Accessing Neutral Weak Coupling C_{3q} Using Polarized Positron and Electron Beams at Jefferson Lab

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Abstract. Electroweak neutral weak couplings are important parameters of the Standard Model of particle physics. The product of lepton and quark couplings, C_{1q}, C_{2q} and C_{3q}, can be accessed from lepton scatterings via either parity violation or charge conjugate violations. In contrast to $C_{1,2q}$ for which experiments have been planned to improve their precisions, the C_{3q} couplings have only been measured at limited facilities due to difficulties in comparing scattering cross sections between lepton and anti-lepton beams. In this document, the current knowledge on $C_{1,2,3q}$ are reviewed first, followed by a sensitivity study of C_{3q} measurement using a possible positron beam at Jefferson Lab.

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NEUTRAL WEAK COUPLINGS

In the Standard Model, electroweak interactions are described by the gauge group SU(2)$_L\times$U(1)$_Y$. Here the SU(2)$_L$ group describes interactions that couple to only left-handed fermions and is described by the weak isospin T, and the U(1)$_Y$ group describes those couple equally to left- and right-handed fermions and is described by the weak hyper charge Y. The two quantum numbers can be related to each other as $T^3+Y/2=Q$ where Q is the electric charge of the particle and T^3 is the 3^{rd} component of the weak isospin. Although the observed charged weak currents, carried by the $W^\pm$ bosons, can be described within the SU(2)$_L$ group, the observed neutral weak and the electromagnetic currents, carried by the Z^0 boson and the photon, respectively, need to be described by linear combinations of the neutral current J^3_μ of the SU(2)$_L$ and the j^Y_μ current of the U(1)$_Y$ group:

$$j^{em}_\mu = J^3_\mu + \frac{1}{2} j^Y_\mu\ , \qquad J^{NC}_\mu = J^3_\mu - \sin^2\theta_W\, j^{em}_\mu\ , \tag{1}$$

where θ_W is the Weinberg or the weak mixing angle which can be determined by experiments.

In this framework, the weak neutral currents of fermions have different left- and right-handed components. This causes the parity symmetry to be violated in weak interactions. For neutrinos, leptons and quarks, respectively, the weak neutral currents are given as:

$$J_\nu = \frac{1}{2}\bar{\nu}\gamma_\mu(1-\gamma^5)\nu\ ,\ \ J_l = \frac{1}{2}\bar{l}\gamma_\mu(g^e_V - g^e_A\gamma^5)l\ , \qquad J_q = \frac{1}{2}\bar{q}\gamma_\mu(g^q_V - g^q_A\gamma^5)q\ , \tag{2}$$

where $g_{V(A)}$ is the vector (axial) coupling of fermions, and in the Standard Model can be related to the weak mixing angle $\sin^2\theta_W$.

Experimentally, parity violation observables can be used to access the lepton or quark neutral weak couplings. Since each neutral weak coupling can be used to extract the weak mixing angle, whether they all provide a single and ubiquitous value for $\sin^2\theta_W$ provides a test of the integrity of the current Standard Model. On the other hand, it is believed that the current Standard Model is not the ultimate theory, but instead is only a subset of a larger theoretical framework, which ultimately describes all four interactions. In other words, the current Standard Model might be only a “low energy” approximation. From this point of view, measurements of the neutral weak couplings and extractions of the weak mixing angle will provide a window to access these New Physics, should their results deviate from the present Standard Model predictions.

