymmetries at the level of $10^{-4} Q^2$ are predicted for the kinematics of our experiment. Previous experiments with muons [8] and electrons [9,10] have not achieved sufficient accuracy to observe such small effects. This same interference of amplitudes may also give rise to measurable effects in

☆ Work supported by the Dept. of Energy.

[1] Permanent address: Annecy (LAPP), 74019 Annecy-le-Vieux, France.
[2] Permanent address: National Laboratory for High Energy Physics, Tsukuba, Japan.
[3] Present address: Department of Physics, Kyoto University, Kyoto, Japan.

Table 1
Kinematic conditions at which data were taken. The average Q^2 and y values were calculated for the shower counter using a Monte Carlo program.

Beam energy E_0 (GeV)	$g-2$ precession angle $\theta_{\rm prec}$ (rad)	Spectrometer setting E' (GeV)	Kinematic quantities averaged over spectrometer	
			Q^2 (GeV/c)^2	y
16.18	5.0π	12.5	1.05	0.18
17.80	5.5π	13.5	1.25	0.19
19.42	6.0π	14.5	1.46	0.21
22.20	6.9π	17.0	1.91	0.21

atomic spectra; experiments on transitions in the spectrum of bismuth have already been reported [11–13].

Of crucial importance to this experiment was the development of an intense source of longitudinally polarized electrons. The source consisted of a gallium arsenide crystal mounted in a structure similar to a regular SLAC gun with the GaAs replacing the usual thermionic cathode. The polarized electrons were produced by optical pumping with circularly polarized photons between the valence and conduction bands in the GaAs, which had been treated to assure a surface with negative electron affinity [14,15]. The light source was a dye laser operated at 710 nm and pulsed to match the linac (1.5 μs pulses at 120 pulses per second). Linearly polarized light from the laser was converted to circularly polarized light by a Pockels cell, a crystal with birefringence proportional to the applied electric field. The plane of polarization of the light incident on the Pockels cell could be varied by rotating a calcite prism. Reversing the sign of the high voltage pulse driving the Pockels cell reversed the helicity of the photons which in turn reversed the helicity of the electrons. This reversal was done randomly on a pulse to pulse basis. The rapid reversals minimized the effects of drifts in the experiment, and the randomization avoided changing the helicity synchronously with periodic changes in experimental parameters. Pulsed beam currents of several hundred milliamperes were achieved, with intensity fluctuations of a few percent.

The longitudinally polarized electrons were accelerated with negligible depolarization as confirmed by earlier tests [16] [‡1]. Both the sign and the magnitude of the polarization of the beam at the target were measured periodically by observing the asymmetry in Møller (elastic electron–electron) scattering from a magnetized iron foil [16]. The polarization, $|P_e|$, averaged 0.37. Each measurement had a statistical error less than 0.01; we estimate an overall systematic uncertainty of 0.02. The beam intensity at the target varied between 1 and 4×10^{11} electrons per pulse.

A schematic of the apparatus is shown in fig. 1. The target was a 30 cm cell of liquid deuterium. The spectrometer consisted of a dipole magnet, followed by a single quadrupole and a second dipole. The scattering angle was 4° and the momentum setting was about 20% below the beam energy (see table 1 for the kinematic settings). The acceptance was ±7.4 mrad in scattering angle, ±16.6 mrad in azimuth and about ±30% in momentum, as determined from a Monte Carlo model of the spectrometer.

Two separate electron detectors intercepted electrons analyzed by the spectrometer. The first was a nitrogen-filled Cerenkov counter operated at atmospheric pressure. The second was a lead-glass shower counter with a thickness of nine radiation lengths (the TA counter). Approximately 1000 scattered electrons per pulse entered the counters.

The high rates were handled by integrating the outputs of each phototube rather than by counting individual particles. For each pulse, i, the integrated output of each phototube, N_i, was divided by the integrated beam intensity (charge), Q_i, to form the yield for that pulse, $Y_i = N_i/Q_i$. For the distributions of the Y_i we verified experimentally that the (charge weighted) means of the distributions, $\langle Y \rangle$, were independent of Q, within errors of about ±0.3%, and that the (charge weighted) standard deviations, ΔY, were consistent with the statistical fluctuations expected from the number of scattered electrons per pulse. For a run with n beam pulses the statistical uncertainty on $|Y|$ was given by $\Delta Y/\sqrt{n}$.

