

# New Measurement of Parity Violation in Electron-Quark Scattering

(The Jefferson Lab Hall A Collaboration)

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**Symmetry** permeates nature and is fundamental to all laws of physics. One example is mirror symmetry, also called “parity symmetry”: it implies that flipping left and right does not change the laws of physics. Laws for electromagnetism, gravity and the subatomic strong force respect parity symmetry, but the subatomic weak

force does not, as first pointed out by Lee and Yang [1] and observed by C.S. Wu [2]. Historically, the observation of parity violation played an important role in establishing the Standard Model of particle physics. We report here on a new measurement of the parity-violating asymmetry in electron-quark scattering and an extrac-

tion of a specific electron-quark weak coupling combination  $2C_{2u} - C_{2d}$  that is five times more precise than the earlier result. These results are the first evidence at more than the 95% confidence level that the  $C_{2q}$ 's are non-zero as predicted by the electroweak theory of particle physics, and lead to new constraints on interactions beyond the Standard Model, particularly on those due to reversing the quark chirality. In today's particle physics research focused on colliders such as the LHC, our results provide specific chirality information on electroweak theory that is difficult to obtain at high energies. The measurement is relatively free of ambiguity in its interpretation, and opens the door to even more precise measurements in the future.

In parity-violating electron scattering (PVES) experiments, one measures an asymmetry that can be expressed as

$$A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \quad (1)$$

where  $\sigma_R(\sigma_L)$  are the cross sections for scattering longitudinally polarized electrons that are in the right-handed (left-handed) helicity state, meaning their spins are parallel (antiparallel) to the electron's momentum. For deep inelastic scattering (DIS) from nuclear targets (DIS is defined as scattering in which the electron interacts with a single quark, almost independent of the surrounding quarks and gluons), this asymmetry can be written in a largely model-independent way as [3]

$$A_{\text{PV}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [a_1(x, Q^2)Y_1(x, y, Q^2) + a_3(x, Q^2)Y_3(x, y, Q^2)], \quad (2)$$

where  $G_F$  is the Fermi constant,  $\alpha$  is the fine structure constant,  $Q^2 \equiv -q^2$  with  $q$  the four-momentum transferred from the electron to the target,  $x$  is the Bjorken scaling variable and describes the fraction of momentum carried by the quark struck by the electron,  $y = (E - E')/E$  is the fractional energy loss of the electron with  $E(E')$  the incident (scattered) electron energy,  $Y_{1,3}$  are kinematic factors, and the variables  $a_{1,3}$  are related to the subatomic structure of the target. (See Supplementary Methods section for a complete description.) The first experiment (SLAC E122) to detect parity violation in electron scattering, led by C.Y. Prescott [4, 5], provided results that strongly favored a model attributed to Weinberg, Salam and Glashow [6–8], establishing it as the keystone of the now highly successful Standard Model of particle physics. PVES has subsequently been used as a sensitive probe to study diverse physics ranging from physics beyond the Standard Model [9, 10] to the structure of both nuclei [11] and the nucleon [12].

In so-called tree-level scattering where the electron exchanges only a single photon or a single  $Z$  boson with the target, very simple expressions for  $a_{1,3}$  in Eq. (2) emerge

for electron DIS from deuterium:

$$a_1 = \frac{6}{5} (2C_{1u} - C_{1d}), a_3 = \frac{6}{5} (2C_{2u} - C_{2d}). \quad (3)$$

The use of the deuterium target simplifies interpretation because it has equal numbers of up and down valence quarks. Here,  $C_{1u(d)}$  and  $C_{2u(d)}$  are the effective weak couplings between the electrons and the up (down) quarks. The subscripts 1 and 2 refer to whether the coupling to the electron or quark is vector or axial-vector in nature:  $C_{1u(d)}$  is the axial-vector-electron vector-quark (AV) coupling, *i.e.* it probes parity violation caused by the difference in the  $Z^0$  coupling between left- and right-handed electron chiral states;  $C_{2u(d)}$  is the vector-electron axial-vector-quark (VA) coupling that is sensitive to parity violation due to the different quark chiral states. In the Standard Model the  $C_1$  and the  $C_2$  couplings are proportional to the quark vector and axial weak charges, respectively. In testing the Standard Model it is important to determine all four  $C_{1u,d,2u,2d}$  as accurately as possible, since new interactions could manifest itself in either set of couplings. Experimentally, one could extract both  $2C_{1u} - C_{1d}$  and  $2C_{2u} - C_{2d}$  by measuring asymmetries at different  $Y_{1,3}$  values in the DIS regime. However, a precise determination of  $2C_{2u} - C_{2d}$  is difficult because of its small value in the Standard Model ( $-0.095$ ), as opposed to  $2C_{1u} - C_{1d} = -0.719$ .

