PVDIS: 6 GeV Results and the SoLID Program

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- PVDIS and electron-quark effective couplings
- The 6 GeV PVDIS experiment
- PVDIS with SoLID
Basics of Electron Scattering on a Fixed Nuclear Target

\[ \lambda = \frac{hc}{6 \text{GeV}} = 0.2 \text{ fm} \]

Before

\begin{itemize}
  \item Electron beam
  \item Target (at rest)
\end{itemize}

\begin{itemize}
  \item \textbf{Inclusive:} only the scattered electron is detected
\end{itemize}

After

\begin{itemize}
  \item Recoil
  \item To detector
\end{itemize}
Three Kinematics Regions of Electron Scattering

“Elastic”: $W = M_+ \text{ or } M_p$
(form factors - fourier transformation of the charge distribution in the nucleon)

“Deep Inelastic”: $W > 2 \text{ GeV}$,
(structure functions, parton distribution functions)

“Resonance”: $1 < W < 2 \text{ GeV}$

$x = 10^{-18} \text{ m or smaller}$
Parity Violation in the Standard Model
Measuring PVES Asymmetry

\[ \lambda = \frac{hc}{6 \text{GeV}} = 0.2 \text{ fm} \]

Electron beam to detector

Target (at rest)

Inclusive: only the scattered electron is detected

Change helicity of the electron beam

Count how many electrons are scattered, using the same detector system
In weak interaction, all elementary fermions behave differently under parity transformation.

They have a preferred chiral state when coupling to the $Z^0$. 

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Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges:  $g_V \sim (g_L + g_R)$  $g_A \sim (g_L - g_R)$

Parity Violation in the Standard Model

\[ -i \frac{g_Z}{2} \gamma^\mu [g_V^e - g_A^e \gamma^5] \]

\[ g_V^f = I_3 - 2Q \sin^2 \theta_W \]

\begin{align*}
\text{fermions} & & g_A^f = I_3 & & g_V^f = I_3 - 2Q \sin^2 \theta_W \\
\nu_e, \nu_\mu & & \frac{1}{2} & & \frac{1}{2} \\
e^-, \mu^- & & -\frac{1}{2} & & -\frac{1}{2} + 2 \sin^2 \theta_W \\
u, c & & \frac{1}{2} & & \frac{1}{2} - \frac{4}{3} \sin^2 \theta_W \\
d, s & & -\frac{1}{2} & & -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W
\end{align*}
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V (g_L + g_R)$, $g_A (g_L - g_R)$

PVES asymmetry comes from $V(e) \times A(\text{targ})$ and $A(e) \times V(\text{targ})$
Effective Couplings in the Standard Model

Unlike electric charge, need two charges (couplings) for weak interaction: $g_L$, $g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

\[ C_{1q} \equiv 2g^e_A g^q_V, \quad C_{2q} \equiv 2g^e_V g^q_A \]

“electron-quark effective couplings”

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Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$.

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

\[ C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q \]

“electron-quark effective couplings”
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

$$C_{1q} = 2 g_A^e q, C_{2q} = 2 g_V^e q$$

“electron-quark effective couplings”

$$C_{1q} = g_{AV}^e q, C_{2q} = g_{VA}^e q$$

Accessing $C_{1q,2q}$

- Need electron beam on hadronic target
- In elastic PVES
  - directly probes $C_{1q}$, electrons' parity-violating property;
  - quarks' parity-violation is represented by the nucleon axial form factor $G_A$, and extracting $C_{2q}$ from $G_A$ is model-dependent
- Only in PVDIS, electron probes the quark and PVDIS asymmetry depends on $C_{2q}$ directly.
Formalism for Parity Violation in DIS

