Measurement of Parity Violation in the Elastic Scattering of Polarized Electrons from ^{12}C

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We have measured the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from ^{12}C nuclei. Our result is $A_{\rm expt}=0.60\pm0.14\pm0.02$ ppm, where the first error is statistical and the second is systematic. With a beam polarization of 0.37, we compute the isoscalar vector hadronic coupling constant $\tilde{\gamma}$ to be $0.136\pm0.032\pm0.009$. The standard model predicts $\tilde{\gamma}=0.155$ at the tree level, in agreement with our data.

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Parity violation in the scattering of polarized electrons has played a vital role in our understanding of the electroweak interaction. Historically, the observation of parity violation in the deep-inelastic scattering of polarized electrons from deuterium[1] helped establish the validity of the SU(2)×U(1) form of the electroweak part of the standard model. The richness of the structure of neutral currents provides polarized electron scattering with great potential for exploring extensions of the standard model, on one hand, and the structure of weak hadronic currents, on the other. In contrast to deep-inelastic scattering where four-momentum-transfer (Q) values larger than 1 GeV/c are practical, elastic scattering is best carried out with Q between 0.1 and 1.0 GeV/c in order that the relevant form factors remain large. Since parity-violating asymmetries are typically proportional to Q^2, they may be extremely small, $\sim10^{-6}$–10^{-7}, for these experiments.

In this paper, we describe a successful measurement of the asymmetry in the elastic scattering of polarized electrons from ^{12}C nuclei, carried out at the MIT-Bates Linear Accelerator Center. We achieved a precision at the level of $\sim10^{-7}$. Our error is a factor of 5 smaller than that of the most sensitive previous electron experiment.[2] In order to achieve our result, we had to exercise extreme care in the control of systematic errors. The techniques we employed, which are described below, should also make future low-Q^2 experiments feasible.

The parity-violating asymmetry is defined as $A=(\sigma_R-\sigma_L)/(\sigma_R+\sigma_L)$, where σ_R (σ_L) is the differential cross section for the scattering of electrons with right (left) helicity. An attractive feature of our experiment is the lack of ambiguity in the theoretical interpretation of its result. Since ^{12}C is spinless and isoscalar, the relevant nuclear physics may be described by a single form factor which cancels in the asymmetry, a fact first noted by Feinberg.[3]

At energies where a phenomenological four-fermion interaction is appropriate, A may be expressed at the tree level as [3,4]

$$A=\tilde{\gamma}\tfrac{3}{2}G_FQ^2(\sqrt{2}\pi\alpha)^{-1},$$

where G_F is the Fermi coupling constant, α is the fine-structure constant, and $\tilde{\gamma}$ is the parity-violating coupling constant[5] for an axial-vector coupling to the electron and an isoscalar coupling to the hadronic constituents. In the standard model, $\tilde{\gamma}$ is given by $\frac{2}{3}\sin^2\theta_W=0.155$, where $\sin^2\theta_W=0.233\pm0.002$.[6] Since $\tilde{\gamma}$ is relatively small, it is particularly sensitive to possible extensions of the standard model which contain extra Z bosons.[7] A value for $\tilde{\gamma}$ may also be obtained by combining other experiments.[7] The main input for this analysis is results from precise studies of Cs,[8] which unfortunately require the computation of complex atomic wave functions for their quantitative interpretation. Hence we were motivated to measure $\tilde{\gamma}$ by a completely different method.

A schematic diagram of the apparatus is given in Fig. 1. We ran with a beam of energy 250 MeV, a scattering angle of about 35°, and a Q of 150 MeV/$c\equiv Q_0$. With a beam polarization $P_e=37\%$, the standard model predicts $A_{\rm expt}=AP_e=0.70\times10^{-6}$. The polarized source,[9] which provided an intense beam of electrons, was based on photoemission by polarized light from a GaAs crystal.[10] Light was provided by a cw Kr-ion laser modulated to

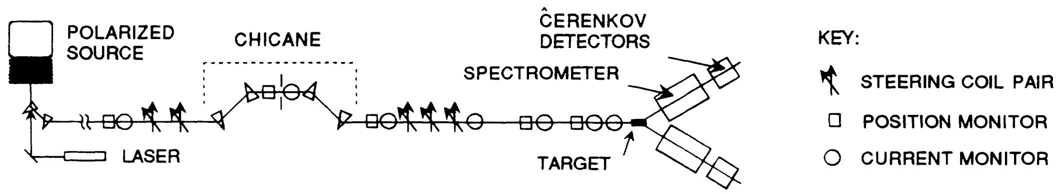

FIG. 1. Schematic diagram of the apparatus. The beam energy was measured in the chicane.

