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Parity Violation Deep Inelastic Scattering Experiments at Jefferson Lab with 6 GeV Electrons

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We report on the measurement of parity-violating asymmetries in the nucleon resonance and deep inelastic scattering (DIS) regions for longitudinally polarized electrons scattered from unpolarized deuterons. The effective weak couplings, denoted by C_{2q}, are accessible through the measured inclusive DIS asymmetries. In these proceedings, we present a measurement of the parity-violating asymmetry, from which a determination of $2C_{2u}$ - C_{2d} with an improved precision of a factor of five relative to the previous result was achieved. This result indicates evidence with 95% confidence that the $2C_{2u}$ - C_{2d} is non-zero. This experiment also provides the first parity-violation data covering the full resonance region, which provides constraints on nucleon resonance models. Finally, the program to extend these measurements at Jefferson Lab in the 12 GeV era using the Solenoidal Large Intensity Device is also mentioned.

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1. Introduction to Parity-Violating Electron Scattering

The parity-violating electron scattering (PVES) asymmetry for the scattering of longitudinally polarized electrons from unpolarized protons can be expressed in terms of the cross section difference for right- and left-handed electrons, $A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where σ_h is the cross section for positive helicity ($h = +1$) or negative helicity ($h = -1$). In the case of positive helicity, the electrons are polarized parallel to their momentum, and for negative helicity, antiparallel to their momentum. This observable is highly sensitive to studies beyond-the-standard-model physics and the structure of both nuclei and nucleons [1].

The general expression for the PVES inelastic asymmetry on a nucleon or nuclear target is related to the electromagnetic structure functions and the electroweak γZ interference structure functions. The full expression for A_{PV} can be found in Refs. [2, 3], where $F_{1,2}^{\gamma Z}$ are the vector γZ interference structure functions, and $F_3^{\gamma Z}$ is the axial-vector γZ interference structure function. $F_1^{\gamma\gamma}$ and $F_2^{\gamma\gamma}$ are the electromagnetic structure functions. These structure functions are functions of two variables: either taken to be Q^2 and the Bjorken scaling variable x or Q^2 and the invariant mass $W = \sqrt{M^2 - Q^2 + 2M\nu}$, where ν is the energy transfer and M is the mass of the proton.

The interference structure functions can be calculated from either parton distribution functions (PDFs) in the case of DIS or nucleon and nuclear models for elastic scattering or the nucleon resonance region. These calculations provide predictions for the asymmetries that can be compared against the measured values, and the predictions can then be used to extract electroweak quantities or to test the models used in the calculations.

In deep inelastic scattering (DIS), the PVES asymmetry can be expressed (mostly model-independent) in terms of the variables $a_{1,3}\left(x, Q^2\right)$:

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1\left(x,Q^2\right)Y_1\left(x,y,Q^2\right) + a_3\left(x,Q^2\right)Y_3\left(x,y,Q^2\right)\right], \tag{1.1}$$

where G_F is the Fermi constant, α is the electromagnetic fine-structure constant, x is the Bjorken scaling variable, y is the fractional energy loss of the electron, and Q^2 is the four-momentum transferred squared. The $a_{1,3}\left(x, Q^2\right)$ variables are related to the subatomic structure of the nucleus and the neutral-weak axial and vector coupling of the electron and the quark, and $Y_{1,3}$ are kinematic factors.

In the approximation where the electron exchanges only a single photon or Z boson with the target, simple expressions for $a_{1,3}$ can be written for a deuteron target in the valence quark model:

$$a_1 = \frac{6}{5}\left(2\mathrm{C}_{1\mathrm{u}} - \mathrm{C}_{1\mathrm{d}}\right), a_3 = \frac{6}{5}\left(2\mathrm{C}_{2\mathrm{u}} - \mathrm{C}_{2\mathrm{d}}\right). \tag{1.2}$$

The $\mathrm{C}_{1u(1d)}$ and $\mathrm{C}_{2u(2d)}$ represent the effective weak couplings between electrons and up (down) quarks. Sometimes, they are collectively expressed as C_{1q} and C_{2q}. The indices 1 and 2 correspond to if the coupling to the electron or quark is vector or axial-vector. C_{1q} is the (AV) combination of the electron's axial-vector weak charge and the quark's vector weak charge. Then C_{2q} is the (VA) combination of the electron's vector weak charge and the quark's axial-vector weak charge. Elastic PVES directly probes the C_{1q} couplings, and though it is possible to extract the C_{2q} couplings from the nucleon axial form factor (G_A), the extraction is model dependent. However the C_{2q}, which

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are sensitive to PV due to the quark chiral states, can be directly accessed in DIS. The SLAC E122 experiment [4] was the first PVES experiment and provided the first measurement for $\sin^2\theta_w$. It also established the gauge model of Weinberg, Glashow, and Salam as the correct theory for the electroweak interactions.

