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Measurement of parity violation in electron–quark scattering

The Jefferson Lab PVDIS Collaboration*

Symmetry permeates nature and is fundamental to all laws of physics. One example is parity (mirror) symmetry, which 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[1,2]. Historically, parity violation in electron scattering has been important in establishing (and now testing) the standard model of particle physics. One particular set of quantities accessible through measurements of parity-violating electron scattering are the effective weak couplings C_{2q}, sensitive to the quarks' chirality preference when participating in the weak force, which have been measured directly[3,4] only once in the past 40 years. Here we report a measurement of the parity-violating asymmetry in electron–quark scattering, which yields a determination of $2C_{2u} - C_{2d}$ (where u and d denote up and down quarks, respectively) with a precision increased by a factor of five relative to the earlier result. These results provide evidence with greater than 95 per cent confidence that the C_{2q} couplings are non-zero, as predicted by the electroweak theory. They lead to constraints on new parity-violating interactions beyond the standard model, particularly those due to quark chirality. Whereas contemporary particle physics research is focused on high-energy colliders such as the Large Hadron Collider, our results provide specific chirality information on electroweak theory that is difficult to obtain at high energies. Our 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, an asymmetry is measured that can be expressed as

$$A_{\mathrm{PV}} = \frac{\sigma_{\mathrm{R}} - \sigma_{\mathrm{L}}}{\sigma_{\mathrm{R}} + \sigma_{\mathrm{L}}} \quad (1)$$

where $\sigma_{\mathrm{R}}(\sigma_{\mathrm{L}})$ are the cross-sections for scattering longitudinally polarized electrons that are in the right-handed R (left-handed L) 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[5]

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

where G_{F} is the Fermi constant, α 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 for a complete description.) The first experiment (SLAC E122) to detect parity violation in electron scattering[3,4] provided results that strongly favoured the model of refs 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 (ref. 12 and references therein).

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 equation (2) emerge for electron DIS from deuterium:

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

The use of the deuterium target simplifies the interpretation because it has equal numbers of up and down valence quarks. Here, $C_{1u(1d)}$ and $C_{2u(2d)}$ are the effective weak couplings between the electrons and the up (down) quarks, often collectively written as C_{1q} and C_{2q}. 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 (AV) combination of the electron's axial-vector weak charge and the quark's vector weak charge, that is, 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 (VA) combination of the electron's vector weak charge and the quark's axial-vector weak charge that is sensitive to parity violation due to the different quark chiral states. In testing the standard model it is important to determine all four $C_{1u,1d,2u,2d}$ as accurately as possible, because new interactions could manifest themselves 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 the Thomas Jefferson National Accelerator Facility (referred to here as Jefferson Lab), in Virginia, USA. A 100-μA, 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 system successfully counted electrons, event-by-event, at rates up to 600 kHz. The relative uncertainty in the measured asymmetries due to pion background was less than 5×10^{-4}, and that due to counting deadtime was less than 0.4%. The leading systematic uncertainty comes from the normalization by the electron beam polarization, which had a relative uncertainty of (1.2–1.8)%. Beam instability was

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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 Jefferson Lab beam allowed the completion of the experiment in just under two months. A total of about 170,000 million scattered electrons were counted at two DIS settings. 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^{-1})^2 was

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

where $\langle x\rangle$ and $\langle Q^2\rangle$ are averaged over the spectrometer acceptance, and stat. and syst. indicate statistical and systematic errors, respectively. This result is to be compared with the standard model (SM) expectation of $A_{\rm SM} = -87.7 \times 10^{-6}$, with an uncertainty of 0.7×10^{-6} dominated by the uncertainty in the parton distribution functions (PDFs), parameterizations of how partons (quarks and gluons) that form the nucleon carry the nucleon's energy. 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 relation was calculated using the MSTW2008 leading-order PDF parametrization[15]. For the kinematics above, it gives $A_{\rm SM} = (1.156 \times 10^{-4})$ $[(2C_{1u} - C_{1d}) + 0.348(2C_{2u} - C_{2d})]$, where the relative uncertainties of the coefficients for the $(2C_{1u} - C_{1d})$ and the $(2C_{2u} - C_{2d})$ terms are 0.5% and 5%, respectively. The second DIS setting 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^{-1})^2, and the result was:

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

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

Using the most recent world data for the coupling $C_{1u,1d}$ (ref. 16), obtained from PVES and caesium 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:

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

Here, exp. refers to the total experimental uncertainty, given by the statistical and the systematic uncertainties of the asymmetry results added in quadrature. The third uncertainty is due to the so-called higher-twist (HT) effects, caused by interactions among quarks inside the target. Further theoretical uncertainties, including QED vacuum polarization and the γZ box diagram, are negligible compared to the uncertainty due to the PDF fits. Electroweak and process-specific radiative corrections have been applied to calculate the values at zero-Q^2, $C_{2u,2d}|_{Q^2=0}$ called $g_{\rm VA}^{eu,ed}$ with e referring to electrons (and similarly $C_{1u,1d}|_{Q^2=0}$ called $g_{\rm AV}^{eu,ed}$) in ref. 21, so that the values in equation (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 those at both Q^2 accessed in this experiment by 0.002–0.003 for both the up and the down quarks.

The asymmetry results in equations (4) and (5) can also be interpreted as a determination of the weak mixing angle θ_W, an important ingredient of the electroweak unification of the standard model. The result, evolved to the mass of the Z boson in the modified minimal subtraction ($\overline{\rm MS}$) scheme, is $\hat{s}_Z^2 \equiv \sin^2\theta_{W(Q^2=M_Z^2,\overline{\rm MS})} = 0.2299 \pm 0.0043$, in agreement with the latest standard-model fit to world data, $\hat{s}_Z^2 = 0.23126 \pm 0.00005$.

The result in equation (6) is compared with the standard-model prediction $2C_{2u} - C_{2d}|_{Q^2=0} = -0.0950 \pm 0.0004$ in Fig. 1. Our results have greatly improved the uncertainty on the effective electron–quark VA 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 deviates from zero. We note that evidence for non-zero values of the $C_{2u,2d}$, possibly in a different combination from what we measured, may have 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, whereas in DIS the electron probes quarks unambiguously. The directness of our approach is essential to reach a significantly higher accuracy in the future, such as through the PVDIS programme planned for the 12 GeV upgrade of Jefferson Lab.

A comparison of the present result with the standard-model predictions can be used to set mass limits Λ 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:

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

where $\left|(2C_{2u} - C_{2d})_{Q^2=0}\right|^{\pm}$ is the difference between the standard-model value and the upper (lower) confidence bound of the data, $v = \sqrt{\sqrt{2}/(2G_{\rm F})} = 246.22$ 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.

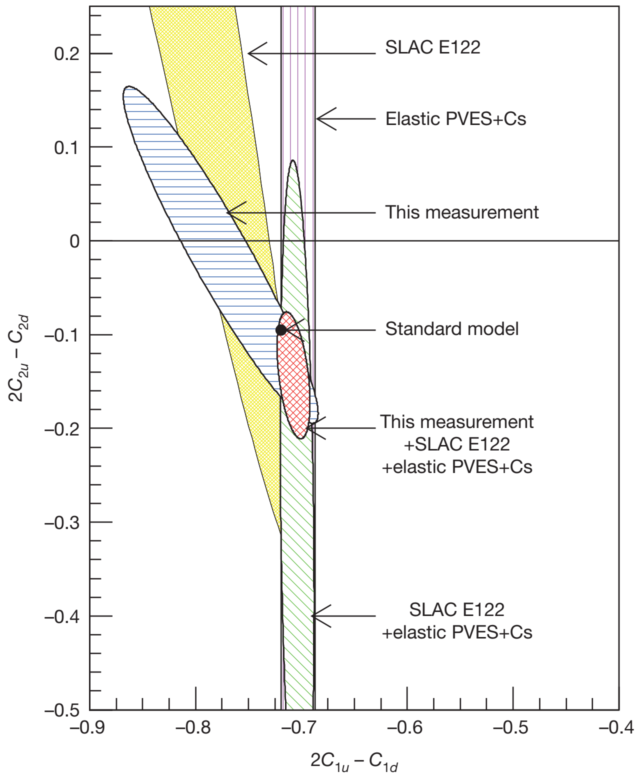

Figure 1 | Comparison of the present results with those of earlier experiments and predictions of the standard model. Values of $(2C_{1u} - C_{1d})|_{Q^2=0}$ and $(2C_{2u} - C_{2d})|_{Q^2=0}$ from this experiment (ellipse with blue horizontal hatching) are compared with those of SLAC E122 (yellow ellipse)[3,4]. The latest data on C_{1q} (from PVES[16] and atomic Cs[17–20]) are shown as the band with magenta vertical hatching. The ellipse with diagonal green hatching shows the combined result of SLAC E122 and the latest C_{1q}, while the ellipse with red cross-hatching shows the combined result of SLAC E122, this experiment, and the latest C_{1q}. The standard model value (with negligible uncertainty) is shown as the black dot, where the size of the dot is for visibility.