As a check on our procedures we measured the asymmetry for a series of runs using the unpolarized beam from the regular SLAC gun for which the asymmetry should be zero. For a given run the experimental asymmetry was given by:

$$A_{\rm exp} = [\langle Y(+)\rangle - \langle Y(-)\rangle] / [\langle Y(+)\rangle + \langle Y(-)\rangle] , \qquad (2)$$

[‡1] The present experiment used the same target as ref. [16], but used a different spectrometer and detectors.

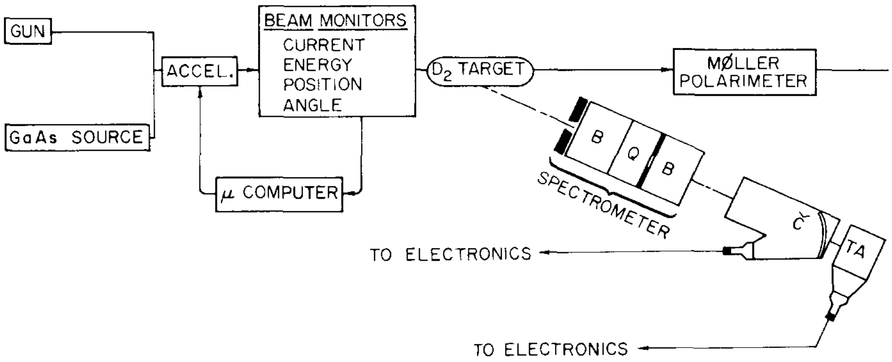

Fig. 1. Schematic layout of the experiment. Electrons from the GaAs source or the regular gun are accelerated by the linac. After momentum analysis in the beam transport system the beam passes through a liquid deuterium target. Particles scattered at 4° are analyzed in the spectrometer (bend-quad-bend) and detected in two separate counters (a gas Cerenkov counter, and a lead-glass shower counter). A beam monitoring system and a polarization analyzer are only indicated, but they provide important information in the experiment.

where + and – were assigned by the same random number generator that determined the sign of the voltage applied to the Pockels cell. For the shower counter we obtained a value of $(-2.5 \pm 2.2) \times 10^{-5}$ for A_{exp} divided by 0.37, the average value of $|P_e|$ for polarized beams from the GaAs source. The individual values were distributed about zero consistent with the calculated statistical errors. We conclude that asymmetries can be measured in this apparatus to a level of about 10^{-5}.

The same procedures were next applied to a similar series of runs using polarized beams. The helicity of the electrons coming from the source depended on the orientation of the linearly polarizing prism as well as on the sign of the voltage on the Pockels cell. Rotation of the plane of polarization by rotating the calcite prism through an angle ϕ_p caused the net electron helicity to vary as $\cos(2\phi_p)$. We chose three operating conditions:

(a) prism orientation at 0°, producing + (–) helicity electrons for + (–) Pockels cell voltage;

(b) prism orientation at 45°, producing unpolarized electrons for either sign of Pockels cell voltage; and

(c) prism orientation at 90°, producing – (+) helicity electrons for + (–) Pockels cell voltage.

Positive helicity indicates that the spin is parallel to the direction of motion. As the prism is rotated by 90°, A_{exp} should change sign since it is defined only with respect to the sign of the voltage on the Pockels cell. We may define a physics asymmetry, A, whose sign depends on the helicity of the beam at the target

$$A_{\mathrm{exp}} = |P_e| A \cos(2\phi_p), \tag{3}$$

where ϕ_p is the angle of orientation of the calcite prism.