The new measurement reported here was performed using the electron beam at Thomas Jefferson National Accelerator Facility (JLab), in Virginia, USA. A 100- $\mu$ A, nearly 90%-longitudinally-polarized electron beam was incident on a 20-cm-long liquid deuterium target held at a temperature of 22 K. Scattered particles were detected in a pair of magnetic spectrometers that determined the momentum and the direction of the detected particles to high precision [13]. To directly access  $C_{2u,2d}$ , the kinematics were chosen so that the bulk of the detected electrons emerged from the target after undergoing a DIS interaction. In contrast, all other PVES experiments after SLAC E122 were performed outside the DIS regime, and thus could not provide clean information on  $C_{2q}$ .

The size of the asymmetry expected for this measurement is at the level of  $10^{-4}$ . The major challenge comes from the combination of the high electron event rate, and the high pion background typical of DIS measurements. This was overcome by the use of a custom electronic and data acquisition (DAQ) system with built-in pion rejection capability [14]. The DAQ successfully counted electrons, event-by-event, at rates up to 600 kHz. The relative uncertainty in the measured asymmetries due to pion background was below  $5 \times 10^{-4}$ , and that due to counting deadtime was below 0.4%. The leading systematic effect comes from normalizing by the electron beam polarization, which had a relative uncertainty at the level of  $(1.2 - 1.8)\%$ . On the other hand, beam stability was not a significant issue because of recent advances in the

monitoring and feedback control of the beam, a direct outcome of some of the earlier PVES studies [9–12].

The high intensity of the JLab beam allowed the completion of the experiment in just under two months. A total of 35.4 million electrons were counted at two DIS kinematics. The asymmetry measured at  $E = 6.067$  GeV,  $\langle x \rangle = 0.241$ ,  $Y_1 = 1.0$ ,  $Y_3 = 0.44$  and  $\langle Q^2 \rangle = 1.085$  (GeV/c)<sup>2</sup> is

$$A_{\text{exp}} = [-91.1 \pm 3.1(\text{stat.}) \pm 3.0(\text{syst.})] \times 10^{-6}, \quad (4)$$

where  $\langle x \rangle$  and  $\langle Q^2 \rangle$  are averaged over the spectrometer acceptance. This is to be compared with the Standard Model (SM) expectation of  $A_{\text{SM}} = -87.7 \times 10^{-6}$ , with an uncertainty at the level of  $0.7 \times 10^{-6}$  which is dominated by the uncertainty in parton distribution functions (PDFs). To allow an extraction of  $C_{1u,1d}$  and  $C_{2u,2d}$ , it is necessary to express the asymmetry in terms of these couplings. This was calculated using the MSTW2008 leading-order PDF parametrization [15]. For the kinematics above, it gives  $A_{\text{SM}} = (1.156 \times 10^{-4}) [(2C_{1u} - C_{1d}) + 0.348(2C_{2u} - C_{2d})]$ , where the uncertainties of the coefficients for the  $(2C_{1u} - C_{1d})$  and the  $2C_{2u} - C_{2d}$  terms are at the relative levels of 0.5% and 5%, respectively. The second DIS kinematics was at  $E = 6.067$  GeV,  $\langle x \rangle = 0.295$ ,  $Y_1 = 1.0$ ,  $Y_3 = 0.69$ ,  $\langle Q^2 \rangle = 1.901$  (GeV/c)<sup>2</sup>, and the result is

$$A_{\text{exp}} = [-160.8 \pm 6.4(\text{stat.}) \pm 3.1(\text{syst.})] \times 10^{-6}. \quad (5)$$

The Standard Model expectation is  $A_{\text{SM}} = (-158.9 \pm 1.0) \times 10^{-6}$ . The coupling sensitivity is  $A_{\text{SM}} = (2.022 \times 10^{-4}) [(2C_{1u} - C_{1d}) + 0.594(2C_{2u} - C_{2d})]$ , with the same relative uncertainties as the first DIS kinematics. Details of the Standard Model calculation and the uncertainty due to PDF fits are given in the Supplementary Methods section.