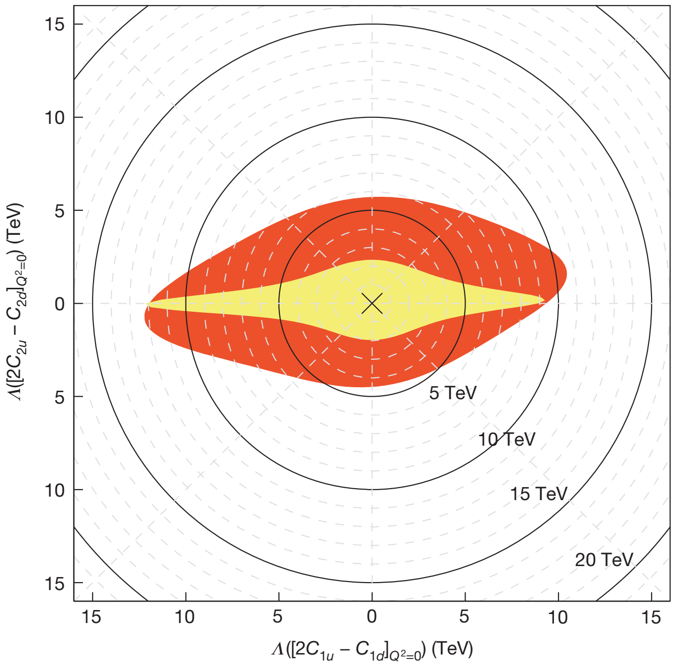

Figure 2 | Mass exclusion limits Λ on the electron and quark compositeness and contact interactions. These limits are obtained from the zero-Q^2 values of $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$ at the 95% confidence level. The outside of the yellow shape shows the limit obtained from SLAC E122 asymmetry results[3,4] combined with the best C_{1q} values[16]. The outside of the red shape shows the limit with our new results added. For visual guidance, mass limit scales in TeV are shown as solid and dashed circles.

For a 95% confidence level, we extracted

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

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 caesium atomic-parity-violation results, but this experiment clearly improves 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 interactions. We note that mass limits on the electron–quark contact interactions have been published by the ZEUS[25] and H1[26] collaborations at the Hadron–Electron Ring Accelerator, HERA. They find $\Lambda^+ = 3.3$ TeV and $\Lambda^- = 3.2$ TeV (ref. 25), and $\Lambda^+ = 3.8$ TeV and $\Lambda^- = 3.6$ TeV (ref. 26), respectively, on the electron–quark VA term. Similar limits of $\Lambda^+ = 9.5$ TeV and $\Lambda^- = 12.1$ TeV have been published by the ATLAS collaboration[27] at the LHC in the left-left isoscalar model. To account for the different chirality structure of the models used, the HERA limits on the electron–quark VA 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 be compared to the mass limits extracted from $C_{2u,2d}$. The HERA and the LHC measurements are sensitive to several different vector and axial-vector weak charge combinations, thus their limits were obtained with the assumption that, apart from 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. The chiral structure of the effective electron–quark weak couplings C_{2q} isolates 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_{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 the statistical error and included an evaluation of helicity correlations in beam current, position and energy, and backgrounds such as pions, scattering from the target aluminium windows, or rescattering inside the spectrometers. A summary of all corrections and the asymmetry results is presented in Supplementary Table 1.

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 PDFs to calculate the structure functions in $a_{1,3}$. Three PDF fits were used. Results of the calculation are shown in Supplementary Table 2. The relative variation among all three fits is less than 0.6% for the a_1 term, and less than 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 compared to the experimental uncertainties.

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Supplementary Information is available in the online version of the paper.

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Author Contributions Authors contributed to one or more of the following areas: proposing, leading, and running the experiment; design, construction, optimization, and testing of the data acquisition system; data analysis; simulation; extraction of the physics results from measured asymmetries; and the writing of this Letter.

Author Information J.E. is currently on sabbatical leave at the PRISMA Cluster of Excellence and MITP, Johannes Gutenberg University. Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to X.Z. (xz5y@virginia.edu).

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