ACCESSING NEUTRAL WEAK COUPLINGS IN CHARGED LEPTON SCATTERING

The neutral weak Lagrangian for electron scattering contains the following terms:

$$\begin{aligned} L_{NC}^{e^- scatt.} &= \sum_q \left[c_A^e c_V^q \bar{e}\gamma^\mu\gamma_5 e\bar{q}\gamma_\mu q + c_V^e c_A^q \bar{e}\gamma^\mu e\bar{q}\gamma_\mu\gamma_5 q + c_A^e c_A^q \bar{e}\gamma^\mu\gamma_5 e\bar{q}\gamma_\mu\gamma_5 q\right] \\ &= \sum_q \left[C_{1q}\bar{e}\gamma^\mu\gamma_5 e\bar{q}\gamma_\mu q + C_{2q}\bar{e}\gamma^\mu e\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\bar{e}\gamma^\mu\gamma_5 e\bar{q}\gamma_\mu\gamma_5 q\right] , \end{aligned} \tag{3}$$

where $C_{1q} \equiv c_A^e c_V^q$, $C_{2q} \equiv c_V^e c_A^q$ and $C_{3q} \equiv c_A^e c_A^q$. The Standard Model predictions for u and d quarks are:

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) , \quad C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) , \qquad C_{3u} = \frac{1}{2} , \tag{4}$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) , \qquad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) , \qquad C_{3d} = -\frac{1}{2} . \tag{5}$$

Among the three terms on the r.h.s. of Eq. (3), the first two terms are parity-violating and will induce a cross section asymmetry between left- and right-handed electron scattering off unpolarized nuclear or nucleon targets, while the third term is charge-conjugate-violating but does not violate parity, and can only be accessed by comparing cross sections of lepton to anti-lepton scatterings.

Current experimental status on C_{iq} was summarized on Table 6 of Ref.[1], and is illustrated in Fig. 1. Compared to $C_{1,2q}$, experimental data on C_{3q} are sparse: There exist only two measurements using comparisons of polarized muon vs. anti-muon deep inelastic scattering (DIS) cross sections off a carbon target at CERN [2, 3]. Using a uncertainty of ± 0.24 for $2C_{2u} - C_{2d}$, the constraint on $2C_{3u} - C_{3d}$ is found to be ± 0.490 from the CERN 200 GeV data. Our knowledge on C_{3q} can be improved by comparing polarized electron vs. positron DIS cross sections should a high luminosity polarized positron beam becomes available.

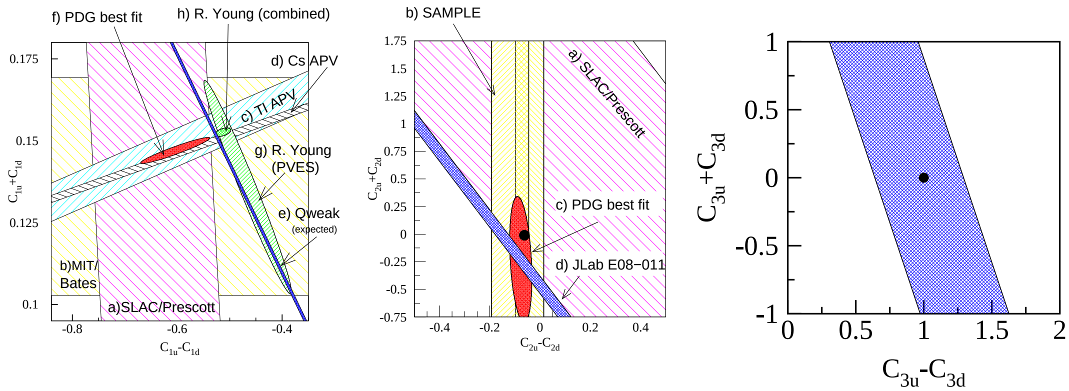

FIGURE 1. The current experimental knowledge of the effective couplings C_{1q} (left), C_{2q} (middle) and C_{3q} (right). The latest world fits for C_{1q} are given by PDG 2008 [4] (f), Ref. [5] (g), and Ref. [6] (h), and will be tested to a high precision in the near future at Jefferson Lab (JLab) [7]. The latest world fit for C_{2q} is given by PDG 2008 [4](c). An experiment is being planned at JLab [8] using the present 6 GeV electron beam to improve our knowledge on $2C_{2u} - C_{2d}$ by a factor of six. See Ref. [8] for explanations of other experimental results. The only experimental result for C_{3q} is drawn based on data from CERN using a 200 GeV muon beam [2, 3]. The Standard Model prediction for C_{2q} and C_{3q} are shown as solid circles.