2. Experimental Procedure

The reported measurements were conducted using a longitudinally-polarized electron beam at Jefferson Lab in Hall A. The data were acquired with incident electron energies of 4.867 GeV and 6.067 GeV, and the beam current was $100-105\ \mu$A with approximately 90% polarization. The electrons were scattered off of a 20-cm long liquid deuterium target, which was controlled at a temperature of 22 K. The scattered electrons were detected in a pair of spectrometers [5] that provided high precision measurements of their momentum and angle. For a significant amount of the run period, the spectrometers were set to detect DIS electrons [6]; however, additional data were also collected in four kinematic settings, which covered the entire nucleon resonance region [7]. These data provide constraints on nucleon resonance models, and for the first time, they also exhibited a feature known as "quark-hadron duality" [8] of electroweak observables. A specially designed data acquisition (DAQ) system and the accompanying electronics were constructed to handle the high electron rates (up to 600 kHz) and reject pion produced backgrounds. The details on the design and performance of this system were reported in [9].

3. Results

3.1 Deep inelastic region

In Fig. 1, the correlation plot of $2C_{2u}$ - C_{2d} versus $2C_{1u}$ - C_{1d} at $Q^2 = 0$ is shown as extracted from the measured asymmetry. The details of the extraction are presented in Ref. [6]. The new results are represented by the ellipse labeled "This measurement". The yellow ellipse shows the results from the SLAC 122 experiment. The vertical band is the latest C_{1q} results [10]. The red ellipse is the combined result from all published measurements. The standard model expected value is represented by the black dot, which is in good agreement with the combined results. With the new results included, $2C_{2u}$ - C_{2d} deviates from zero by 2σ.

The extracted values of $2C_{1u}$ - C_{1d} and $2C_{2u}$ - C_{2d} can be used to determine mass limits Λ below which new interactions are not likely to occur. The mass exclusion limits on the electron and quark compositeness and contact interactions are plotted in Fig. 2. The yellow region shows the determined limits from the SLAC E122 data and the best values for C_{1q}, whereas the boundaries of the red shape indicate the updated mass limits determined with the recent data presented in these proceedings. At a 95% confidence level, the extracted limits for constructive and destructive interference from beyond-the-standard-model physics are Λ^+ = 5.8 TeV and Λ^- = 4.6 TeV, respectively.

3.2 Nucleon resonance region

For the resonance region, data at four kinematic settings were taken centered at W = 1.263, 1.591, 1.857, and 1.981 GeV with values of Q^2 below 1 GeV^2 for the three lowest W regions and

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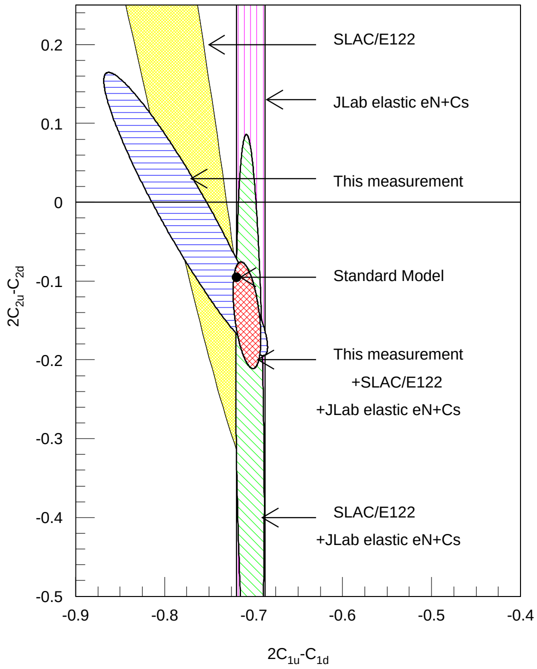

Figure 1: (color online) Comparison of current results (blue ellipse) compared with earlier experiments for the effective weak couplings. See text for details. Reproduced from Ref. [6].

Q^2 = 1.472 GeV^2 for the highest W region. A summary of the measured asymmetries with detailed kinematics and corrections can be found in Table I of Ref. [7]. Figure 3 displays the measured PV asymmetries, scaled by $1/Q^2$, from $\vec{e}$-^{2}H scattering in the resonance region versus W. The vertical error bars represent the statistical uncertainties, and the horizontal lines indicate the RMS value of the W coverage for each bin. Then the shaded bands near the bottom of the graph show the experimental systematic uncertainties. The measured asymmetries are consistent with the three resonance models [11, 12, 3]. In the figure, theory A (dashed lines), theory B (dotted lines) and theory C (solid lines) correspond to Refs. [11], [12] and [3], respectively. For theories B and C, three curves are shown, which indicate the upper and lower bands and central values of the two calculations. In addition, these data agree well with the DIS estimation (dash-double-dotted lines) from the CTEQ-Jefferson Lab (CJ) [13] PDF fits. The agreement with the DIS calculation indicates that quark-hadron duality holds at the $10-15\%$ level throughout the entire resonance region.