Fig. 2 shows the results at 19.4 GeV for $A_{\mathrm{exp}}/|P_e|$. For the 45° point we used a value of 0.37 for $|P_e|$. These data are in satisfactory agreement with expecta-

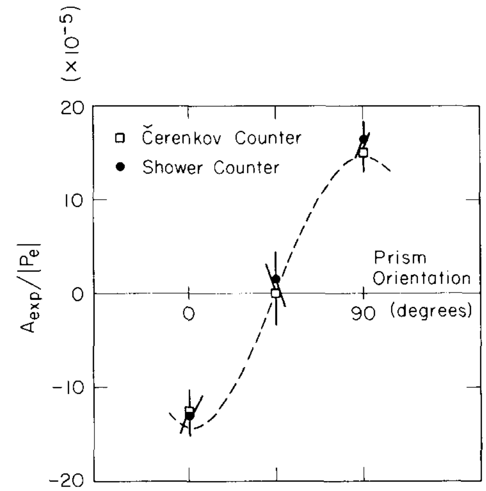

Fig. 2. The experimental asymmetry shows the expected variation (dashed line) as the beam helicity changes due to the change in orientation of the calcite prism. The data are for 19.4 GeV and deuterium. Since the same scattered particles strike both counters, they are not statistically independent. No systematic errors are shown. No corrections have been made for helicity dependent differences in beam parameters.

tions, and serve to separate effects due to the helicity of the beam from possible systematic effects associated with the reversal of the Pockels cell voltage. Only statistical errors are shown. The results at 45° are consistent with zero and indicate that other sources of error in A_{exp} must be small. Furthermore, the asymmetries measured at 0° and 90° are equal and opposite, within errors, as expected. Fig. 2 shows data from both the Cerenkov counter and the shower counter. Although these two separate counters were not statistically independent, they were analyzed with independent electronics and responded quite differently to potential backgrounds. The consistency between these counters serves as a check that such backgrounds are small.

At 19.4 GeV with the prism at 0° the helicity at the target was positive for positive Pockels cell voltage. However, this helicity depended on beam energy, owing to the $g-2$ precession of the spin in the transport magnets which deflected the beam through 24.5° before reaching the target. Because of the anomalous magnetic moment of the electron, the electron spin direction precessed relative to the momentum direction by an angle

$$\theta_{\mathrm{prec}} = \frac{E_0}{m_e c^2}\,\frac{g-2}{2}\,\theta_{\mathrm{bend}} = \frac{E_0\,(\mathrm{GeV})}{3.237}\,\pi\ \mathrm{rad}, \qquad (4)$$

where m_e is the mass and g the gyromagnetic ratio of the electron. Thus we expect

$$A_{\exp} = |P_e|\,A\cos[(E_0\,(\mathrm{GeV})/3.237)\pi], \qquad (5)$$

where the signs of values of A_{exp} for the prism at 90° have been reversed before combining with values for the prism at 0°. Fig. 3 shows the results for the kinematic points in table 1 as a function of beam energy. At each point Q^2 is different. Since we expect A to be proportional to Q^2, we divide A_{exp} by Q^2 ‡2. Fig. 3 also shows the expected curve normalized to the point at 19.4 GeV. The data clearly follow the $g-2$ modulation of the helicity. At 17.8 GeV the spin is transverse; any effects from transverse components of the spin are expected to be negligible, in agreement with our data.

We conclude from figs. 2 and 3 that the observed asymmetries are due to electron helicity. Nevertheless,

‡2 This fact is true in all models. It arises because the electromagnetic amplitude has a $1/Q^2$ dependence, giving an asymmetry proportional to Q^2.

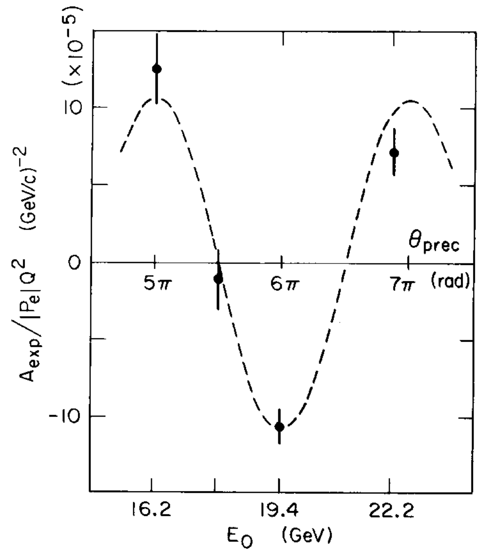

Fig. 3. The experimental asymmetry shows the expected variation (dashed line) as the beam helicity changes as a function of beam energy due to the $g-2$ precession in the beam transport system. The data are for the shower counter and the deuterium target. No systematic errors are shown. No corrections have been made for helicity dependent differences in beam parameters.

it is essential to search for and set limits on asymmetries due to effects other than helicity. Systematic effects due to slow drifts in phototube gains, magnet currents, etc., were minimized by the rapid, random reversals of polarization, and had negligible effects on A_{exp}. Effects due to random fluctuations in the beam parameters were small compared to the 3% pulse to pulse fluctuations due to counting statistics in the detectors. This was verified experimentally by measuring A_{exp} with unpolarized beams from the regular SLAC gun, and also by generating "fake" asymmetries using pulses of the same helicity from the polarized data runs themselves.