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \left[ a(x) + Y(y) b(x) \right] \]

\[ a(x) = \frac{1}{2} g_A^e \frac{F_1^\gamma}{F_1^\gamma} = \frac{1}{2} \sum_i C_{1i} Q_i q_i^+(x) \]

\[ b(x) = g_V^e \frac{F_3^\gamma}{F_1^\gamma} = \frac{1}{2} \sum_i C_{2i} Q_i q_i^-(x) \]

\[ a(x) = \frac{3}{10} \left( 2 C_{1u} - C_{1d} \right) \left( 1 + \frac{0.6 s^+}{u^+ + d^+} \right) \]

\[ b(x) = \frac{3}{10} \left( 2 C_{2u} - C_{2d} \right) \left( \frac{u_v + d_v}{u^+ + d^+} \right) \]

For an isoscalar target \(^2\text{H}\), structure functions largely simplifies:

\[ x \equiv x_{Bjorken} \quad y \equiv 1 - E'/E \]

\[ q_i^+(x) \equiv q_i(x) + \bar{q}_i(x) \]

\[ q_i^-(x) = q_i^V(x) \equiv q_i(x) - \bar{q}_i(x) \]
Best Data on $C_{1q}$ (eq AV couplings) from PVES+APV

Androic et al., PRL 111, 141803 (2013);
Projecting to $C_{1q}$ vs $C_{2q}$ (e-q AV vs. VA couplings)
Add E122
and combine them
then zoom in
PVDIS at 6 GeV (JLab E08-011)
- **Staff:** ~700
- **User community:** ~1300
- Beam first delivered in 10/95
- ~1/3 of US PhDs in Nuclear Physics
- **Energy:** 6 GeV, 12 GeV ongoing
- The largest superconducting RF accelerator in the world, the highest polarized luminosity.
PVDIS at 6 GeV (JLab E08-011, ran in Oct-Dec. 2009)

- Measured two DIS points: $Q^2=1.085$ and 1.901 (GeV/c)$^2$
- Collected 170 billion (E9) electrons in total

Students: Xiaoyan Deng, Kai Pan, Diancheng Wang (PhD)

Postdoc: Ramesh Subedi

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From Measured to Physics Asymmetry (Unblinded in 2012)

\[ A_{Q^2=1.085, x=0.241}^{\text{raw}} = -78.45 \pm 2.68 \pm 0.07 \text{ ppm} \]

\[ A_{Q^2=1.901, x=0.295}^{\text{raw}} = -140.30 \pm 10.43 \pm 0.16 \text{ ppm (L)} \]
\[ A_{Q^2=1.901, x=0.295}^{\text{raw}} = -139.84 \pm 6.58 \pm 0.46 \text{ ppm (R)} \]

- beam polarization
- counting deadtime
- EM radiative correction
- box correction
- target aluminum endcap
- beam depolarization
- beam-normal asym
- \(Q^2\) determination
- pair production
- target impurity
- charged pion background

\[ A_{Q^2=1.085, x=0.241}^{\text{phys}} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm} \]
\[ A_{Q^2=1.901, x=0.295}^{\text{phys}} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm} \]
Compare to Standard Model?

\[ A_{Q^2=1.085, x=0.241}^{\text{phys}} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm} \]

\[ A_{SM} = (1.156 \times 10^{-4}) \left[ (2 C_{1u} - C_{1d}) + 0.348 (2 C_{2u} - C_{2d}) \right] = -87.7 \text{ ppm} \]

\[ A_{Q^2=1.901, x=0.295}^{\text{phys}} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm} \]

\[ A_{SM} = (2.022 \times 10^{-4}) \left[ (2 C_{1u} - C_{1d}) + 0.594 (2 C_{2u} - C_{2d}) \right] = -158.9 \text{ ppm} \]
Extracting Effective Couplings

$$A^{phys}_{Q^2=1.085, x=0.241} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm}$$

$$A^{SM} = \left(1.156 \times 10^{-4}\right) \left[ (2 C_{1u} - C_{1d}) + 0.348 (2 C_{2u} - C_{2d}) \right] = -87.7 \text{ ppm}$$

uncertainty due to PDF: 0.5%  5%
uncertainty due to HT: 0.5%/Q^2, 0.7 ppm

$$A^{phys}_{Q^2=1.901, x=0.295} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm}$$

$$A^{SM} = \left(2.022 \times 10^{-4}\right) \left[ (2 C_{1u} - C_{1d}) + 0.594 (2 C_{2u} - C_{2d}) \right] = -158.9 \text{ ppm}$$

uncertainty due to PDF: 0.5%  5%
uncertainty due to HT: 0.5%/Q^2, 1.2 ppm

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Previous data: Elastic PVES + APV
Add JLab 6 GeV PVDIS
Wang et al., Nature 506, no. 7486, 67 (2014);

factor five improvement
$2C_{2u} - C_{2d}$

$2\sigma$ from zero - clearly identified parity-violating contribution from quarks' axial charge