match the 1% duty factor of the accelerator. Although only moderate average laser power was available after modulation, we were able to provide a high average current, between 30 and 60 μA at the target, by achieving a high quantum efficiency of the crystal ($>1.5\%$). The helicity of the electron beam was controlled by the polarity of the voltage applied to a Pockels cell in the laser beam. A set of monitors in the beam line measured the characteristics of the beam: Seven toroid current monitors measured the intensity; four position monitors in front of the target determined the position and angle of the beam; and a position monitor located at a point where the beam was dispersed in momentum served to analyze the energy. The beam impinged on a 5-g/cm^2 carbon target, and the elastically scattered electrons were focused by a pair of single-quadrupole spectrometers onto Lucite Čerenkov detectors. Since about 10^5 electrons were detected during each 17-μs burst, individual events were not counted but rather the integrated responses over the beam burst were recorded by 16-bit analog-to-digital converters.

Since the accelerator was operated at 600 Hz locked to the 60-Hz line frequency, we reduced the noise associated with the 60-Hz frequency by first dividing the data into ten "times slots," corresponding to the 60-Hz subharmonics, and then analyzing the data for each time slot independently. We set the helicity of the beam quasirandomly for each pulse according to the following pattern. Ten random helicities were chosen, one for each time slot. The pattern was complemented for the next ten beam pulses, and ten asymmetries were computed, each based on a complementary pulse pair. This procedure was repeated every twenty pulses. Our accumulated data amounted to 307 half-hour runs, each of which filled a magnetic tape. With each time slot treated independently, we therefore generated 3070 individual "miniruns." We computed the statistical error for each minirun using the variance of the asymmetries. We note that about 1% of the data were rejected by loose cuts that identify accelerator malfunctions. A histogram of the result for each minirun normalized to its statistical error is presented in Fig. 2. The shape, as demonstrated by the solid curve also shown in the figure, is Gaussian with the expected width over more than two decades. Thus we believe that our statistical errors are well understood.

Correlations with helicity of various beam parameters, such as energy, position, and intensity, constitute the most important class of systematic errors associated with our experiment. We approached the control of these errors by minimizing helicity correlations during data collection and by correcting the asymmetries with the use of the position-monitor data during analysis.

We can identify two important causes of such correlations. First, the intensity of the laser light reaching the photocathode may depend slightly on helicity, thereby causing the energy of the electron beam to depend on the helicity through accelerator beam loading. Since electromagnetic cross sections depend strongly on energy, a spurious asymmetry results. One cause of the laser-intensity correlation is the polarization-induced transport-asymmetry (PITA) effect,[9] in which the transmission efficiency of the optical system from the Pockels cell to the photocathode depends upon helicity. A slight deviation in the voltage applied to the Pockels cell from quarter-wave retardation produces light that is slightly elliptical instead of perfectly circular in polarization. The transmission of elliptically polarized light through an optical system generally depends on the direction of the principal axis of the ellipse, which is different for the right- and left-handed beams, giving rise in our case to a helicity-dependent light intensity on the GaAs crystal.

A convenient feature of the PITA effect is that it can be controlled. By intentionally changing the voltage applied to the Pockels cell, we were able to change the appropriate phase and in turn control the intensity asymmetry. The response is ideal for the use of a slow feed-

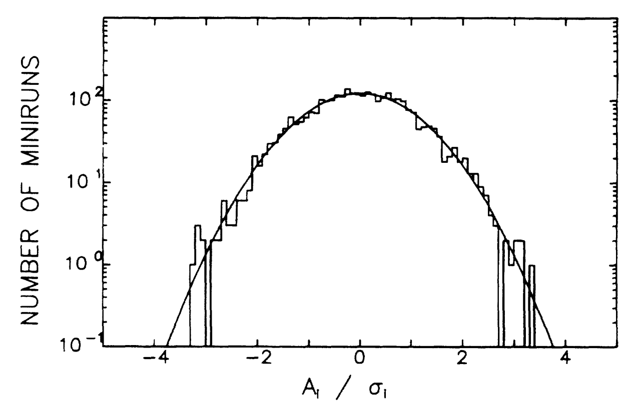

FIG. 2. Histogram of asymmetry A_i, normalized to its statistical error σ_i, for each of 3070 miniruns. The solid curve is a Gaussian of unit variance with area equal to the number of miniruns.

back loop. Indeed, we calculated the intensity asymmetry on-line every 3 min and used the result to correct the voltage applied to the Pockels cell. As a result, the intensity asymmetry averaged over the entire run was reduced to about 1 ppm.

The second cause of correlations is the helicity dependence of the position of the laser beam on the crystal, an effect which couples the trajectory of the electron beam to helicity. Since the number of detected events depends on the position and angle of the beam incident upon the target, spurious asymmetries result. One source of this problem is a deflection of the beam by the Pockels cell. By carefully aligning[11] the Pockels cell and by using point-to-point focusing of the Pockels cell onto the GaAs crystal, we were able to suppress this effect.