A more serious source of potential error came from small systematic differences between the beam parameters for the two helicities. Small changes in position, angle, current or energy of the beam can influence the measured yields. If these changes are correlated with reversals of the beam helicity, they may cause apparent parity violating asymmetries. Using an extensive beam monitoring system based on microwave cavities, measurements were made for each beam pulse of the average energy and position [17]. Angles were determined from cavities 50 m apart. The beam charge was determined using the standard toroid monitors [18]. The resolutions per pulse were about 10 μm in position, 0.3 μrad in angle, 0.01% in energy, and 0.02% in beam intensity. A microcomputer driven feedback system used position and energy signals to stabilize the average beam position, angle, and energy. Using the measured pulse to pulse beam information together with the measured sensitivities of the yield to each of the beam parameters, we made corrections to the asymmetries for helicity dependent differences in beam parameters. For these corrections, we have assigned a systematic error equal to the correction itself. The most significant imbalance was less than one part per million in E_0 which contributed -0.26×10^{-5} to A/Q^2.

We combine the values of A/Q^2 from the shower counter for the two highest energy points to obtain

$$A/Q^2 = (-9.5 \pm 1.6) \times 10^{-5}\ (\text{GeV}/c)^{-2}\ \text{(deuterium)}. \tag{6}$$

We do not include the point at 16.2 GeV because it contains fairly strong elastic and resonance contributions. The sign implies a greater yield from electrons with spin antiparallel to momentum. For this combined point the average value of $y = 1 - E'/E_0$ is 0.21 and the average value of Q^2 is 1.6 $(\text{GeV}/c)^2$. The quoted error, based on preliminary analysis, is derived from a statistical error of $\pm 0.86 \times 10^{-5}$ added linearly to estimated systematic uncertainties of 5% in the value of $|P_e|$, and of 3.3% from asymmetries in beam parameters. We determined experimentally that the π^- background contributed less than 0.1×10^{-5} to A/Q^2. The result in eq. (6) includes normalization corrections of 2% for the π^- background, and 3% for radiative corrections.

Any observation of non-conservation of parity in interactions involving electrons adds new information on the nature of neutral currents and gauge theories. Certain classes of gauge theory models predict no observable parity violations in experiments such as ours. Among these are those left–right symmetric models in which the difference between neutral current neutrino and anti-neutrino scattering cross sections is explained as a consequence of the handedness of the neutrino and anti-neutrino, while the underlying dynamics are parity conserving. Such models are incompatible with the results presented here.

The simplest gauge theories are based on the gauge

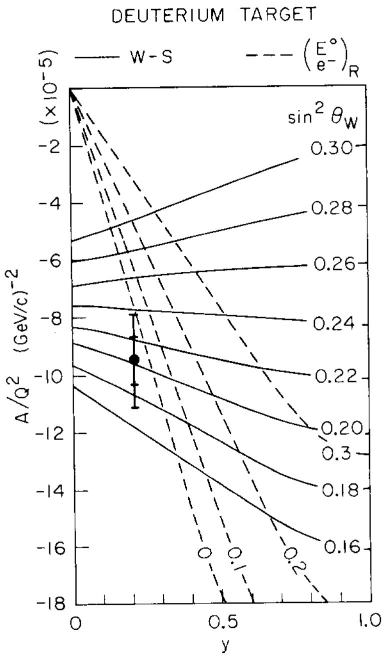

Fig. 4. Comparison of our result for deuterium with two SU(2) × U(1) predictions using the simple quark-parton model for nucleons. The outer error bars correspond to the error quoted in the text (eq. (6)). The inner error bars correspond to the statistical error. The y-dependence of A/Q^2 for various values of $\sin^2\theta_W$ is shown for two models: Weinberg–Salam (solid lines) and the hybrid model (dashed line).

group SU(2) × U(1). Within this framework the original Weinberg–Salam (W–S) model makes specific weak isospin assignments: the left-handed electron and quarks are in doublets, the right-handed electron and quarks are singlets [19]. Other assignments are possible, however. In particular, the "hybrid" or "mixed" model that assigns the right-handed electron to a doublet and the right-handed quarks to singlets has not been ruled out by neutrino experiments.