"Measurement of parity violation in electron-quark scattering"

Wang et al., Nature 506, no. 7486, 67 (2014);
Quarks are not ambidextrous

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. See Letter P.67

Marciano., Nature 506, no. 7486, 43 (2014);

"Measurement of parity violation in electron-quark scattering"

Wang et al., Nature 506, no. 7486, 67 (2014);
BSM Mass Limit on eq VA contact interaction

Complementary to LHC results on the mass limit of eq contact interactions

Wang et al., Nature 506, no. 7486, 67 (2014);
Coherent PVDIS Program with SoLID @ 11 GeV

"SoLID" spectrometer

SoLID Physics topics:
- PVDIS
- SIDIS
- J/ψ

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Coherent PVDIS Program with SoLID @ 11 GeV

Goal on $C_{2q}$: one order of magnitude improvement over 6 GeV

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Coherent PVDIS Program with SoLID @ 11 GeV

Goal on $C_{2q}$: one order of magnitude improvement over 6 GeV
Coherent PVDIS Program with SoLID @ 11 GeV

$[2 g^{e_u} - g^{e_d}]_{AV}$

$[2 g^{e_u} - g^{e_d}]_{VA}$

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What do you expect a biologist to get from reading your paper?

Wang et al., Nature 506, no. 7486, 67 (2014);
Marciano., Nature 506, no. 7486, 43 (2014);
Disclaimer: The following slides are for promoting curiosity and new ideas ONLY.
Well, the whole biological world is chiral

All living organisms contain almost only 'left-handed' amino-acids and 'right-handed' sugars

An object that cannot be superimposed on its mirror image is called chiral

For physicists: do you know the difference between chirality and helicity?

pharmaceuticals must be chirally correct to work.

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Well, the whole biological world is chiral. All living organisms contain almost only ‘left-handed’ amino-acids and ‘right-handed’ sugars.

An object that cannot be superimposed on its mirror image is called chiral.

Physicists are studying the same thing – chirality of elementary particles!

Pharmaceuticals must be chirally correct to work.

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Why is the whole world chiral?

How does parity violation “show up” in the macroscopic world?

CP violation

The existence of our universe

10,000,000,000 10,000,000,001

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Why is the whole world chiral?

How does parity violation “show up” in the macroscopic world?

The existence of our universe

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Chirality contributes to complexity of molecules, which is essential for the origin of life.
Why is the whole world chiral?

How does parity violation “show up” in the macroscopic world?

- CP violation
- Parity violation
- The existence of our universe
- The existence(?) of life?

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Symmetry in the macroscopic world comes from symmetry in the underlying building blocks and interactions. So what is the cause of the chiral structure of our biological world? Could it be explained from physics? Could it come partially from parity violation?

How does parity violation affect the macroscopic world?
Summary and Perspectives

The 6 GeV PVDIS from JLab:

- Improved world data on the eq VA effective coupling term $2C_{2u}-C_{2d}$ by factor of five
- agrees with the SM
- showed $2C_{2u}-C_{2d}$ is $2\sigma$ from zero - indicating a nonzero contribution to PVDIS asymmetry due to quark's chirality preference
- BSM mass limits complimentary to collider experiments.

“New construction” experiments at JLab 12 GeV:

- Will improve $C_{2q}$ by another order of magnitude.

Subedi et al, NIM-A 724, 90 (2013); Wang et al., PRL 111, 082501 (2013); Wang et al., Nature 506, no.7486, 67 (2014); long paper accepted by Phys. Rev. C.