ACCESS TO C_{3q} USING POLARIZED e^-, e^+ SCATTERING

Formalism in Ref. [9] are used to derive the C-violating asymmetry in electron vs. positron DIS. The observable of interest is:

$$A^{l_L^- - l_R^+} = \frac{d\sigma\left(l_L^- + N \to l_L^- + X\right) - d\sigma\left(l_R^+ + N \to l_R^+ + X\right)}{d\sigma\left(l^- + N \to l^- + X\right) + d\sigma\left(l^+ + N \to l^+ + X\right)} \qquad (6)$$

where l^- and l^+ are electrons and positrons beams, respectively, and the subscript L, R denotes the helicity of the beam. The DIS parity-violating asymmetry, which has been measured at SLAC [10, 11] and will be measured soon at JLab [8], was also derived in Ref. [9] as the observable:

$$A^{l_L^- - l_R^-} = \frac{d\sigma\left(l_L^- + N \to l_L^- + X\right) - d\sigma\left(l_R^- + N \to l_R^- + X\right)}{d\sigma\left(l_L^- + N \to l_L^- + X\right) + d\sigma\left(l_R^- + N \to l_R^- + X\right)} . \qquad (7)$$

By comparing these two asymmetries, and to the PVDIS asymmetries in Ref. [8], it is found that to a good approximation, the C-violating asymmetry for the proton is:

$$A_p^{e_L^- - e_R^+} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{2C_{2u}u_V - C_{2d}d_V + 2C_{3u}u_V - C_{3d}d_V}{4u+d} , \qquad (8)$$

where G_F is the Fermi constant, Q^2 is the four-momentum transfer square, $y = \nu/E$ with E the lepton beam energy and ν the lepton energy transfer to the target, u, d, s the parton distribution functions, and $q_V \equiv q - \bar{q}$ are the corresponding valence quark distributions with $q = u, d$. Similarly, the C-violating asymmetry for the deuteron is:

$$A_d^{e_L^- - e_R^+} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d})R_V}{5}, \tag{9}$$

where $R_V \equiv (u_V + d_V)/(u + d)$. Note that contributions from s and c quarks have been neglected in this derivation.

Assuming no significant hadronic effects are present in $A_d^{e_L^- - e_R^+}$ (this might be a strong assumption given that some sizable effects have already been discussed during this Workshop), one can in principle measure the C-violating asymmetry using either a hydrogen or a deuterium target and extract $2C_{3u} - C_{3d}$. However, in order to minimize the uncertainty from ratio d/u, deuterium targets are preferred. The asymmetry $A_d^{e_L^- - e_R^+}$ in fact is very sensitive to C_{3q} since contributions from C_{2q} are rather small. Putting in G_F and ignoring the two C_{2q} terms one has

$$A_d^{e_L^- - e_R^+} = \frac{y(2-y)}{2}(108\text{ ppm})Q^2 R_V (2C_{3u} - C_{3d}) \tag{10}$$

Using the kinematic setting in Ref.[12]: $E = 11$ GeV, $Q^2 = 3.3$ (GeV/c)^2, $W^2 = 7.3$ GeV^2, $E' = 6.0$ GeV and the Bjorken scaling variable $x = 0.34$, one has $A_d^{e_L^- - e_R^+} \approx 169$ ppm. This asymmetry can be measured to a 3% statistical precision using a 40-cm long liquid deuterium target within 30 days if one can be provided a polarized positron beam interchangeably with the polarized electron beam. The beam current needed will be $3 \sim 5$ μA with a 80% or better polarization. In addition, the beam quality difference between the electron and the positron beams, such as current, position, direction and spot size, need to be controlled to the level of helicity-correlated beam quality differences being maintained for parity-violation experiments at JLab presently. This 3% measurement on $A_d^{e_L^- - e_R^+}$ will determine $2C_{3u} - C_{3d}$ to a relative uncertainty of 3%, i.e. a factor of 10 improvement to the current knowledge on this combination.

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