In our analysis, we corrected the raw asymmetries using the equation $A_{\rm expt}=A_{\rm raw}-\sum a_i \delta M_i$, where $A_{\rm raw}$ is the uncorrected asymmetry, δM_i are the differences in the beam monitors correlated with helicity, and a_i are correction coefficients, which are a measure of the sensitivity of the asymmetry to fluctuations in the beam parameters. We obtained data while the steering coils in the beam line were ramped and used the information to compute the correction coefficients involving the position and angle of the beam. Since there were large, real fluctuations in the beam current and hence the energy, we were able to use a correlation analysis to extract the coefficient involving energy. An energy vernier on one of the klystrons in the accelerator provided an independent test of our analysis. Since the a_i were obtained concomitantly with data taking, they are valid for our exact running conditions. Typical values for the a_i were <10 ppm/μm, and the position differences were <0.1 μm.

A different approach for detecting and eliminating systematic errors relies on the reversal of the helicity of the beam by an independent method. Using a half-wave plate, we changed the direction of the linear polarization of the laser light incident on the Pockels cell. Thus we were able to change the sign of the parity-violating asymmetry without altering the contribution of most of the unwanted effects.

A list of all of the corrections to our experimental asymmetry, together with their estimated uncertainties, is given in Table I. The root-mean-square value of the corrections arising from the position- and energy-monitor differences for individual runs is 0.3 ppm, and the average over the entire data sample is only 0.04 ppm. We paid careful attention to ground loops in order to reduce to a negligible level the amount of electronic cross talk arising from pulsing high voltage on the Pockels cell. We also determined limits for possible contributions of transverse polarization to the asymmetry by comparing the difference in the asymmetries measured with each (left and right) of the two spectrometers shown in Fig. 1. Systematic errors arising from nonlinearities in the electronics, helicity-dependent phase-space differences of the beam, and helicity-dependent backgrounds arising from beam electrons scattering from polarized electrons in magnetized iron are all estimated to be negligible.

TABLE I. Corrections for experimental asymmetry $A_{\rm expt}$ in ppm. The raw asymmetry is 0.56 ± 0.14.

Correction	Value	Error
Energy and position monitors	0.04	±0.006
Electronic cross talk	...	±0.001
Transverse polarization	...	±0.005
Nonlinearities	...	±0.007
Phase space	...	±0.006
Background from magnetized iron	...	±0.010
Net asymmetry	$0.60\pm0.14\pm0.02$	

An independent test of our method is the calculation of asymmetries that should be zero. For example, the result is 0.04 ± 0.14 ppm if we neglect the reversal of the half-wave plate. Also, the difference in the asymmetry between the two spectrometers is 0.14 ± 0.14 ppm.

Our result is $A_{\rm expt}=0.60\pm0.14\pm0.02$ ppm, where the first error is statistical and the second is systematic. To determine $\tilde{\gamma}$, we need to apply various scale factors, including the average effective Q^2, the beam polarization, and the backgrounds due to inelastic nuclear levels[12] and neutrons. These factors are given in Table II. We obtain $\tilde{\gamma}=0.136\pm0.032\pm0.009$, which is consistent with the prediction of the standard model.

Given our small systematic errors, significant improvements in the ^{12}C measurement are possible with a higher data rate. A factor-of-10–30 increase in solid angle, which could be obtained with the use of a large-acceptance spectrometer, together with substantially longer running time, would give a statistical error approaching 1%. Uncertainties in the theory, including hadronic contributions to the radiative corrections,[13] parity admixtures in nuclear states,[14] and isospin mixing,[15] should contribute well below this level. The only possible significant correction that we are aware of would be a large radius of the strange quarks in the nucleon,[16,17] which is a fundamental parameter of great interest in itself.

Another interesting experimental program which will benefit from the use of our techniques is elastic scattering from hydrogen.[18] The phenomenology is much richer, with different physics being emphasized at different angles and Q^2 values.[19] For example, an experiment at

TABLE II. Scale factors. The beam polarization was measured 24 times during the run by using Møller scattering.

Beam polarization P_e	0.37 ± 0.02
Nuclear structure	1.00 ± 0.01
Background	0.98 ± 0.02
$\langle Q^2\rangle/\langle Q_0^2\rangle$	1.00 ± 0.02

low Q^2 and large angles, which has been approved at the Bates Linear Accelerator Center, is sensitive to the possibility that strange quarks contribute to the static anomalous magnetic moment of the proton.[20] At more forward angles, the electric form factor of the neutron contributes.[21] At backward angles and low Q^2, the asymmetry is sensitive to poorly measured axial-vector hadronic coupling constants such as $\tilde{\beta}$. Finally, measurements at extremely forward angles may be used to extract a precise value for $\sin^2\theta_W$.[22]

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