To make specific predictions for parity violation in inelastic electron scattering, it is necessary to have a model for the nucleon, and the customary one is the simple quark-parton model. The predicted asymmetries depend on the kinematic variable y as well as on the weak isospin assignments and on $\sin^2\theta_W$, where θ_W is the Weinberg angle. Fig. 4 compares our result for two SU(2) × U(1) models. The simplest model (W–S) is in good agreement with our measurement for $\sin^2\theta_W = 0.20 \pm 0.03$ which is consistent with the values obtained in neutrino experiments. The hybrid model is consistent with our data only for values of $\sin^2\theta_W \lesssim 0.1$.

We took a limited amount of data at 19.4 GeV using a liquid hydrogen target with the result

$$A/Q^2 = (-9.7 \pm 2.7) \times 10^{-5}\ (\mathrm{GeV}/c)^{-2}\ (\text{hydrogen}), \tag{7}$$

where the error contains both statistical and systematic uncertainties. A proton target provides a different mix of quarks and is expected to give a slightly smaller asymmetry than deuterium [7]. Our results are not inconsistent with this expectation.

It is a pleasure to acknowledge the support we received from many people at SLAC. In particular we would like to thank M.J. Browne, G.J. Collet, R.L. Eisele, Z.D. Farkas, H.A. Hogg, C.A. Logg and H.L. Martin for especially significant contributions.

References

[1] A. Love et al., Nucl. Phys. B49 (1972) 513.
[2] E. Derman, Phys. Rev. D7 (1973) 2755.
[3] W.W. Wilson, Phys. Rev. D10 (1974) 218.
[4] S.M. Berman and J.R. Primack, Phys. Rev. D9 (1974) 2171; D10 (1974) 3895 (erratum).
[5] M.A.B. Beg and G. Feinberg, Phys. Rev. Lett. 33 (1974) 606.
[6] S.M. Bilenkii et al., Sov. J. Nucl. Phys. 21 (1975) 657.
[7] R.N. Cahn and F.J. Gilman, Phys. Rev. D17 (1978) 1313; further references to the theory may be found in this reference.
[8] Y.B. Bushnin et al., Sov. J. Nucl. Phys. 24 (1976) 279.
[9] M.J. Alguard et al., Phys. Rev. Lett. 37 (1976) 1258, 1261; 41 (1978) 70.
[10] W.B. Atwood et al., SLAC preprint SLAC-PUB-2123 (1978).
[11] L.L. Lewis et al., Phys. Rev. Lett. 39 (1977) 795.
[12] P.E.G. Baird et al., Phys. Rev. Lett. 39 (1977) 798.
[13] L.M. Barkov and M.S. Zolotorev, Zh. Eskp. Teor. Fiz. Pis'ma 26 (1978) 379.
[14] E.L. Garwin, D.T. Pierce and H.C. Siegmann, Swiss Physical Society Meeting (1974), Helv. Phys. Acta 47 (1974) 393 (abstract only); the full paper is available as SLAC-PUB-1576 (1975) (unpublished).
[15] D.T. Pierce et al., Phys. Lett. 51A (1975) 465; Appl. Phys. Lett. 26 (1975) 670.
[16] P.S. Cooper et al., Phys. Rev. Lett. 34 (1975) 1589.
[17] Z.D. Farkas et al., SLAC-PUB-1823 (1976).
[18] R.S. Larsen and D. Horelick, in: Proc. Symp. on Beam intensity measurement, DNPL/R1, Daresbury Nuclear Physics Laboratory (1968); their contribution is available as SLAC-PUB-398.
[19] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264; A. Salam, in: Elementary particle theory: relativistic groups and analyticity, Nobel Symp. No. 8, ed. N. Svartholm (Almqvist and Wiksell, Stockholm, 1968) p. 367.