Using the most recent world data for the coupling  $C_{1u,1d}$  [16], obtained from PVES and cesium atomic parity violation experiments [17–20], a simultaneous fit of  $2C_{1u} - C_{1d}$  and  $2C_{2u} - C_{2d}$  to our results and to the asymmetries from SLAC E122 was performed, yielding

$$\begin{aligned} (2C_{2u} - C_{2d})|_{Q^2=0} &= -0.145 \pm 0.066(\text{exp}) \\ &\quad \pm 0.011(\text{PDF}) \pm 0.012(\text{HT}) \\ &= -0.145 \pm 0.068(\text{total}). \end{aligned} \quad (6)$$

The third uncertainty is due to the so-called “higher-twist” (HT) effects caused by interactions among quarks inside the target. Additional theoretical uncertainties, including QED vacuum polarization and the  $\gamma Z$  box diagram, are negligible compared to the uncertainty due to the PDF fits. The zero- $Q^2$  values  $C_{2u,2d}|_{Q^2=0}$  are called  $g_{VA}^{eu,ed}$  (and similarly  $C_{1u,1d}|_{Q^2=0}$  are  $g_{AV}^{eu,ed}$ ) in Ref. [21], where electroweak and process-specific radiative corrections have been applied such that the values in Eq. (6) can be compared directly to results from other precision

experiments using different kinds of processes. The values for  $C_{2u,2d}|_{Q^2=0}$  differ from the values at the  $Q^2$  accessed in this experiment by 0.002–0.003 for both the up and the down quarks, at both kinematics.

The asymmetry results in Eqs. (4–5) can also be interpreted as a determination of the weak mixing angle, an important ingredient of the Weinberg-Salam-Glashow theory. The result, evolved to the mass of the  $Z$  boson in the modified minimal subtraction ( $\overline{\text{MS}}$ ) scheme, is  $\hat{s}_Z^2 \equiv \sin^2 \theta_W|_{(Q^2=M_Z^2, \overline{\text{MS}})} = 0.2299 \pm 0.0043$ . This can be compared to the latest Standard-Model fit to world data  $\hat{s}_Z^2 = 0.23126 \pm 0.00005$ .

The result in Eq. (6) is to be compared with the Standard Model prediction  $2C_{2u} - C_{2d}|_{Q^2=0} = -0.0950 \pm 0.0004$  as shown in Fig. 1. Our results have greatly improved the uncertainty on the effective vector-electron axial-quark weak couplings  $C_{2u,2d}$  and are in good agreement with the Standard Model prediction. This is also the first direct measurement of the coupling combination  $2C_{2u} - C_{2d}$  that shows a deviation from zero. We note that evidence for non-zero values of the  $C_{2u,2d}$ , possibly a different combination from what we measured, may have also been observed in experiments measuring the nucleon axial form factors [22]. However, extraction of  $C_{2u,2d}$  from the nucleon axial form factor is model-dependent, while in DIS the electron probes quarks unambiguously. The directness of our approach is an important feature that makes it possible to reach significantly higher accuracy in the future, such as through the PVDIS program planned for the 12 GeV Upgrade of JLab.

A comparison of the present result with the Standard Model predictions can be used to set mass limits  $\Lambda$  below which new interactions are unlikely to occur. For the cases of electron and quark compositeness and contact interactions, we used the convention of Ref. [23] and the procedure in Ref. [24]. The limit for the constructive (destructive) interference contribution to the Standard Model is:

$$\Lambda^\pm = v \left[ \frac{8\sqrt{5}\pi}{|(2C_{2u} - C_{2d})_{Q^2=0}|^\pm} \right]^{1/2}, \quad (7)$$

where  $|(2C_{2u} - C_{2d})_{Q^2=0}|^\pm$  is the difference between the Standard Model value and the upper (lower) confidence bound extracted from the data,  $v = \sqrt{\sqrt{2}/(2G_F)} = 246.22$  GeV is the Higgs vacuum expectation value setting the electroweak scale, and the  $\sqrt{5}$  is a normalization factor taking into account the coefficients of the  $C_{2u,2d}$  in the denominator. For a 95% confidence level, we extracted

$$\Lambda^+ = 5.8 \text{ TeV} \text{ and } \Lambda^- = 4.6 \text{ TeV}, \quad (8)$$

for constructive and destructive interference from beyond-the-Standard-Model physics. Figure 2 illustrates these limits. The limits set by  $C_{1u,1d}$  are determined

mostly by previous PVES and cesium atomic-parity-violation results, but this experiment has clearly improved the limits set by  $C_{2u,2d}$ .