4. Future Perspectives

With the upgrade of the Jefferson Lab electron beam, the PVDIS program will continue with the Solenoidal Large Intensity Device (SoLID) [14]. This device is a multi-purpose spectrometer with physics topics including PVDIS on proton and deuteron targets, semi-inclusive DIS on polarized proton and ^{3}He targets and threshold J/ψ production. The main motivation for the PVDIS experiment is to investigate possible new interactions beyond the Standard Model and to measure the PDF ratio d/u at high x. The experiment will obtain data over a wide kinematic range: $x > 0.2$,

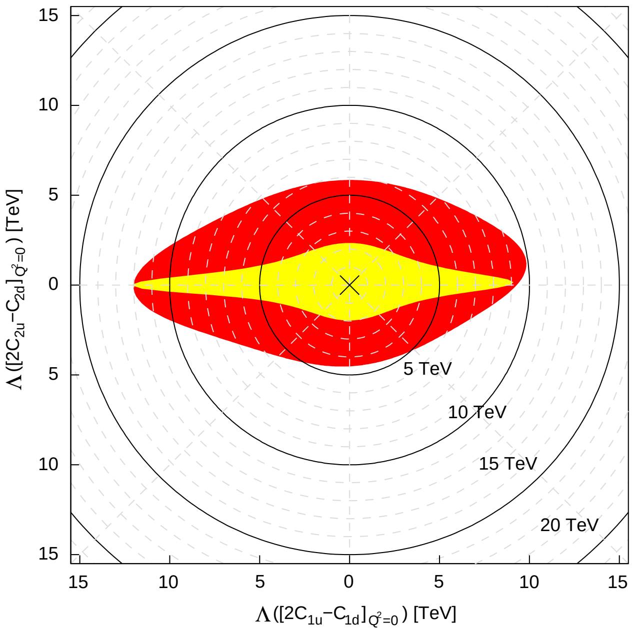

Figure 2: (color online) The mass exclusion limits on electron and quark compositeness and contact interactions. The outer edge of the yellow region shows the limits that were obtained from the SLAC 122 results combined with the best measurements [10] of C_{1q}. The outer edge of the red region illustrates the updated limits with the results presented in these proceedings. The solid and dashed circles indicate the mass limit scales in TeV. Reproduced from Ref. [6].

$2\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$ and will improve the measurement of the effective weak couplings (C_{2q}) by one order of magnitude compared with the 6 GeV results presented here.

5. Summary

In conclusion, recent measurements of the parity-violating asymmetries, including the nucleon resonance region and the deep-inelastic regime were reported. We have improved our knowledge on the electron-quark VA effective coupling term $2\mathrm{C}_{2u}$ - C_{2d} by a factor of five. This result provides the first evidence that $2\mathrm{C}_{2u}$ - C_{2d} deviates from zero at the 2σ level and is in agreement with the standard model prediction. Additionally, the nucleon resonance asymmetries agree with DIS-based calculations, indicating for the first time that quark-hadron duality may also exist in electroweak observables. The resonance data provide constraints on nucleon resonance models, which are relevant for background estimations to elastic PVES measurements [15]. Finally, the construction of SoLID will allow us to continue these measurements and improve our knowledge on C_{2q} by another order of magnitude with the upgraded Jefferson Lab 12-GeV electron beam, .

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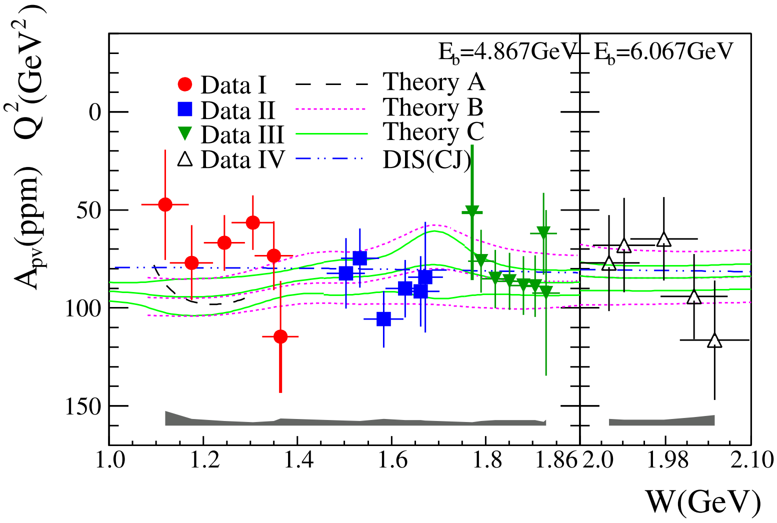

Figure 3: Invariant mass dependence of the measured $\vec{e}$-^{2}H parity-violating asymmetries in the nucleon resonance region. The DIS calculation uncertainties are less than 1 ppm and too small to be seen. See text for details. Reproduced from Ref. [7].

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