The strength of our results reported here is that they isolate a well-defined combination of the electron-quark contact interaction. We note that mass limits on the electron-quark contact interactions have been published by ZEUS [25] and H1 [26] at HERA. They find  $\Lambda^+ = 3.3$  TeV and  $\Lambda^- = 3.2$  TeV [25]; and  $\Lambda^+ = 3.8$  TeV and  $\Lambda^- = 3.6$  TeV [26], respectively, on the vector-electron axial-vector-quark term. Similar limits have been published by ATLAS [27] at the LHC in the left-left isoscalar model, which are  $\Lambda^+ = 9.5$  TeV and  $\Lambda^- = 12.1$  TeV. To account for the different chirality structure of the models used, the HERA limits on the vector-electron axial-vector-quark model need to be scaled by  $2^{-1/4} = 0.84$ , while the LHC limits using the left-left isoscalar model need to be scaled by  $2^{1/4} = 1.19$  in order to compare to the mass limits extracted from  $C_{2u,2d}$ . The HERA and the LHC measurements are sensitive to several different vector and axial-vector coupling combinations, thus their limits were obtained with the assumption that besides the particular chirality combination used in the model, all other contact interactions are zero. This assumption is unnecessary for the extraction of mass limits from our results.

In summary, we have measured to a high precision the parity-violating asymmetry of electron-deuteron deep inelastic scattering and improved our knowledge of the effective electron-quark weak coupling combination  $2C_{2u} - C_{2d}$  by a factor of five. The results provide the first direct and unambiguous evidence that  $2C_{2u} - C_{2d}$  differs from zero at more than the 95% confidence level. They significantly improve the limits on certain types of interactions beyond the Standard Model in which it is the chirality of the quarks that is responsible for the observed parity violation.

## METHODS SUMMARY

The parity-violating asymmetry  $A_{\text{exp}}$  between right- and left-handed electrons was computed from the detected counts  $C$ , normalized by the beam intensity  $I$ , and integrated over periods of stable beam helicity. Two kinds of corrections were then made to the asymmetries: overall normalization factors and possible systematic shifts due to false asymmetries arising from backgrounds or helicity correlations in the beam parameters. The normalization factors include the beam polarization, measurements of scattered-electron kinematics, electromagnetic radiative corrections, and effects from two-photon exchange between the electron and target. The false-asymmetry corrections were all very small compared to our statistical error and included an evaluation of helicity correlations in beam current, position, and

energy; and backgrounds such as pions, scattering from the target aluminum windows, or rescattering inside the spectrometers. A summary of all corrections and the asymmetry results is presented in Table I of Supplementary Information.

To calculate the Standard Model expectation of the measured asymmetry and its sensitivity to  $2C_{1u} - C_{1d}$  and  $2C_{2u} - C_{2d}$ , we used parton distribution functions (PDFs) to calculate the structure functions in  $a_{1,3}$ . Three PDF fits were used. Results of the calculation are shown in Table II of Supplementary Information. The variation among all three fits is below relative 0.6% for the  $a_1$  term, and below relative 5% for the  $a_3$  term of the asymmetry. Effects from interactions among quarks inside the target, called “higher-twist effects”, were evaluated using the most recent theoretical bounds combined with data on neutrino structure functions. It was found that the uncertainty in the extraction of  $2C_{2u} - C_{2d}$  due to the higher-twist effects is at the same level as that due to the PDFs, and is quite small compare to the experimental uncertainties.

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FIG. 1: Results for  $(2C_{1u} - C_{1d})|_{Q^2=0}$  and  $(2C_{2u} - C_{2d})|_{Q^2=0}$  from this experiment (blue horizontal-line-hatched ellipse) compared with SLAC E122 (yellow ellipse) [4, 5]. The latest data on  $C_1$  [16] (from PVES and Atomic Cs [17–20]) are shown as the magenta vertical-line-hatched band. The green slanted-line-hatched ellipse shows the combined result of SLAC E122 and the latest  $C_1$ , while the red line-cross-hatched ellipse shows the combined result of SLAC E122, this experiment, and the latest  $C_1$ . The Standard Model value (with negligible uncertainty) is shown as the black dot, where the size in the dot is for visibility.

FIG. 2: Mass exclusion limits on the electron and quark compositeness and contact interactions obtained from the zero- $Q^2$  values of  $2C_{1u} - C_{1d}$  and  $2C_{2u} - C_{2d}$  at the 95% confidence level. The yellow contour shows the limit obtained from SLAC E122 asymmetry results [4, 5] combined with the best  $C_1$  values [16]. The red contour shows the limit with our new results added.

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**Competing Interests** The authors declare that they have no competing financial interests.

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